

**MULTI-FREQUENCY WIDEBAND MICROSTRIP PATCH ANTENNA
FOR WIRELESS APPLICATIONS**

A

Thesis

submitted for the award of the degree of

DOCTOR OF PHILOSOPHY

by

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Certificate

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Declaration

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Abstract

Remarkable equipment development in the field of communication and the growing end user requirement has lifted the need for multi-functional wireless communication devices. Since the antenna is the most basic part of each wireless communication scheme, therefore, multi-functional antennas are looked for to meet up the present day requirements. The antennas are so designed that these could be able to sustain compound functions in a particular single antenna system rather than sustaining one operational frequency. For this reason multiband/multi-frequency/multi-standard antennas can be used basically to lessen the amount of antennas needed for any projected system application. The purpose of this thesis is to investigate novel methods to develop microstrip patch antennas (MPAs) that exhibit multi-frequency/wideband behavior. Because of the rapid advancements in the industry of wireless communication, original and new antenna design structures that could be utilized in more than one single frequency band and those that permit size reduction are in great essential activity. For example, services relating mobile telephony need conveniently transported devices congenial with Global System for Mobile Communication (GSM)/Digital Cellular Service (DCS)/Universal Mobile Telecommunications System (UMTS) technology and the afore mentioned equipment should also colligate the users to Wireless Local Area Network (WLAN) networks established on 2.5 GHz/5 GHz communication standards. Thus, the design of compact antennas suited for these devices is of extraordinary concern. Several techniques have been suggested for the design of radiating elements of this type, the relatively large majority of which are microstrip antennas. An ordinary feature of virtually the whole of the multi-frequency printed elements is that they generally come from an initial patch of common shape which is perturbed in the succeeding stage. Depending upon the method of shape perturbation or disturbance, the development and analysis of multi-frequency/multi-standard microstrip antennas can be carried out. The design aims of getting an appreciable reflection coefficient, wide impedance bandwidth, increased gain, perfect impedance matching, increased frequency ratio and reasonable antenna size with multi-frequency operation are considered as the main goals of the present thesis. This thesis describes original work done for getting multi-frequency and wideband behavior of microstrip antennas. Microstrip antennas suffer from many constraints on their performance. One major restriction is their narrow

impedance bandwidth. An effective method to resolve this is adding more resonators and slots to the antenna structure to achieve multi-resonance and hence wider bandwidth. Bandwidth can also be increased using a Defected Ground Structure (DGS). On the basis of dimensions and shape of the defect in the 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 a simple shape to the complicated shape for getting the desired performance as discussed in chapters three. Also, by making slight modifications in the conducting patch and ground structures in the form of slits or slots, excitation of an additional resonance beside the fundamental resonating frequency can be allowed as discussed in chapter four. The current distribution may be changed accordingly. With the correct coupling between the resonant modes, the impedance bandwidth can be significantly increased. Furthermore, four more novel antenna designs with their simulated reflection coefficient and radiation pattern results have been presented in chapter five. Overall, all the proposed six antenna designs presented in chapters three, four and five are capable of exhibiting dual or multi-frequency wideband or broadband behavior. This whole research is verified through analytical simulations using three dimensional electromagnetic simulator - Computer Simulation Technology Microwave Studio Version 9.0 (CST MWS V9.0). Experimental investigations and measurements have been carried out using Vector Network Analyzer (VNA) available in Microwave and Antenna Laboratory, T.U., Patiala and Anechoic Chamber available in Millimeter Wave Laboratory, I.I.T., Roorkee.

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Contents

	Page No.
Certificate	ii
Declaration	iii
Abstract	iv
Acknowledgements	vi
Contents	ix
List of Figures	xii
List of Tables	xvii
Acronyms and Abbreviations	xviii
1. INTRODUCTION	1-8
1.1. General Introduction	1
1.2. Motivation for Thesis	2
1.3. Problem Statement, Research Objectives and Scope	3
1.4. Methodology	6
1.5. Organization of Thesis	7
2. PRELIMINARIES AND REVIEW	9-68
2.1. Introduction	9
2.2. Background	9
2.3. Microstrip Antennas: An Overview	12
2.3.1. Microstrip Antenna Basic Structure	12
2.3.2. Advantages and Disadvantages of Microstrip Antennas	14
2.3.3. Feeding Methods of Microstrip Antennas	16
2.3.4. Antenna Design Parameters	23
2.3.5. Methods of Analysis of Microstrip Antennas	27
2.3.6. Applications of Microstrip Antennas	33
2.4. Multi-frequency Microstrip Antennas	34
2.5. Techniques for Multi-frequency Operation	36
2.5.1. Slot Loaded Multiband Microstrip Antennas	38
2.5.2. Dual Port Excited Multiband Microstrip Antennas	43

2.5.3.	Corner Excited Multiband Microstrip Antennas	44
2.5.4.	Multiple Patches	44
2.5.5.	Bowtie Patches Loaded with Slots	45
2.5.6.	Spiral Antennas	47
2.5.7.	Fractal Antennas	48
2.5.8.	Reduced Ground Plane	52
2.5.9.	Stacked Multiband Microstrip Antennas	53
2.5.10.	Multiband Microstrip Antennas using DGS	54
2.6.	Some Relevant Developments in Multi-frequency Microstrip Antennas	55
3.	DUAL BAND MULTISTRIP MONOPOLE ANTENNA WITH DGS	69-79
3.1.	Introduction	69
3.2.	Monopole Antenna Design and Simulated Results	70
3.2.1.	Reflection Coefficient and Voltage Standing Wave Ratio	71
3.2.2.	Current Distribution Results	73
3.2.3.	Simulated Reflection Coefficient without DGS	74
3.3.	Fabrication and Measurement Results	76
3.4.	Discussion	79
4.	TRIPLE BAND O-SHAPE MPA WITH MODIFIED GROUND PLANE	80-93
4.1.	Introduction	80
4.2.	Antenna Design and Simulated Results	81
4.2.1.	Reflection Coefficient and Voltage Standing Wave Ratio	82
4.2.2.	Parametric Study of Antenna	84
4.2.3.	Current Distribution Results	87
4.3.	Fabrication and Measurement Results	88
4.4.	Discussion	93
5.	SIMULATION STUDIES OF SOME NEW MPAs	94-125
5.1.	Design I - Multi-Frequency Wideband MPA for 5.2/5.5/5.8 GHz	94
5.1.1.	Introduction	94
5.1.2.	Antenna Geometry	95
5.1.3.	Simulated Results	96

5.1.4. Discussion	100
5.2. Design II - CPW-Fed Miniature Slotted Multi-Frequency Wideband MPA for WLAN/Wi-Fi/WiMAX/IMT/AMSAT/WAVE Applications	100
5.2.1. Introduction	101
5.2.2. Antenna Geometry	102
5.2.3. Simulated Results	103
5.2.4. Discussion	109
5.3. Design III - Design of Coaxial Fed MPA for WiMAX/IMT Applications	109
5.3.1. Introduction	110
5.3.2. Antenna Geometry	111
5.3.3. Simulated Results	112
5.3.4. Discussion	116
5.4. Design IV - Design of Coaxial Fed Broadband Single Layer Rectangular MPA for WLAN/WiMAX Applications	117
5.4.1. Introduction	117
5.4.2. Antenna Geometry	118
5.4.3. Simulated Results	120
5.4.4. Discussion	125
6. CONCLUSIONS AND FUTURE SCOPE OF WORK	126-131
6.1. Conclusions	126
6.2. Future Scope of Work	130
REFERENCES	132-156
AUTHOR'S PUBLICATIONS	157-158
VITA	159

List of Figures

Figure No.	Description	Page No.
Figure 2.1	Geometrical Structure of a MPA	13
Figure 2.2	General configurations of microstrip patch elements	13
Figure 2.3	Microstrip feed at the radiating edge	17
Figure 2.4	Gap coupled microstrip feed	18
Figure 2.5	Microstrip inset feed	18
Figure 2.6	Coaxial fed rectangular microstrip patch antenna	19
Figure 2.7	Aperture-coupled feed	20
Figure 2.8	Proximity-coupled feed	21
Figure 2.9	Coplanar waveguide feed	22
Figure 2.10	Microstrip line	28
Figure 2.11	Electric field lines	28
Figure 2.12	Geometrical configuration of a rectangular MPA	29
Figure 2.13	Top view of antenna	29
Figure 2.14	Side view of antenna	29
Figure 2.15	Charge distribution and current density creation on the microstrip patch	31
Figure 2.16	Geometries of shorted rectangular patch antenna for dual frequency operation with (a) an L-shape slit (b) a folded slit and (c) U-slot	39
Figure 2.17	Microstrip elements coated with (a) single and (b) multiple T-notches	40
Figure 2.18	Configurations of MPAs (a) dual U-slot loaded patch (b) patch loaded with unequal slits and tiny circular slots	40
Figure 2.19	Dual-band microstrip antenna with multilayered substrate (a) Top view (b) Side view (c) Reflection coefficient	41
Figure 2.20	Reconfigured slotted antenna and its reflection coefficient	42
Figure 2.21	Multi-frequency RMPA with its reflection coefficient curve	43
Figure 2.22	3D model of the proposed E-shape MPA with its insertion & return Loss	43

Figure 2.23	Reflection coefficient of the proposed MPA having two single frequency antennas joined at the corner and fed at the connecting point	44
Figure 2.24	Top and side-view of a multi-frequency MPA with three conductively connected rings	45
Figure 2.25	Geometry of the bowtie MPA	46
Figure 2.26	Bowtie MPAs (a) the ordinary configuration, (b)-(d) patches modified by loading slots of various shapes for multiband operation	46
Figure 2.27	Microstrip spiral configurations (a) the ordinary shape (b) conductor folded back onto itself (c) small number of bends and truncated corners	47
Figure 2.28	The generator and first three stages of the Koch fractal curve (a)-(d), and Koch fractal island antenna (e)-(h)	50
Figure 2.29	The generator and first three stages of Sierpinski fractal gasket (a)-(d)	51
Figure 2.30	The generator and first three stages of Hilbert fractal antennas (a)-(d)	51
Figure 2.31	The generator and two lower stages of Square Curve fractal (a)-(c)	52
Figure 2.32	Proposed antenna with reduced ground plane	53
Figure 2.33	Geometry of proposed stacked patch antenna (a) Top view, (b) Side view	53
Figure 2.34	Proposed dual frequency patch antenna and its reflection coefficient	54
Figure 2.35	Multiband MPA using DGS (a) The schematic of a spiral cell used in DGS (b) the cell design for optimized antenna size reduction	55
Figure 3.1	Configuration of the proposed antenna with defected ground structure	71
Figure 3.2	Simulated reflection coefficient of proposed antenna showing bandwidths of 327 MHz and 604 MHz at respective resonating frequencies of 2.385 and 5.4 GHz	72
Figure 3.3	VSWR of the proposed antenna at 2.385 GHz and 5.4 GHz	73
Figure 3.4	Surface current distributions of the proposed antenna at (a) 2.385 GHz and (b) 5.4 GHz bands	73-74
Figure 3.5	Simulated reflection coefficient of antenna without the DGS showing	75

	bandwidths of 190 MHz and 200 MHz at respective resonating frequencies of 2.385 GHz and 5.4 GHz	
Figure 3.6	Photograph of the proposed antenna	76
Figure 3.7	Measured reflection coefficient of the proposed antenna	77
Figure 3.8	Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 2.385 GHz	78
Figure 3.9	Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 5.4 GHz	78
Figure 3.10	Simulated (solid) and Measured (dash) gains of the proposed antenna at (a) 2.385 GHz and (b) 5.4 GHz	79
Figure 4.1	Antenna configuration of the proposed antenna (a) Patch side (Front view) (b) Ground side (Back view)	82
Figure 4.2	Simulated reflection coefficient curve of proposed triple-band antenna at three different resonating frequency bands	83
Figure 4.3	VSWR of the designed antenna at 2.24 GHz, 3.12 GHz and 5.92 GHz	84
Figure 4.4	L-C resonator circuit	84
Figure 4.5	Simulated reflection coefficients with different values of lengths of L_2 ($L_3 = 16$ mm and $L_4 = 10$ mm)	85
Figure 4.6	Simulated reflection coefficients with different values of lengths of L_3 ($L_2 = 7.6$ mm and $L_4 = 10$ mm)	85
Figure 4.7	Simulated reflection coefficient against frequency for the proposed antenna without shorter slit of length $L_4 = 10$ mm ($L_2 = 7.6$ mm and $L_3 = 16$ mm)	86
Figure 4.8	Simulated surface current distributions of the proposed antenna at two stop-bands (a) 2.8 GHz (b) 5.16 GHz	87
Figure 4.9	Photograph of the proposed antenna	88
Figure 4.10	Measured reflection coefficient curve of the proposed antenna	89
Figure 4.11	Simulated and measured reflection coefficient curves of the designed antenna	90
Figure 4.12	Simulated (solid) and measured (dash) (a) E-plane radiation pattern,	91

	(b) H-plane radiation pattern at 2.45 GHz	
Figure 4.13	Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 3.5 GHz	91
Figure 4.14	Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 5.8 GHz	92
Figure 4.15	Gain plots of the proposed antenna at (a) 2.45 GHz, (b) 3.5 GHz and (c) 5.8 GHz frequency bands	92
Figure 5.1	Front & Back view of proposed MSA	95
Figure 5.2	Simulated reflection coefficient of the proposed patch antenna	97
Figure 5.3	Radiation pattern of proposed patch antenna at 5.551 GHz (a) 3-D plot (b) E-plane and (c) H-plane	98
Figure 5.4	Radiation pattern of proposed patch antenna at 6.34 GHz (a) 3-D plot (b) E-plane and (c) H-plane	99
Figure 5.5	Configuration of the proposed antenna with modified ground plane	103
Figure 5.6	Simulated reflection coefficient of proposed antenna	104
Figure 5.7	Simulated surface current distributions of the proposed antenna at (a) 2.45 GHz (b) 4 GHz	105
Figure 5.8	Radiation pattern of proposed patch antenna at 2.45 GHz (a) 3-D plot (b) E-plane and (c) H-plane	106
Figure 5.9	Radiation pattern of proposed patch antenna at 3.5 GHz (a) 3-D plot (b) E-plane and (c) H-plane	107
Figure 5.10	Radiation pattern of proposed patch antenna at 5.5 GHz (a) 3-D plot (b) E-plane and (c) H-plane	108
Figure 5.11	Geometry of slot loaded single layer patch antenna	112
Figure 5.12	Reflection coefficient vs. frequency graph	113
Figure 5.13	Radiation pattern of proposed patch antenna at 2.66 GHz (a) 3-D plot (b) E-plane and (c) H-plane	114
Figure 5.14	Radiation pattern of proposed patch antenna at 4 GHz (a) 3-D plot (b) E-plane and (c) H-plane	115
Figure 5.15	Geometry of proposed modified E-shaped patch antenna	119

Figure 5.16	Simulated reflection coefficient of proposed antenna	120
Figure 5.17	Radiation pattern of proposed patch antenna at 5.2 GHz (a) 3-D plot (b) E-plane and (c) H-plane	121-122
Figure 5.18	Radiation pattern of proposed patch antenna at 5.5 GHz (a) 3-D plot (b) E-plane and (c) H-plane	123
Figure 5.19	Radiation pattern of proposed patch antenna at 5.5 GHz (a) 3-D plot (b) E-plane and (c) H-plane	124

List of Tables

Table No.	Description	Page No.
Table 1.1	Wireless frequency bands	5
Table 2.1	Comparison of various types of feed structures for MPAs	23
Table 3.1	Optimal design parameters of the proposed MPA	71
Table 3.2	Comparative analysis of bandwidth with and without DGS	75
Table 4.1	Optimal design parameters of the proposed antenna configuration	83

Acronyms and Abbreviations

AMSAT	Amateur Satellite
BW	Bandwidth
CPW	Coplanar Waveguide
CRLHTL	Composite Right Left Handed Transmission Line
CSRR	Complementary Split Ring Resonator
CST MWS V9.0	Computer Simulation Technology Microwave Studio Version 9.0
DBS	Direct Broadcast Service
DCS	Digital Cellular Service
DGS	Defected Ground Structure
DRA	Direct Radiating Antennas
EBG	Electromagnetic Band Gap
E-GSM	Extended-Global System for Mobile Communication
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
FIT	Finite Integral Technique
FRSPMA	Frequency Reconfigurable Stacked Patch Microstrip Antenna
GHz	Giga-Hertz
GPS	Global Positioning System
GSM	Global System for Mobile Communication
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunication
ISM	Industrial, Scientific and Medical
ITS	Intelligent Transport System
LCD	Liquid Crystal Display
MATLAB	Matrix Laboratory
MIMO	Multiple Input Multiple Output
MMIC	Microwave and Millimeter-Wave Integrated Circuit
MoM	Method of Moments

MPA	Microstrip Patch Antenna
MTL	Multi-conductor Transmission Line
NRL	National Research Laboratory
PBA	Perfect Boundary Approximation
PBG	Photonic Band Gap
PC	Personal Computer
PCB	Printed Circuit Board
PCS	Personal Communications Service
PEC	Perfect Electric Conductor
PIFA	Planar Inverted-F Antenna
PIN	p-type semiconductor intrinsic n-type semiconductor
PSO	Particle Swarm Optimization
RF	Radio Frequency
RFID	Radio Frequency Identification
RL	Return Loss
RLC	Resistance Inductance Capacitance
RMPA	Rectangular Microstrip Patch Antenna
SAR	Synthetic Aperture Radar
SDT	Spectral Domain Technique
SMPA	Stacked Microstrip Patch Antenna
TEM	Transverse Electric Magnetic
TM	Transverse Magnetic
UHF	Ultra High Frequency
USGRMAA	U-Slot Gap coupled Rectangular Microstrip Array Antenna
UWB	Ultra Wide Band
VNA	Vector Network Analyzer
WAVE	Wireless Access in Vehicular Environment
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

WMTS	Wireless Medical Telemetry Service
XP	Cross-Polarized
3D	Three Dimensional

Chapter 1

Introduction

1.1. General Introduction

Communication has become highest in importance to humanity ever since the beginning of cultural, intellectual and material development. It has basically become the crucial element to significant modifications in the organized arrangement of industries and businesses because they themselves adapt to the alteration to an information economy. Certainly, information is the indispensable part of ultramodern economics and antennas offer Mother Nature a resolution to a wireless communication system [1]. In ancient times, communication was achieved by sound through voice. Nevertheless, as the intervening space of communication became larger, many devices were interpolated, such as drums, horns and so on. The fundamental element in all radio systems is a radio antenna. An antenna is a device which stipulates a method for diverging or receiving radio waves. It may be clearly characterized as the structure confederated with the region of transmutation within a free space wave and a guided wave, or vice versa [2]. Alternatively, electromagnetic energy is coupled via radio antennas from one medium (space) to another e.g. coaxial cable, waveguide, or wire. Hence, information can be caused to pass within distinct locations without any interfering structure. Moreover, antennas are obligatory in such circumstances where it is extremely difficult, incapable or inefficient to yield guiding structures among the receiver and transmitter. A guided wave traversing over the length of a transmission line will disseminate as a free space wave. The guided wave and the free space wave can be considered as a plane wave and a spherically expanding wave respectively [2]. In accordance with the unvaried part of the line, energy is guided as a plane wave with scarce loss, as long as the openness within the wires is a small fragment of a wavelength λ . As the transmission line detachment/breakup is in close approximation to a wavelength or more, the wave experiences a tendency to be radiated so that the opened-out line behaves like an antenna, which established the free space wave. Currents on the transmission line emanate on the transmission line and terminate there; however, on the contrary the fields affiliated with them keep on prevailing. Becoming unreserved in expression, the region of transmutation/rectification within the free space wave and the guided wave can be clearly outlined as an antenna. In this vigorous and vast field, the antenna technology has been an unavoidable collaborator of the communication innovation. Several outstanding advances that happened over the years are nowadays in general use. Regardless of countless disputes/challenges, the antenna technology

CHAPTER-1

INTRODUCTION

has grown with a fast pace to harness the electromagnetic spectrum, which is one of the greatest gifts of nature. Microstrip patch antennas developed as an upshot of microstrip circuits, which had become a fully-fledged sophisticated field of study [3]. Their design and actualization took assistance of the techniques especially designed for microstrip circuits and utilized microstrip substrates [4]. The expanding requirement of multi-frequency personal communications handsets promotes evolution of small-size integrated multi-frequency antennas. The favored solutions are normal metallic patches resonating at multiple frequencies. These patches permit an extraordinary versatility in the antenna design, as they are simple and cost-effective to manufacture. The need for extraordinary performance of multi-standard communication devices has led to the extensive investigation and research of this attractive topic. Consequently, it is noteworthy to examine the fundamental ideas of multi-frequency antenna structures, a structure which evokes the world of wireless communication to a novel modern generation. Concurrently, with the blooming phase of these antennas, it is essential that the designer retains in mind two critical aspects: the ergonomic and the physical properties of the antenna that are intended to maximize productivity by reducing operator fatigue and discomfort. Also, the overall expenditure must satisfy the customer's anticipations. The first quantum jump to learn about multi-frequency wideband MPA systems lead to the basic knowledge on antenna theory and their design parameters. Establishing a good groundwork is necessary, as we will be going to examine the multi-frequency wideband antennas. The reflection coefficient/ S_{11} , radiation pattern performance and gain plots of these multi-frequency microstrip antennas at distinct resonating frequency bands will have to be looked into and thus research will be executed to a greater extent to bring a good understanding by studying various simulation techniques and finally implementing one of them. Hence, our aim is not only to study, simulate and analyze dual and multi-frequency microstrip antenna systems but also to fabricate and test those antennas and compare the simulated and measured results for any possible errors.

1.2. Motivation for Thesis

The concept of multi-frequency/wideband antennas has intrigued the microwave engineering community. An antenna satisfying several communication standards simultaneously with a quite good bandwidth over all the resonating frequency bands is called a multi-frequency wideband MPA. Currently, the capability to merge/incorporate multiple communication standards into an

individual system has emerged as an augmenting demand for a modern portable wireless communication device. A latest antenna necessitates not only the task of stipulating a dual, triple or multi-frequency operation, but also an easy and non complex structure, small size, and simple integration with the system circuit. Several auspicious/encouraging dual or multi-frequency planar antenna structures have been discussed in literature. Nevertheless, most of these antennas possess either a huge overall size or a complicated design to limit the application areas of a particular antenna. Thus, seeing the scenario, the main aim of our thesis is to design simple, compact, inexpensive, multi-frequency wideband MPAs using novel designs of radiating structures feasible for wireless communication applications. For instance, a multistrip monopole antenna to be discussed in chapter three that incorporates a novel shape of DGS has been proven to exhibit dual band behavior covering several frequency bands simultaneously. A DGS enhances the performance of MPAs without increasing much the complexity. A DGS includes an additional/redundant degree of freedom in microwave circuit configuration and unlocks the doorway to a broad scope of applications. Recently, a number of new DGSs have been investigated and they have become one of the most enthralling areas of research in microwave engineering discipline. Moreover, a triple-band O-shaped patch antenna for wireless communication applications has been discussed in chapter four and verified to cover many frequency bands simultaneously with suitable resonance characteristics. In this antenna design, a strip is incorporated on the right side of an O-shaped radiating patch element and ground plane has been remodeled with an inverted L-slot and two unequal rectangular slits. This multiband property of present antenna structures has provided the basic impetus and motivation to take-up the present research problem of designing multi-frequency wideband MPAs.

1.3. Problem Statement, Research Objectives and Scope

Problem Statement:

The problem statement of the proposed research work is to prepare a state-of-the-art overview of MPAs with multi-frequency wideband behavior using novel designs of patch (radiating element) and ground structures [5]. Our goal is to study multi-frequency MPAs suitable for wireless applications and to provide a framework for solving various design problems of MPAs with the incorporation of newer techniques for obtaining multi-frequency operation. For obtaining the deep understanding of antennas suitable for numerous applications, various antenna designs have

CHAPTER-1

INTRODUCTION

been studied which are already reported in literature [6-10]. Also, the antennas are simulated and implemented with different feed structures [11]. Gathering the overall knowledge about single, dual and multiband antennas feasible for various applications, the main objectives were designed as the following:

Research Objectives:

- To design and simulate a dual wideband antenna to cover the Wireless Local Area Network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) frequency bands.
 - Parametric studies on the proposed antenna.
 - Fabrication and testing of the proposed design.
- To design and simulate a compact multi-frequency MPA for wireless applications covering Cellular systems/WLAN/WiMAX frequency bands.
 - Parametric studies on the proposed MPA as aforesaid.
 - Fabrication and testing of proposed MPA design.
- To compare the simulated and measured results for both dual wideband MPA and multi-frequency MPA.

In order to accomplish the above stated/intimated research objectives and illustrate the potential effectiveness of the proposed multi-frequency wideband MPAs, a collection of diversified problems with varied confrontations have been considered and solved. These problems are as follows:

- Effect of DGS on a multistrip monopole antenna (Chapter 3 of thesis).
- Effect of incorporating/coupling a strip on the right side of O-shaped radiating patch with inverted L-slot and two unequal rectangular slits in ground plane (Chapter 4 of thesis).
- A number of antenna design configurations have been simulated and presented; out of which some possess dual band behavior while others possess multiband/multi-frequency behavior (Chapter 5 of thesis).

Scope:

A distinctive microwave design activity consists of problem recognition, specification generation, notion/thought development, electromagnetic analytical investigation, performance evaluation, primary design, concluding design, fabrication/construction, and testing. Our

research work in the current thesis is concentrated on transforming primary design to concluding design which comprises steps such as designing, computer-assisted investigation, fabrication and testing. Therefore, the supposition is made that the primary designs and some information related to the design parameters (such as some ranges, and prescriptions etc.) are accessible. In the present work, this information is acquired from previously published works and from a person who has extensive skill/proficiency and knowledge in a particular field.

Table 1.1: Wireless Frequency Bands

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

Furthermore, the present research work emphasizes multi-frequency microstrip antennas and the fabrication and testing of the designed MPAs is performed for the validation of results. Multi-frequency MPAs maintaining high gain, appreciable reflection coefficient and good radiation pattern designed in this thesis will be helpful in the field of wireless communication covering several wireless communication standards viz. WLAN, WiMAX, Wireless Fidelity (Wi-Fi), International Mobile Telecommunication (IMT), Industrial, Scientific and medical (ISM) and

CHAPTER-1

INTRODUCTION

Bluetooth, Multiple Input Multiple Output (MIMO), Amateur Satellite (AMSAT), Wireless Access in Vehicular Environment (WAVE) and Intelligent Transport System (ITS) simultaneously. Thus, the expected outcome of thesis will be mainly designing a small size and inexpensive MPA which integrates numerous wireless applications covering different bands in a single device. The MPAs proposed in this thesis can be used for commercial production. They can be patented also. The different wireless frequency bands which are to be covered/satisfied while designing various antenna structures that exhibit dual or multi-frequency wideband behavior in this thesis have been summarized in Table 1.1.

1.4. Methodology

- Extensive literature survey is conducted to study the literature available in the field of dual and multi-frequency microstrip antennas.
- Detailed study of dual band and multi-frequency resonant antenna structures.
- The effects on gain, reflection coefficient and radiation pattern are analyzed when antenna dimensions are changed.
- For conducting simulation of proposed antenna designs, the Full Wave Electromagnetic Simulator CST MWS V9.0 has been used. The complete parametric study for all the designed antennas presented in chapters three, four, and five has been done by using the “parameter sweep” option which is in built in the transient solver window in CST MWS V9.0.
- The proposed antenna designs are projected on “Fiber-glass Reinforced epoxy” FR-4 material which is an inexpensive and readily available substrate material.
- The reflection coefficient or S_{11} parameters of the proposed antennas have been measured using Vector Network Analyzer available at Microwave and Antenna Laboratory, ECED in Thapar University, Patiala.
- The field patterns and gain measurements have been analyzed using Anechoic Chamber available at Millimeter Wave Laboratory, ECED in Indian Institute of Technology, Roorkee.
- For showing the comparative analysis of simulated and measured results for reflection coefficient and radiation pattern, the simulation software Mathworks-Matrix Laboratory Version 7 (MATLAB R2007b) has been used for making various types of plots.

1.5. Organization of Thesis

This thesis aims to detail some specific MPA configurations and the study of various novel techniques for obtaining multi-frequency behavior along with them, accumulating in a single mass/quantity, the information that is presently dispersed around in different journals, proceedings of conferences, and books. This thesis interprets basic fundamentals of specific antenna design methods, rendering appropriate examples. Many theoretical simulations and parametric studies have been carried out to provide physical insight into multi-frequency MPAs. In addition, several tips and practical verifications are included for quick validations. An attempt has been made to make the text self-contained and to cover different aspects of MPAs to exhibit multi-frequency behavior. This thesis has been written keeping in mind its usefulness for students, teachers, practicing engineers, and researchers. In accordance with this goal, the linguistic communication of the present thesis is kept as easy as possible failing to lose its technological objectivity, so that readers can promptly apprehend the ideas contained inside. A brief epitome/summary is given at the last of each chapter to accentuate/emphasize the significant points given in the chapter. The thesis incorporates six chapters including the present one. In the first chapter, a very general introduction to antennas including the need of multi-frequency microstrip antennas has been given. In addition to that, motivation for writing the thesis, various research objectives, problem statement and scope of thesis has been discussed. Chapter two has been totally devoted to the basics of microstrip antennas, working principle, advantages, disadvantages, feeding techniques, analytical models of microstrip antennas, techniques for multi-frequency behavior and latest developments in multi-frequency MPAs. The main body of the thesis that is the design and simulation of multi-frequency MPAs will be seen in chapters three, four and five. Chapter three discusses a novel approach to increase the impedance bandwidth of a MPA with multi-frequency operation. In this antenna design, a dual band multistrip monopole antenna with DGS and double microstrip stub feedline has been presented which operates at WLAN/IMT/Bluetooth/WiMAX wireless frequency bands. Chapter four describes a simple, compact and triple band operation of an O-shape MPA suitable for WLAN/Bluetooth/ISM/WiMAX/IMT/ITS/Satellite applications. In this antenna design, a strip is coupled on the right side of O-shaped radiating patch and an inverted L-slot and two unequal rectangular slits are engraved/inscribed in ground plane which play an important role in rejecting

CHAPTER-1

INTRODUCTION

the interfering signals in desired frequency bands. Chapter five presents four more antenna configurations that are designed and simulated using CST MWS V9.0. Design I presents a new single layer rectangular MPA with broadband behavior for WLAN and WiMAX applications. The broadband multi-standard behavior so obtained is due to the pi-shape slot embedded into the ground. Design II presents a new compact MPA comprising two horizontal modified E-shape slots fed by a coplanar waveguide (CPW) suitable for WLAN/Wi-Fi/WiMAX/IMT/AMSAT/WAVE/Satellite applications. Design III presents a broadband and a compact rectangular MPA comprising a single layer and single co-axial feed mechanism that is manufactured by embedding a T-shape slot under a pi-shape slot in the patch. Moreover, four circular slots have been cut down into the radiating/diverging terminals of patch for broadband operation covering WiMAX and IMT standard frequency bands. Design IV demonstrates a new co-axial fed, single layer, E-shape rectangular MPA having planar geometry with broadband behavior for WLAN and WiMAX applications. The simulation study for all the chapters three to five has been performed using three dimensional electromagnetic simulation software CST MWS V9.0. Finally, chapter six draws the concluding remarks with the indication to possible future work.

Chapter 2

Preliminaries

&

Review

2.1. Introduction

Wireless communication has been evolved speedily in the preceding few decades and has put an impressive influence on human life. In the previous some years, the advancement of WLANs delineated one of the paramount involvements in the communication and information field. The compact MIMO antenna arrays have also been very popular for long term evolution standardized handsets [12-13]. Accordingly, the most recent vogue in government and commercial communication systems has been to formulate a minimal weight, a low profile and a low cost antenna which is susceptible of maintaining distinguished performance over a huge spectrum of frequencies. This technical inclination has centered a great labor into the design of a MPA that is one of the most thrilling evolutions in the history of electromagnetic [2-3] [14-16]. MPAs come under the family of printed patch radiating elements which are identical to parallel plate capacitors that take the advantage of printed circuit fabricating processes to explicate the radiating structure and feed. Out of all the printed microstrip antennas, comprising slots, tapered slots and dipoles; microstrip patch antenna is an intensive favored and conformable due to its boundless conspicuous characteristics which are not normally revealed in other antenna arrangements. These include effortless fabrication, efficient radiation potency, inexpensive production, low profile, relatively little weight, consistent with microwave and millimeter-wave integrated circuits (MMICs), easy and inexpensive to manufacture utilizing current trend printed circuit board technology and conformable to non-planar and planar surfaces [2] [17-20]. These characteristics are mainly accountable for the conquest of MPA as a subject for novel research and investigation.

2.2. Background

MPA engineering has a history of over 60 years [2] [17], they were initially introduced back in the 1950's. However, serious attention to microstrip radiators was not given until the 1970's, where they started maturing considerably and many of their constraints were overcome. Yet it remains in the words of recent articles that MPA is a vibrant field which is bursting with activity, and is likely to remain so in the foreseeable future [19]. In particular, there has been an augmenting enthusiasm in circular microstrip patch antennas technologies. In 1952, Englemann proposed the invention of the MPA [1], following this in 1953, Deschamps and Sichak proposal was one of the first to introduce the concept of microstrip radiators [21-26]. Two years later a

CHAPTER-2

PRELIMINARIES AND REVIEW

patent was issued to Gutton and Baissinot in France [17] [22] [24-25]. In 1960, Lewin shown interest in the radiation from stripline discontinuities, and towards the end of that decade, in unreported work, Kaloi studied rectangular and square structures [25]. In the sixties, Collings filed a patent for a strip radiator with multiple feed points [24] [27]. Troughton and Watkins have also studied open circuited circular resonant structures in microstrip, and also considered the energy loss due to radiation [28-29]. There was apparently no interest in making use of this nature of striplines or radiation from these resonant structures, and this is where the antenna concept went dormant until the early seventies. In the seventies, the accessibility of good substrates having little value of loss tangent and provocative/seductive mechanical and thermal features accelerated the development and fabrication [24]. Byron presented the concept of a conducting half wave length wide and several wavelength long strip radiator built on a dielectric substrate, and fed by coaxial connections. Also mentioned is that Theo Cheston from National Research Laboratory (NRL) has suggested that such an element is well-suited for phased array applications [24-25]. Howell and Munson were the first to practically develop MPAs in the seventies [21] [26] [30-31]. Various microstrip geometries were developed by Weinschel in 1973 for use on rockets, and in the following year, Sanford presented microstrip elements in conformal phased array for aircraft applications [25]. Extensive research and development followed shortly after, exploiting their numerous advantages, including reduction in size, weight and cost, besides the need for low-profile antennas on the emerging new generation of missiles. In 1975, microstrip patch antenna elements were further investigated by Garvin et al., Howell, Janes and Wilson [25] [30], studying missile based mounted MPAs and new design techniques for antenna arrays. Mathematical analysis and modeling started to get attention that year to further understand the theory. Initial investigations applied the concept of transmission lines to simple rectangular patches, and a year later Carver presented a paper describing the radiation pattern of microstrip disc antennas [25] [30]. MPAs have been of huge interest to the military as well. In 1977, John Kerr, US Army Electronics Command presented a new technique of controlling the resonant frequency of MPA [21]. This was accomplished by interjecting a cut in the centre of radiating patch, removing metallization and making the patch electrically smaller. The full theory was presented by Mink three years later [32], as well as introducing the concept of ring antennas. In 1978, Kerr also introduced the concept of tunable antennas by adding reactance to the

resonance, this was done by utilizing a length of transmission line [21]. In the same paper, he employed the concept of removal of metallization to achieve the appropriate conditions for circular polarization from patch antennas having single feed [21]. Following Kerr's discovery, Jones et al presented a technique for tuning the operating frequency of microstrip patch antennas using vias, or shorting posts adding inductive reactance that leads to raising the resonant frequency [21]. In the same year, Lo et al. introduced the first theoretical electromagnetic solution [21] [33], this is the Cavity model. In the same meeting, Montgomery introduced the full wave method [21], which also considers thicker dielectric and various shapes. Other similar work by Demeyard, Shen and Long, and Carver and Coffey were reported on advanced theoretical investigations [25]. October 1979 witnessed the earliest international workshop on Printed Circuit Antennas which was held in New Mexico. Its proceedings were presented in a major IEEE Transactions special edition, alongside co-sponsorship by the US Army research office and NMSU's Physical Science Laboratory [25] [30]. The initial 1980s were a principal focus in publications, there was practical realism of MPAs, two books were promulgated/publicized by Hall & Wood and Bahl, Bhartia & James, which go on in present use [22] [26]. Also substrates manufacturers started to offer wider ranges of products which could be used for MPAs. Advantages of MPAs, mainly ease of manufacture, low cost and profile, outweighed their performance disadvantages, i.e. narrow bandwidth. Therefore more interest was given for patch antennas to be used for applications operating at frequencies higher than 30 GHz such as aircraft to satellite communications. Studies on thick substrates and higher dielectric constants MPAs were also reported [34]. Nonetheless, most of the research in the early eighties was aiming to improve the inherent issue of microstrip patch antenna, i.e. the narrow impedance bandwidth [35]. Edge and probe fed antennas were the first two methods known for feeding into MPAs. Both excitation methods are inductive, dominating the frequency response at lower frequencies. However, for the patch to resonate, the inductive and capacitive components should cancel each other to achieve a zero reactance [26]. New feeding techniques, proximity and aperture coupled patch, were introduced to overcome this issue and achieve a wider bandwidth [35-36]. Microstrip patch antenna arrays were widely studied and developed in the eighties, as well as circular and other types of polarization [35] [37]. By the end of the eighties, there was a better insight into microstrip patch antennas. Microstrip patch antennas started invading the

CHAPTER-2

PRELIMINARIES AND REVIEW

commercial systems market in the nineties, thus satisfying the increasing need for mobile communication systems [18]. The availability of high speed processors and sophisticated simulation tools aided the fast developments in the field, and gave the opportunity for companies to develop their own version of MPAs to meet their own demands. Extensive studies on impedance bandwidth of MPAs were reported, including excellent results of up to 67% [35] and investigations to improve the efficiency as well as further methods of integrating MPAs into MMIC technology [38]. By the mid-nineties the development of handheld communications devices had increased the demand for smaller and lighter antennas, and hence, investigations were performed to reduce the size of MPAs [35] [39]. At the start of the 21st century, MPAs have been very popular for mobile systems; various methods of further improving the performance have been studied, such as Genetic Algorithm [40]. More interest and research are being pursued, trying to optimize the design in terms of wider bandwidth, radiation efficiency, controlling polarization properties and array architecture. At present, MPAs remain the topic of many publications and industrial development and indeed exciting a continuous development on electronic system design.

2.3. Microstrip Antennas: An Overview

In this section, a brief discussion on MPAs and their feeding mechanism is given along with the related design parameters and applications of such antennas.

2.3.1. Microstrip Antenna Basic Structure

Microstrip antennas are printed circuits functioning in the scope of microwave electromagnetic spectrum across the region of gigahertz frequencies [41]. Typical patch antennas are used for frequencies ranging from 1 GHz to 100 GHz [42]. In its most basic form, the conventional MPA comprises of a duet of equidistant and non intersecting conducting layers separated by a substrate (thickness $\ll \lambda$) as demonstrated in Figure 2.1 [2]. In this design arrangement, the topmost conducting layer or “patch” is a considerable fraction of the wavelength and the origin of emanation/emission where electromagnetic energy fringes off into the dielectric medium and the peripheries of the patch [2] [35]. The subordinate conducting layer behaves as an entirely reflecting ground plane, moving energy into free space and back through the substrate in a roughly opposite direction after an appreciable impact [17-18] [21]. MPAs emit principally due to the fringing fields amidst the patch boundary and the ground [17]. Alternatively, radiation can

be delineated with respect to the distribution of surface current densities on the patch metallization. Generically, the patch is composed of conducting stuff like gold or copper and can adopt any realistic configuration. The feed lines and radiating patch are normally engraved on the insulating substrate by a photomechanical process.

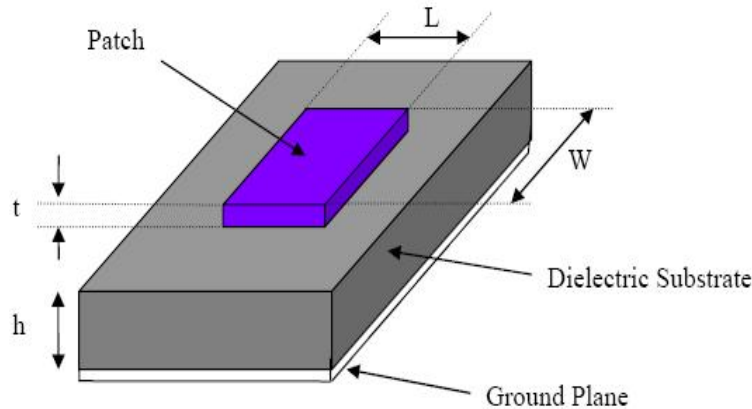


Figure 2.1: Geometrical structure of a MPA [2]

The functioning procedure of a MPA is impelled primarily by the material attributes of dielectric substrate onto which the antenna is impressed and the spatial shape of printed radiating element. Almost, in all pragmatic applications, patch antenna is circular or rectangular in configurable shape; nevertheless, any geometrical contour like rectangular, square, triangular, elliptical and circular is possible in general as illustrated in Figure 2.2 [2] [17] [22] [35].

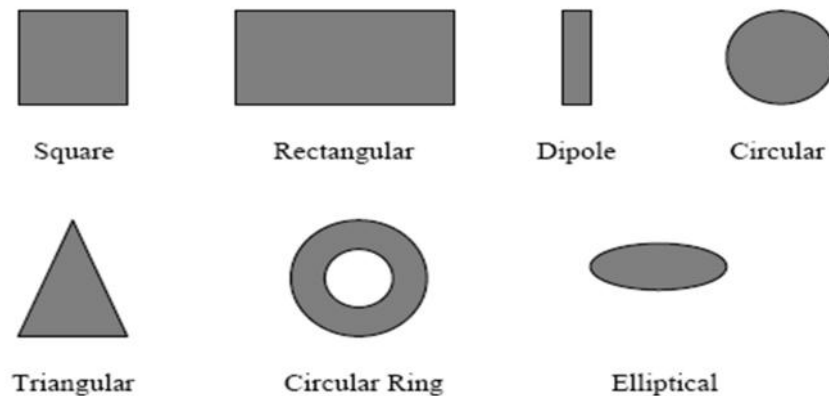


Figure 2.2: General configurations of microstrip patch elements [17]

MPA should be designed using such a technique so that its uttermost wave pattern is perpendicular to the patch. It is achieved by the appropriate selection of excitation mode under the patch. In general, MPA has a thickness 't' that is very thin in the scope of $t \ll \lambda_0$ (λ_0 is free

CHAPTER-2

PRELIMINARIES AND REVIEW

space wave length) and has a height 'h' of dielectric material that is within $0.003 \lambda_0 < h < 0.05 \lambda_0$ [3]. The length 'L' of element is usually $\lambda_0/3 < L < \lambda_0/2$ for a rectangular patch. Indefinite number of substrate materials with their dielectric constants normally in the range of $2.2 < \epsilon_r < 10$ can be utilized for the designing purpose of microstrip antennas. Here, ϵ_r is the relative dielectric constant. For acceptable operation of microstrip antenna, a thick dielectric substrate possessing a low dielectric constant is preferable as it renders respectable efficiency, significant bandwidth and improved radiation characteristics [17] [22] [35]. All the same, such a conformation results in a bigger antenna size. Different dielectric constants with higher values must be utilized for designing a small size and compact microstrip patch antenna, which are competent to a lesser extent and lead to limited bandwidth of 1-5% in a typical manner, lower gain and lower power handling susceptibility [43]. Such a limited bandwidth is a leading restricting factor for the far-flung application of these antennas. Therefore, a middle way between two extremes must be attained among the dimensions and performance of antenna. Increasing the bandwidth of MPAs has been the major thrust of research in this field and broad bandwidth up to 70 % has been achieved by the researchers [18] [44-45]. The techniques of analysis for MPAs can be generically bifurcated into two groups. The techniques are based on equivalent magnetic current distribution in the vicinity of the patch edges in the first group. Transmission line model and cavity model are two famous analytical methods that are employed for the design and analysis of MPAs. Second group comprises the methods that are based on distribution of electric current along the ground plane and patch conductor. Few of the numerical techniques used for analyzing/examining MPAs are the finite-element method (FEM), the method of moments (MoM), the finite integral technique (FIT), the finite-difference time domain (FDTD) method, and the spectral domain technique (SDT), etc [46-49].

2.3.2. Advantages and Disadvantages of Microstrip Antennas

The reasons why this class of antennas has become so popular compared to the conventional microwave antennas include the following [2] [50]. Some of the primary advantages talked about by Kumar and Ray [18] are listed further as:

Advantages of MPAs:

MPAs possess various advantages in comparison to the traditional microwave antennas. The chief advantages of microstrip antennas are discussed further in a point-wise manner [18]:

- Simple fabrication
- Good radiation control
- Mechanically sturdy and strong in form when assembled for use on inflexible surfaces
- Lightweight, low profile, easy, durable and affordable to construct in large quantities utilizing contemporary impressed circuit board technology
- Compatible with MMICs
- Capable of dual and triple frequency operations
- Can be designed to produce a variety of patterns depending on the mode shape of patch used
- Easily conformable to planar and non planar surfaces
- Sustains both circular as well as linear polarization
- Dual-polarization and dual frequency antennas can be conveniently manufactured
- Designer flexibility as components can be appended to and eliminated from the Printed Circuit Board (PCB)
- Matching networks and feed lines can be conceived with the antenna structure at the same instant.

Disadvantages of MPAs:

Microstrip patch antennas are subjected to drawbacks/flaws to a greater extent when compared to traditional antenna structures. Few of the prima disadvantages discoursed by [2] and Pues et al. [51] are revealed below:

- Reduced power handling potentiality (~ 100 W)
- Decreased efficiency and advanced levels of mutual coupling and cross polarization to an unacceptable degree at high frequencies
- Marginal gain to a moderately sufficient extent or degree
- Significant ohmic loss in the feed
- Majority of MPAs send out rays into half-space
- Complicated feeding strategies necessary for high performance arrays
- Narrow bandwidth and associated tolerance problems
- Made for very specific frequency ranges
- Problematic achievement of polarization purity
- Unsatisfactory end-fire radiator

CHAPTER-2

PRELIMINARIES AND REVIEW

- Irrelevant radiation from feeds
- Surface wave excitation
- MPAs constructed on a substrate having high dielectric constant are desired in a strong manner for simple consolidation with radio frequency front-end circuitry. Nevertheless, utilization of high dielectric constant substrate results in pathetic efficiency and limited bandwidth.

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

2.3.3. Feeding Methods of Microstrip Antennas

There are various techniques procurable to feed or impart/broadcast electromagnetic energy to a microstrip patch antenna. These techniques are categorized into two classes-contacting and non-contacting. Contacting techniques are the easiest feeding techniques to understand suchlike microstrip transmission line and coaxial probe. The Radio Frequency (RF) power is to be feed straightway/instantaneously to the radiating patch by the proper utilization of a connecting element such as a microstrip line in the contacting scheme. The contact point is adaptable, facilitating the designer to manage/regulate the impedance match among antenna and feed, excitation frequency and polarization mode of operation. Normally, for direct contact feeds, the optimal impedance match is incurred when the contact point is situated away from center. This gives rise to imbalance in the excitation of patch that renders higher order modes [52]. The generated higher order modes accelerate a cross-polarized component in the principal plane antenna patterns that take out power from the dominant transverse magnetic (TM_{010}) and ensues degradation of the antenna's main beam. Consequently, a trial-and-error approach is utilized frequently to incur the most favorable match for the direct contact feeds. Some other disadvantage of the direct contact feeds is that they are narrowband devices in an inherent manner. These feeding techniques, whether microstrip or coaxial are "matched" to peculiar impedance of 50-ohm in most case for an elected scope of frequencies. The operation beyond this range aggrades antenna performance in a reflex manner because of the integral mismatching within the feed and antenna structure. In order to overtake few of the deficiencies of the contacting/direct-coupled feeds, a miscellany of "non-contacting coupled feeds" have been formulated. The two principal configurations of non-contacting coupled feeds are the proximity-

coupled and aperture-coupled feeds. The electromagnetic field coupling is done to channelize power among the microstrip line and radiating patch in the non-contacting scheme [53]. CPW feed line is another popular feeding technique in which the radiating patch and ground are in the same conducting plane. This type of feeding technique is suitable for multilayer fabrication technology. Moreover, this type of transmission line has relatively low attenuation and dispersion and enables us to design easily a wide range of characteristic impedances. It is a promising solution for planar antennas in millimeter-wave band. Lastly, it can be articulated that reduction of radiation and the impression of it on the radiation pattern are the most significant aspects for the rating of feed [44]. Further, all these feeding techniques are discussed in greater detail with relevant diagrams.

Microstrip Line (Coplanar) Feed

The inflammation/excitation of the microstrip antenna by a microstrip line on the identical substrate seems to be a realistic option for the reason that the patch can be regarded as the prolongation of the microstrip line, and both can be manufactured at the same instant. The coupling source between the microstrip line and patch could be radiating edge/gap or inset feed.

(a) Radiating Edge Coupled Microstrip Feed

As the name suggests, in edge coupled feeding mechanism, a conducting strip is coupled straightway to the radiating corner of the microstrip patch as illustrated in Figure 2.3 [1-2] [44]. The conducting strip is little in breadth in comparison with the radiating patch.

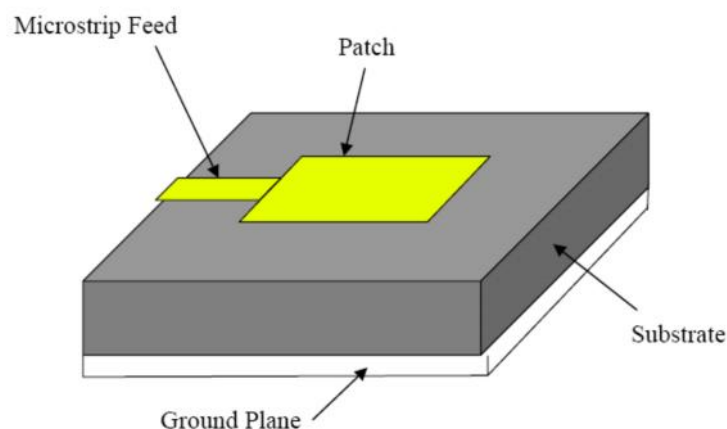


Figure 2.3: Microstrip feed at the radiating edge [1]

It is a simple feeding scheme, as it caters effortless fabrication and simple modeling. Even so, as the thickness of the dielectric medium being utilized increments, spurious feed radiation and

CHAPTER-2 PRELIMINARIES AND REVIEW

surface waves also increase, which shackles the bandwidth of antenna system [53-54]. The feed radiation results in unwanted cross polarized radiation as well. The edge coupled feed undergoes a serious restriction of impedance mismatch as the input impedance of the patch at its radiating boundary is very high in comparison with the 50-ohm impedance of feed line. Hence, an extrinsic impedance matching circuit is utilized amongst the 50-ohm microstrip line and patch boundary. The impedance matching circuit, in addition to giving rise to unauthentic radiation, cannot be conciliated in arrays due to non availability of physical expanse/area on the substrate. The microstrip line also occludes radiation from the part of the patch with which it is in close interaction ensuing diminished radiation.

(b) Gap Coupled Microstrip Feed

The gap coupled feed illustrated in Figure 2.4 demands a constricted/limited gap width for competent power coupling. Nevertheless, a limited gap size will throttle the power handling potentiality of the antenna. Furthermore, the open end of the microstrip line feed produces unauthentic radiation.

(c) Inset cut Microstrip Feed

The patch has been inset-cut with a microstrip line as demonstrated in Figure 2.5. The position of feed is elected such that the input impedance of the antenna is 50-ohm. This type of feed is used in integrated MPAs in a widespread way.

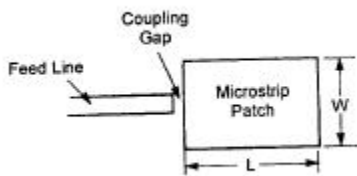


Figure 2.4: Gap coupled microstrip feed [44]

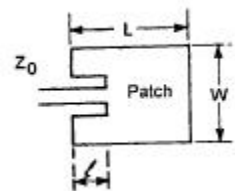


Figure 2.5: Microstrip inset feed [44]

All these above mentioned coplanar microstrip feeds are simple to formulate and construct. Nonetheless, microstrip feed lines impart unauthentic/false radiation. Hence, they have been utilized in applications where the requirement on performance is not excessively demanding and the feed must be lying in the same plane with the patch.

Coaxial Feed/Probe Coupling

The coaxial feed or probe coupling is an extremely popular feeding method utilized for MPAs as coupling of power via a probe is the standard process for the carryover of microwave power. The outer conductor of coaxial connector is colligated to the ground plane and innermost conductor excerpts through the dielectric substrate and is fused with solder to the radiating patch as illustrated in Figure 2.6.

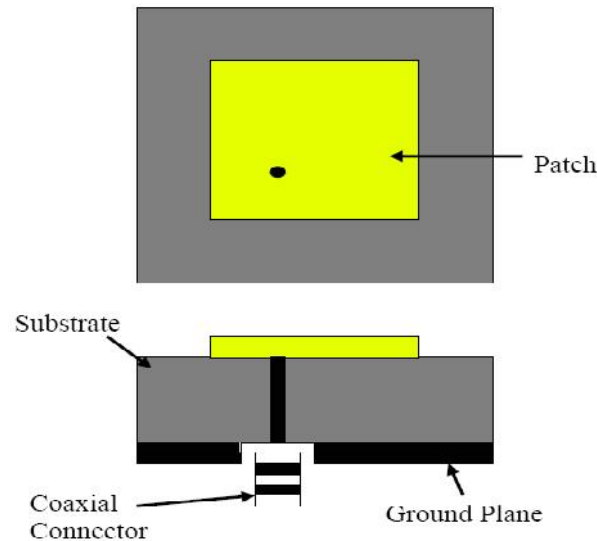


Figure 2.6: Coaxial fed rectangular microstrip patch antenna [1]

The feed can be located at any coveted location within the patch with an objective of matching with its input impedance and this is the only chief benefit that makes this type of feeding strategy as the most demanding. However, on the contrary, it has numerous shortcomings. Firstly, coaxial feeding of an array demands a significant number of solder joints, which makes fabrication a herculean task and compromises reliability. Secondly, for enhanced bandwidth of a patch antenna, a thicker substrate material is utilized and needs an elongated probe. This produces increased unauthentic or spurious radiation from the probe, incremented surface wave power, and additional feed inductance resulting in matching difficulties [55-56]. Thirdly, it is troublesome to model, as the connector projects/bulges outside the ground plane and a hole has to be bored in the dielectric substrate, therefore not forming it entirely planar for thick substrates ($h > 0.02 \lambda_0$). The non-contacting feed techniques i.e. proximity coupled feed and aperture coupled feed solve these problems and have been discussed and demonstrated in the following section.

CHAPTER-2 PRELIMINARIES AND REVIEW

Aperture Coupled Microstrip Feed

The widely known and esteemed characteristics of this feed configuration are broader bandwidth, and the concealment of the radiating patch from the radiation coming out from the feed structure. Figure 2.7 demonstrates this type of feed mechanism and shows that the radiating patch and the microstrip feed line subsidized by their own substrates are detached with a common ground plane [1]. As shown there, electromagnetic coupling is attained between a microstrip feed line on the lower substrate and the patch through an aperture in the common ground structure. Whatsoever size or shape can be assigned to a slot and these arguments such as conforming the configuration and length of the coupling aperture/slot, breadth of feed line can be employed to ameliorate the bandwidth.

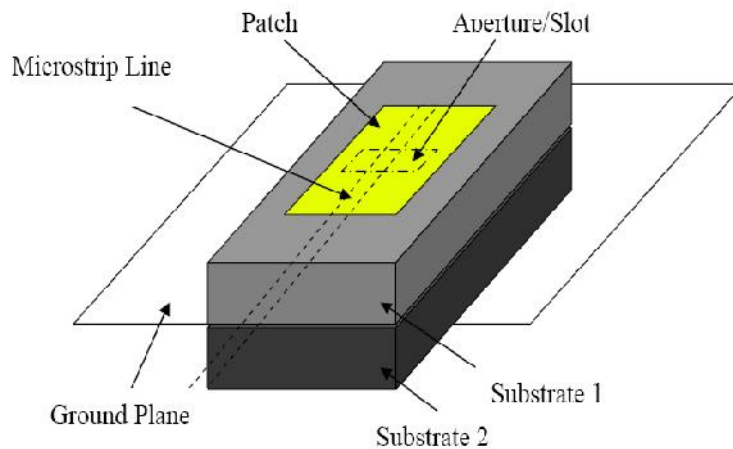


Figure 2.7: Aperture-coupled feed [1]

The coupling slot is generally centered beneath the patch, directing to reduce cross-polarization because of balance/symmetry of the shape. The measure of coupling from the microstrip feed line to the patch is also ascertained by the position of slot/aperture. Because the ground plane secernates the patch and the feed line, hence radiation from the open terminal of feed line does not intervene with the radiation pattern of the patch and thus spurious radiation is minimized moderately. This feature also improves polarization purity. Mostly, a high dielectric constant material is employed for the underside substrate and a thick, low dielectric constant material is utilized for the upside substrate to get maximum efficient radiation from the patch [53] [57-58]. The leading disadvantage of this feed technique is that it is challenging to manufacture due to multiple layers, which also heightens the thickness of an antenna.

Proximity (Electromagnetically) Coupled Microstrip Feed

This feeding method is known as the electromagnetic coupling scheme as well. As exhibited in Figure 2.8 [2] [26] [53], two substrates with different dielectric constants are utilized so that the feed line remains within the two dielectric substrates and the patch radiator is upside the top substrate material. Primary benefit of this type of feed method is that it obviates unauthentic radiation from feed and renders dominating bandwidth as high as 13% [2], on account of overall increment in the thickness of MPA. This strategy also furnishes alternatives between two distinct dielectric media, one for the patch and other for the feed line to get the most optimistic idiosyncratic operations.

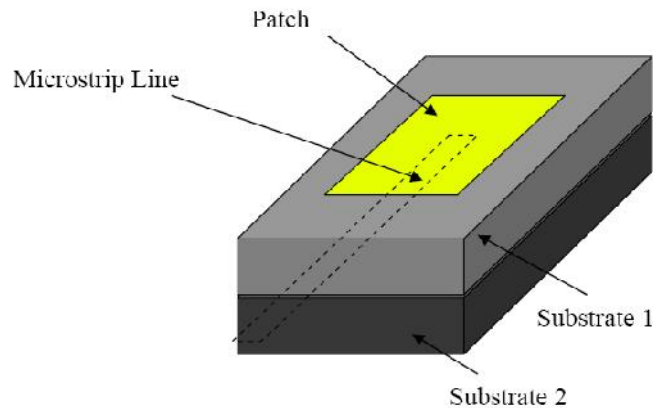


Figure 2.8: Proximity-coupled feed [1]

Matching can be accomplished by manipulating the ratio of width-to-line of radiating patch and length of microstrip line feed [59]. The primary weakness of this feed scheme is that it is troublesome to manufacture as result of the usage of two dielectric layers which postulate appropriate alignment. Furthermore, there is an increment in the gross thickness of the antenna.

Coplanar Waveguide (CPW) Feed

In CPW feed mechanism, the patch radiator and ground structure (symmetrical/non symmetrical), which are both perfect electric conductors (PECs) are embedded in the same plane as depicted in Figure 2.9.

CHAPTER-2 PRELIMINARIES AND REVIEW

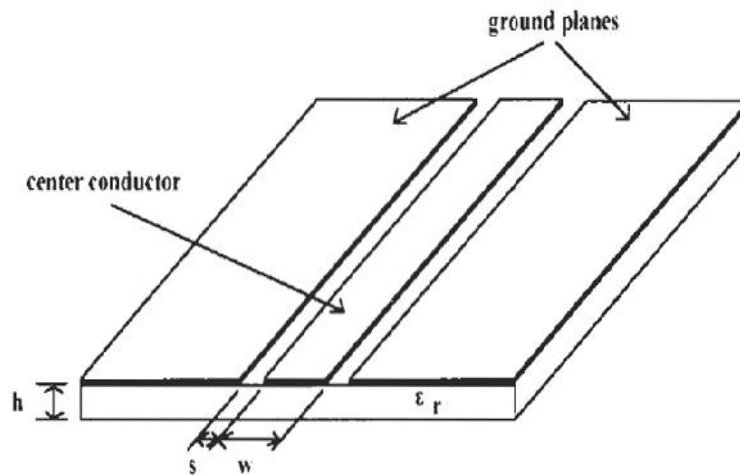


Figure 2.9: Coplanar waveguide feed [44]

CPW feed as equated with the microstrip feed line, has reduced transmission loss, insufficient dispersion, degraded radiation leakage, the possession of efficaciously controlling their characteristic impedance, and their comfort of integration with active devices [60–62], lower profile especially on high frequency band. CPW feed is a unilateral three-conductor transmission line. It has two grounds in the synoptic plane of middle conductor, shrinking the coupling effects, permits for effortless involvement of series and shunt elements and can be manufactured with microstrip lines, lump and active elements not including visas to the ground [62]. As microwave integrated circuits are fundamentally coplanar in structure, coplanar waveguide lines are employed as interconnecting lines and as circuit elements in a widespread manner. Coplanar waveguide provides the potential of lower conductor and radiation losses as equated to microstrip lines at millimeter-wave frequencies. The 10-dB return loss bandwidth reported for CPW feed mechanism is 2-3%. Besides, it permits for altering the dimensional properties of the transmission line without modifying the characteristic impedance. The antenna, when fed by a microstrip line can lead to misalignment as etching is needed on both sides of the dielectric substrate. The coalition fault error can be ruled out if a CPW feed is utilized to stimulate the slot, as engraving of the slot and the feed line is unilateral. The superlative/highest weakness of CPW feed is its overall significant physical magnitude and complex structure which brings down the antenna's application. Table 2.1 tabulates a brief summary for the characteristics of the different types of feed structures for MPAs.

Table 2.1: Comparison of various types of feed structures for MPAs [57]

Characteristics	Radiating Edge coupled Microstrip Feed	Gap coupled Microstrip Feed	Inset cut Microstrip Feed	Coaxial/Probe Feed	Aperture Coupled Feed	Proximity Coupled Feed	Coplanar Waveguide (CPW) Feed
Polarization Purity	Respectable	Pathetic	Pathetic	Pathetic	Awesome	Pathetic	Respectable
Spurious feed radiation	Lesser	Greater	Greater	Greater	Greater	Greater	Lesser
Impedance matching	Pathetic	Simple	Simple	Simple	Simple	Simple	Simple
Ease of Fabrication	Simple	Simple	Simple	Soldering needed	Alignment needed	Alignment needed	Alignment needed
Reliability	Better	Better	Better	Pathetic because of soldering	Respectable	Respectable	Respectable
Bandwidth	≈ 9-12%	≈ 2-5%	≈ 2-5%	≈ 2-5%	≈ 21%	≈ 13%	≈ 3%

2.3.4. Antenna Design Parameters

For designing an impressive and powerful antenna, there are a definite number of parameters that have to be perceived about. The performance of an antenna is expressed using a number of design parameters such as electric field distribution, radiation pattern, current distribution, Voltage Standing Wave Ratio (VSWR) and input impedance etc. Although design parameters related to antennas are discussed in detail elsewhere [63], they have been duly mentioned in brief here for the completeness of the thesis and additional information. Some of these design parameters for the antenna are discussed in this section [64-65].

Radiation Pattern

The radiation pattern of an antenna is clearly characterized as the comparative dispersion of radiated power which is associated with the spatial directional coordinates. These coordinates are expressed in terms of the azimuth angle and the elevation angle. Generally, it is a diagram of the

CHAPTER-2

PRELIMINARIES AND REVIEW

radiated power from the antenna per unit solid angle. Radiation properties of the antenna let in phase, power flux density, polarization and field strength.

Electric Field Distribution

In an antenna, the influential component/element of the electric field E_z is equalized be zero at the shorting strip and the intensity of the electric field at the opposite edge is significantly large. There is a specific part for the electric field components in the Y-direction and X-direction that are consistent to the feed source. It implies that the electric lines of force are oriented to the ground plane from the feed source. As soon as the breadth of the shorting strip is made slenderer/narrower in comparison to the two-dimensional component/element, the electric field components E_x and E_y initiate yielding radiation at all open-circuit edges of the planar component. These fields are fringing fields and are the radiating roots in any two-dimensional antenna.

Current Distribution

In the MPAs there is an extremely large current flow underneath the surface of the planar element and the ground plane in comparison with the field on the upper surface of the element. This conduct of the antenna plays a crucial purpose/role on the execution of an antenna and there is no effect on the antenna characteristics from the external objects. The ground surface radiations can create unauthentic/false radiations or couple energy at discontinuities thus resulting in distortions in the principal pattern. These effects can be controlled by simply using air as the dielectric. Hence, the restriction of pathetic efficiency and limited bandwidth of an antenna is solved.

Input Impedance

The input impedance of an antenna is clearly characterized as the impedance exhibited by the antenna at its ends or the ratio of the voltage to the current at the ends or the ratio of the proper components of the electric to magnetic fields at that point. The input impedance of the antenna can be scripted as

$$Z_{in} = R + jX, \quad (2.1)$$

where Z_{in} is the antenna impedance, R is the antenna resistance and X is the antenna reactance at the ends. The imaginary component X of the input impedance symbolizes the power stacked in the near field of an antenna. R is the resistive component of the input impedance comprising of

two parts namely the radiation resistance R_r and the loss resistance R_L . The power colligated with the radiation resistance is the power that is really spread outwards by the antenna, while the power profligate in the loss resistance is wasted as heat in the antenna itself owing to conducting or dielectric losses. The impedance level for an antenna is normally 50-ohm. If the input impedance of the antenna is different from 50-ohm at any frequency, more or less portion of the power is reflected backwards leading to create a standing wave.

Voltage Standing Wave Ratio (VSWR)

For the efficient operation of an antenna, appropriate impedance matching must be in transmitter/receiver and antenna so that the transversal of power must take place to a supreme extent. Utmost power can be transposed only when the impedance of the sender/transmitter is a complex conjugate of the impedance of the antenna and vice-versa. Whenever matching is not flawless, then a portion of the input power may be reflected back and this result in an innovation of standing waves, which can be revealed by a parameter known as VSWR.

The VSWR is expressed by [65]

$$S = \frac{1+\Gamma}{1-\Gamma}, \quad (2.2)$$

where Γ is called the reflection coefficient, and clearly characterized as a relative magnitude of reflected wave to the incident wave. The VSWR is fundamentally a quantity of impedance mismatch within the antenna and transmitter. An utmost value of the VSWR stands for a large mismatch. The negligible small value of VSWR stands for a perfect match that is taken as one.

Return Loss

The Return Loss (RL) is a parametric quantity that designates the measure of power which is squandered to the load and does not reflect as a reflection from the antenna. Thus the return loss is a parameter synonymous to the voltage standing wave ratio that shows how comfortable the matching is among the antenna and the transmitter.

The RL is depicted as

$$RL = -20 \log_{10} |\Gamma| \quad (\text{dB}). \quad (2.3)$$

A perfect match between the transmitter and the antenna designates $\Gamma = 0$ and $RL = \infty$ dB, which states that the incident power is not reflected back, while on the contrary, $\Gamma = 1$ has a $RL = 0$ dB, states that all the incident power is reflected back to the source. A VSWR of 2 is unobjectionable for realistic applications and this represents a RL of -9.5 dB.

CHAPTER-2 PRELIMINARIES AND REVIEW

Radiation Efficiency

Radiation efficiency of an antenna is clearly understood as the relative magnitude of the total radiated power to the total input power. The metallic elements of the antenna structure and other lossy stuff within the terminal are responsible for losses to the highest degree in free space.

Antenna Efficiency

The antenna efficiency is a parametric quantity that takes into account the measure of losses at the antenna ends and inside the construction of an antenna. These losses are named as the reflection losses and the $I^2 R$ losses. The reflection losses are due to mismatch between the antenna and the transmitter. On the other hand, $I^2 R$ losses are due to the dielectric and conduction losses. The overall antenna efficiency is a function of the mismatch (reflection) efficiency (e_r), conduction efficiency (e_c), and dielectric efficiency (e_d), and presented as

$$e_t = e_r e_c e_d, \quad (2.4)$$

where e_t is the total antenna efficiency.

Directivity/Gain

An antenna has its directivity and gain. It has capability of focusing the RF power toward a desired direction. The gain is cognated to the directivity of the antenna in an attentive manner. The directivity shows/indicates how much an antenna centralizes energy in either direction in favour to radiation in other directions. The directivity is comparable to antenna gain when efficiency is one and the antenna behaves as an isotropic radiator. Every antenna radiate to a greater extent in a specific direction than in others, hence the gain is a measure of power which can be accomplished in either direction at the sacrifice of the power squandered in the others. The gain is clearly characterized in terms of antenna directivity and efficiency by [66]

$$G = e_t D, \quad (2.5)$$

where G is the gain of antenna, e_t and D are the total antenna efficiency and the directivity of the antenna, respectively. The gain is affiliated to the main lobe at all times and is explicitly stated in the direction of uttermost radiation except when designated/suggested.

Bandwidth

The bandwidth is a general classification of the frequencies over which an antenna is effective. It is clearly characterized as the scope of frequency bands across which the value of the input

VSWR enhances from one to a permissible limit value S . The bandwidth (BW) of a MPA is given by [66]

$$BW = \frac{f_H - f_L}{f_0}, \quad (2.6)$$

where f_H shows the upper frequency and f_L shows the lower frequency limits where VSWR is $S:1$ and f_0 is the resonance frequency of the patch. In case of the perfectly matched MPA, bandwidth is given as

$$BW = \frac{S - 1}{Q\sqrt{S}}, \quad (2.7)$$

where S is the VSWR and Q is the quality factor.

Polarization

The condition of having or giving polarity of an antenna is the relative alignment of the electric field (E-plane) of the radio wave in connection with the earth's surface and is ascertained by the physical construction of an antenna and by its orientation. Hence, an easy straight wire antenna will have different states of polarization when mounted vertically and horizontally.

2.3.5. Methods of Analysis of Microstrip Antennas

The targets of methods of analysis of microstrip antennas are to forecast the radiation properties such as gain, polarization, input impedance, antenna efficiency, bandwidth, radiation patterns and mutual coupling. The analytical treatment of MPAs is complex by the current existence of inhomogeneous boundary and dielectric circumstances, limited frequency band properties, and a broad miscellany of substrate, patch shape and feed configurations. A good model has the under-mentioned fundamental features:

- It can be utilized to compute all radiation and impedance properties of the antenna.
- Its outcomes are veracious enough for the premeditated role.
- It is easy and executable, while catering the suggested accuracy for the radiation and impedance.

It imparts itself to rendition in terms of familiar physical phenomena. In common practice, MPAs are estimated and evaluated utilizing any one of three methods of analysis: the transmission line model, the cavity model, and the full-wave model. The transmission line model is the simplest of all, it gives acceptable physical insight. But it is veracious to a lesser extent and more troublesome to model coupling effect of antenna. In contrast to the transmission line model, the

CHAPTER-2 PRELIMINARIES AND REVIEW

cavity model is correct to a greater extent but at the same time more complicated and hard to model coupling effect. Generally, when used decently, the full wave model is extremely true, and extremely versatile. It can analyze single element, finite array, layered elements and arbitrary shape element of MPA and also coupling effect of the antenna. It gives a little feeling of understanding in comparison to the other two models cited earlier and is far complicated in nature to a greater degree.

Transmission Line Model

In this model, the microstrip antenna is symbolized by two slots having height h and width W , isolated by a transmission line having length L as demonstrated in Figure 2.10 [2]. The microstrip is basically a non homogeneous line of two dielectrics, ordinarily the air and substrate.

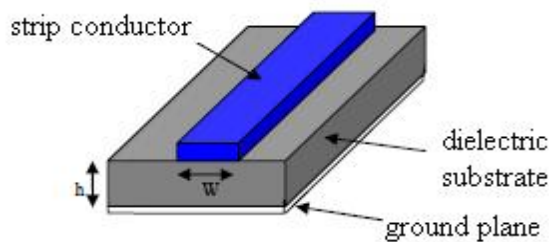


Figure 2.10: Microstrip line [2]

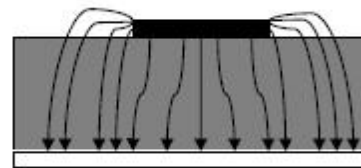


Figure 2.11: Electric field lines [67]

Therefore, as realized from Figure 2.11 [67], majority of the electric field lines domicile in the substrate and portions of some lines in air. As a consequence, this transmission line cannot sustain pure transverse electric-magnetic (TEM) mode of transmission, as the phase velocities would be divergent/distinct in the air and the substrate. Alternatively, the dominant mode of propagation would be the quasi-TEM mode. So, an effective dielectric constant (ϵ_{reff}) must be prevailed with an objective of accounting for the fringing and the wave propagation in the line. The value of ϵ_{reff} is marginally less than ϵ_r as the fringing fields just around the outer boundary of the patch are not restricted in the dielectric substrate but are also dispersed widely in the air as demonstrated above in Figure 2.11.

The expression for ϵ_{reff} is presented by Balanis [2] as

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}}, \quad (2.8)$$

where ϵ_{reff} = Effective dielectric constant

ϵ_r = Dielectric constant of substrate

h = Height of dielectric substrate

W = Width of the patch

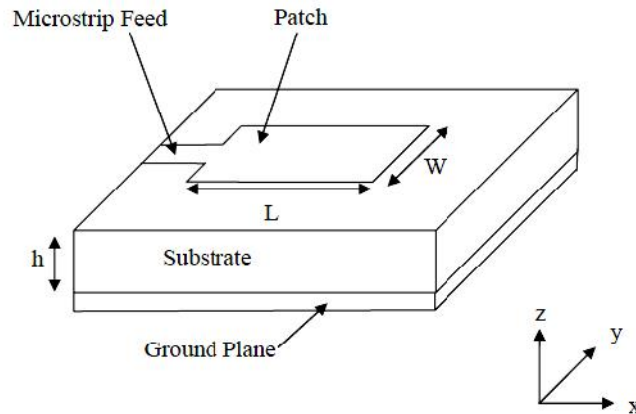


Figure 2.12: Geometrical configuration of a rectangular MPA [57]

Consider Figure 2.12 [57] as depicted above, that displays a rectangular microstrip patch antenna of length L , width W residing on a substrate of height h . The co-ordinate axis is chosen such that the length is across the x direction, width is across the y direction and the height is across the z direction. With an objective of operation in the fundamental TM_{10} mode, the linear extent of the patch is necessarily somewhat less than $\lambda/2$ where λ is the wavelength in the dielectric medium equal to the free space wavelength. The TM_{10} mode connotes that the field changes one $\lambda/2$ cycle across the length, and there is no fluctuation across the breadth of patch. Figure 2.13 [67] shown below depicts a microstrip patch antenna that has been represented by two slots, isolated by a transmission line of length L and open circuited at both the terminals.

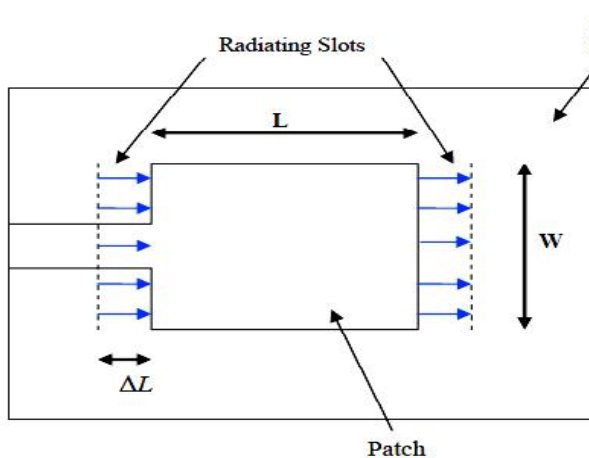


Figure 2.13: Top view of antenna [67]

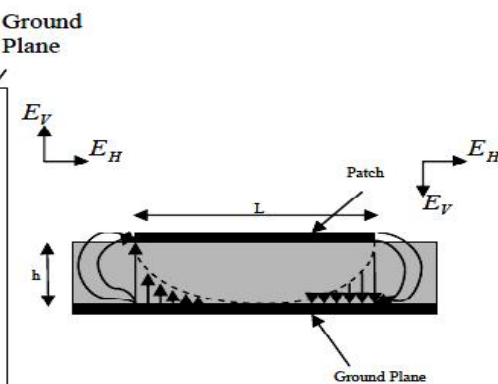


Figure 2.14: Side view of antenna [67]

CHAPTER-2

PRELIMINARIES AND REVIEW

Across the breadth of the patch, the voltage is the greatest and current is the least because of the open ends. The fields at the terminating edges can be settled into tangential and normal components in connection with the ground plane. It has been realized from Figure 2.14 [67] that the perpendicular components of the electric field at the two edges across the breadth are in inverse directions and therefore out of phase as the patch is $W/2$ in length and thus they declare each other null and void in the broadside direction. The tangential components visualized in Figure 2.14 that are in phase justify that the resulting fields unite to impart utmost radiated field perpendicular to the surface of the structure. Therefore, the terminating corners across the breadth can be symbolized as two radiating slots, that are $W/2$ aside and stimulated in phase and radiating in the half space over the ground plane. The fringing fields across the width can be postured as radiating slots and the patch of the microstrip antenna appears relatively large in size than its physical attributes electrically. The attributes of the patch across its length have now been increased in scope on each terminal by a distance L , that is presented empirically by Hammerstad [68] further as

$$L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{\text{reff}} - 0.258) \left(\frac{W}{h} + 0.8\right)}. \quad (2.9)$$

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

$$L_{\text{eff}} = L + 2L. \quad (2.10)$$

For a given frequency of resonance f_0 , the effective length is illustrated by [43] as

$$L_{\text{eff}} \approx \frac{c}{2f_0 \sqrt{\epsilon_{\text{reff}}}}. \quad (2.11)$$

The resonance frequency for any TM_{mn} mode in case of a rectangular microstrip patch antenna, is presented by James and Hall [26] [67] as

$$f_0 = \frac{c}{2\sqrt{\epsilon_{\text{reff}}}} \left[\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2 \right]^{\frac{1}{2}}, \quad (2.12)$$

where m and n are modes along L and W in a respective manner.

For effective radiation, the width W is expressed by Bahl and Bhartia [57] as

$$W = \frac{c}{2f_0 \sqrt{\frac{(\epsilon_r + 1)}{2}}}. \quad (2.13)$$

Cavity Model

Even though the transmission line model considered in the just preceding section is simple to utilize, it has few integral weaknesses and flaws. Generally, it is helpful for patches of rectangular design and it neglects field variations across the diverging/radiating corners. These flaws can be sweep over by utilizing the cavity model. A concise overview of this model is taken into account below. In this model, the interior region of the dielectric substrate is postured as a cavity restrained by electric walls on the top and bottom. The fundamentals for this assumption are the under-mentioned observations for thin substrates ($h \ll \lambda$) [2-3].

- As the substrate is thin, the fields in the interior region do not alter a lot in the z direction, i.e. perpendicular to the patch.
- The electric field is z oriented only, and the magnetic field has only the transverse components H_x and H_y in the region restrained by the patch coated with metal and the ground plane. This remarkable notice offers for the electric walls at the top and the bottom.

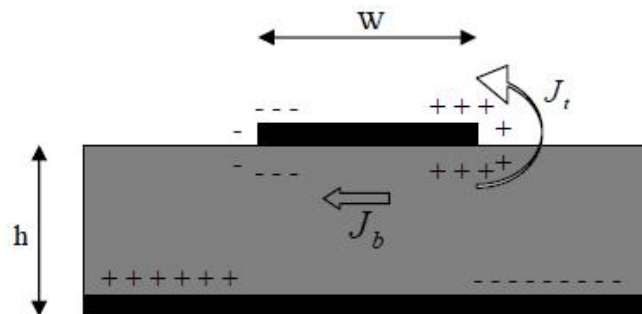


Figure 2.15: Charge distribution and current density creation on the microstrip patch [2]

Giving close and careful consideration to Figure 2.15 shown above, it has been inferred that when a microstrip patch is supplied power, a charge distribution is visualized on the lower and upper surfaces of the patch and at the lower side of the ground plane. This charge distribution is governed by two mechanisms-an attractive mechanism and a repulsive mechanism. The attractive mechanism is within the reverse charges on the lower side of the patch and the ground plane that assists in sustaining the intact charge concentration at the lower side of the patch. The repulsive mechanism is within the similar charges on the lower side of patch that gives rise to pushing of few charges from the lower side to the upper side of the patch. Consequently, currents flow at the top and bottom surface of the patch on account of charge movement. The cavity

CHAPTER-2 PRELIMINARIES AND REVIEW

model presumes that the ratio of height of substrate to width of the patch is very limited in size and consequently, the attractive mechanism prevails and engenders majority of the charge concentration and current to be underneath the surface of patch. Current would flow along the upper surface of the patch to a much lesser extent and as the height to width ratio decreases to a more advanced stage, the current on the upper surface of the patch would be nearly zero, that would not permit the origination of any magnetic field components that are tangential to the patch edges. Therefore, the four sidewalls could be postured as magnetic conducting surfaces absolutely. This entails that the electric field and magnetic field distribution under the patch would not be interrupted. Nevertheless, in practical applications, a limited width to height ratio would be there and this would not stimulate the tangential magnetic fields to be entirely zero, however they being very diminished in nature, the side walls could be behaving as pluperfect magnetic conducting walls approximately. As the walls of the cavity and the material inside them are lossless, the cavity would not be radiating and its input impedance would be exclusively reactive. Thus, with an objective of accounting for radiation and a loss mechanism, one must acquaint radiation resistance R_r and a loss resistance R_L . A lossy cavity would directly stand for an antenna and the loss is considered by the effective loss tangent ϵ_{eff} which is presented as

$$\epsilon_{eff} = 1/Q_T. \quad (2.14)$$

- Q_T is the total antenna quality factor and has been stated by [69] in the form

$$\frac{1}{Q_T} = \frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_r}. \quad (2.15)$$

- Q_d corresponds to the quality factor of the dielectric and is conveyed as

$$Q_d = \frac{\omega_r W_T}{P_d} = \frac{1}{\tan \delta}, \quad (2.16)$$

where ω_r is the angular resonant frequency.

W_T is the total energy stored in the patch at resonance.

P_d is the dielectric loss.

$\tan \delta$ is the loss tangent of the dielectric.

- Q_c corresponds to the quality factor of the conductor and is presented as

$$Q_c = \frac{\omega_r W_T}{P_c} = \frac{h}{\lambda}, \quad (2.17)$$

where P_c is the conductor loss.

h is the skin depth of the conductor.

h is the height of the substrate.

- Q_r corresponds to the quality factor of the radiation and is stated as

$$Q_r = \frac{rW_T}{P_r}, \quad (2.18)$$

where P_r is the power radiated from the patch

Replacing these above equations for Q_d , Q_c and Q_r in the equation for Q_T , we obtain

$$\epsilon_{eff} = \tan \delta + \frac{\Delta}{h} + \frac{P_r}{rW_T}. \quad (2.19)$$

Hence, the above equation depicts the total effective loss tangent for the microstrip patch antenna.

Full Wave Solutions-Method of Moments

As the name suggests, a Full Wave Solutions-Method of Moments renders the full wave analysis technique for the microstrip patch antenna. In this technique, the surface currents are utilized to posture the microstrip patch and the volume polarization currents are utilized to simulate the fields in the dielectric slab. It has been exhibited by Newman and Tulyathan [70] and Harrington [71] that how an integral equation is incurred for these unfamiliar currents and utilizing the Method of Moments, these electric field integral equations are commuted into matrix equations which can then be puzzled out by different methods of algebra to furnish the outcome.

Hence, utilizing any of the algebraic schemes cited earlier, these equations can be worked out to give the current and subsequently the other parameters such as the scattered electric and magnetic fields can be computed instantaneously from the evoked currents. Therefore, these analytical schemes have been concisely explicated for application in antenna problems.

2.3.6. Applications of Microstrip Antennas

Microstrip patch antennas are renowned for their recognized accomplishments and their strong design, construction and their prolonged utilization. The benefits of these antennas enclose simple and effortless design process, light weight etc. The applications of microstrip antennas can be observed in several fields like in military systems like rockets, aircrafts and missiles, satellites and in medical applications as well. The utilization of these antennas is dispersing broadly in almost all the areas and fields and presently they are prospering in the technical prospects because of their easy fabrication and low cost features. The MPAs found a variety of applications as given in [44] [72-73]. Some important application areas of MPAs are:

CHAPTER-2

PRELIMINARIES AND REVIEW

- Mobile Communications
- Satellite Communications, direct broadcast services (DBS)
- Global Positioning Systems (GPS)
- Radio Frequency Identification (RFID)
- Remote sensing and environmental instrumentation
- Worldwide Interoperability for Microwave Access
- Radio Altimeters
- Doppler as well as other radars
- Wireless Fidelity (Wi-Fi)
- Telemedicine and Medicinal applications
- Telemetry and Missiles
- Control and command systems
- Smart Weapon Systems
- Feed elements in complex antennas
- Pagers
- Global System for Mobile communication
- Integrated antennas
- Biomedical radiators and intruder alarms

2.4. Multi-frequency Microstrip Antennas

With the recent procession and development in wireless and mobile communication systems peculiarly for data communication, the requirement for broadband, multi-frequency and multiband patch antenna systems was accomplished. These demands compelled workers for alteration in geometries of patch antenna designs. In some applications when enhanced bandwidth is required for functioning of two or more distinct sub-bands, an effectual option for the widening of entire bandwidth is the utilization of dual or multi-frequency MPAs [74-77]. As already mentioned, MPA has its significant benefit above conventional antennas, suchlike low weight, easy fabrication, small size, mechanically strong, compatible with planar and non-planar surfaces, ease integration with circuits, ease of producing antenna array and best-suited for multi-

frequency performance of antennas [57]. These mesmerizing features provoked microstrip patch antennas to be more relevant in several perceptible communication systems. However communication in these times is not restricted to an individual frequency band. Distinct frequency bands are being used for the similar communication systems that propose the requirement for the antenna functioning in multi-frequency band with low weight, compact size, wide impedance bandwidth, increased gain and reduced size etc. [2]. Resonant MPAs usually take the form of a conducting printed patch. The patch shape can be arbitrarily determined, but the most common types are rectangular, square, circular, triangular, elliptical, rings, and their derivatives. Because a printed patch is usually over a conducting ground plane, it stores electric charge and energy and acts as a reactive circuit element. Consequently, the impedance bandwidth of a microstrip patch is typically very small, and depending on its substrate parameters and thickness, it can be less than one percent, or at best, a few percent. This range of bandwidths is smaller than the bandwidths of other antenna types and is insufficient for most current applications in communication and remote sensing, especially in new areas like microwave and medical imaging. Thus a need has arisen for broadening the bandwidth of microstrip patch antennas. Fortunately, researchers always respond to a challenge, and a variety of effective practical methods have been evolved to increment the bandwidth of microstrip antennas from a few percent to around 50 percent and more, such as performing slots into the radiator patch, increasing the substrate height, increasing the substrate thickness, colligating many patch components to constitute an antenna array, introducing parasitic elements either in coplanar or in multilayer configuration, acquainting a capacitive coupling within the radiating element and the ground plane, adding a shorting pin and manipulating the modeling of radiating element. Consequently, using all the above mentioned techniques microstrip patch antennas are no longer narrowband antennas. However, a price has been paid for broadening the bandwidth of the patch antenna, either in gain, polarization, or in the complexity of the antenna configuration. The drawbacks will be reviewed and discussed in relation with each multi-frequency wideband antenna type. Moreover, the reduction of size in conjunction with bandwidth and gain improvement is becoming starring design conditions for most realistic applications of MPAs for wireless communication. Thus, seeing the overall scenario, we need to design a multi-frequency

CHAPTER-2

PRELIMINARIES AND REVIEW

wideband MPA that is suitable to cover multiple communication standards simultaneously with all the features altogether viz. wide impedance bandwidth, increased gain and reduced size.

2.5. Techniques for Multi-frequency Operation

The development of current ultramodern wireless communication systems has exaggerated the necessity of antennas in a very impressive manner, susceptible to be enclosed firmly in portable, or not, devices that conduce to a terrestrial-satellite or a wireless land mobile network. Due to the continuous increase in overall requirements with time, the antennas postulated for receive and transmit signals have to become lightweight and smaller in size. In actuality, microstrip patch antennas are the best candidates that can meet these requirements. Because of the advantages of being light in weight and having low profile, they are easily conformable to the mounting hosts. Furthermore, these are fabricated and integrated easily into microwave printed circuits or into arrays and have low cost. Hence, they are the most appealing options for the above referred type of applications. Fast advancements in industry of wireless and mobile communication necessitate new antenna designs that could be utilized in multiple frequency bands and also permit reduction of size. From the seventies through until the mid eighties, most research in the field of MPAs developments was addressing the narrow bandwidth property of MPAs, and little attention was given to multi-frequency operation [78-79]. Applications such as GSM, WLAN and GPS require multiband antennas which can operate at multiple frequency bands. For designing multiband MPAs, main challenge is to obtain a good match with the feeding network, maintain the radiation pattern and keeping the design simple while operating at more than one frequency [18] [80]. Mobile telephony services require movable devices that can be easily transported and congenial with GSM/DCS/UMTS technology and can be combined with WLAN standards (2.5 GHz/5 GHz) as well. Thus, the designing of antennas that are limited in size and are suitable for these devices is a topic of remarkable involvement or concern. Several methods have been suggested for the design of radiating structures of MPAs. The standard distinguishing quality of almost all the printed multiband antenna elements is that these normally originate from an initial patch of general configuration that is decomposed or disintegrated in the following. Depending upon the method of the shape decomposition/disruption, the multiband MPAs could be arranged in classes as a) printed elements incorporated with slots or slits [81-87] b) patches with multiple radiating elements inductively coupled and/or conductively connected [88] c) patches having

particular shape as conductively coupled cross dipoles [89], the bowtie [90], the spiral [91-92] d) and the stacked patches [93]. A distinguished class of fractal microstrip antenna comes from a simple printed element initially which is then formulated by an algorithmic process. The patches in all the aforementioned classes are created, initiating from fundamental theory based concepts. Nevertheless, it is observed that none of these techniques provide an accurate design procedure that will help the researcher to commence from the similar idea occurring at the beginning to till end in every case in the similar configuration of patch, targeting at a particular dimension of operation. Therefore, the designing a patch with multi-frequency operation is considerably an artistic creation. Moreover, the most effective tools comprise the techniques of texturing the surface of patch and the techniques that are utilized for an optimal performance of the configuration. Scheming or design procedure of a multi-band microstrip antenna necessitates that all the impressive operational characteristics must be guaranteed in all the operational resonating bands like small return loss at the feeding port, gain greater than 0 dB, circular polarization and uniform distribution of the radiated power. Furthermore, these characteristic features should not be incurred at the price of complicated feed network or a large size antenna system. Thus, the design of a microstrip antenna is not always simple, indeed the antenna designer is confronted with various troubles emerging from i) intrinsic flaws of a printed antenna resonating element like restricted impedance bandwidth and ii) different required activities pertaining the operation of the radiating element that cannot be contented by a printed scheme with a common conformation for peculiar/specific applications. The microstrip element necessitates to pertain appreciable gain features that potentially disproportionate to its size or/and frequency bandwidth, considering that it functions like a resonant cavity. Hence, in order to configure such a challenging antenna, any novel concept or alteration of the present methods not within the scope of used standard techniques would be helpful and that would result in stimulating antenna strategies. Many conventional techniques such as the use of PIN (p type-intrinsic-n type) diodes, switches and varactor diodes are used for multiband operation [94-96]. But, these designs provide reconfigurable frequency operations with bi-state ON/OFF control. Also, the use of active components increases complexity in the design and their use are difficult to handle because it needs extra biasing network. In [97], multiband characteristics that operate in the range of 1.9-2.1 GHz were achieved through a triangular patch. In this case, chip capacitors are

CHAPTER-2

PRELIMINARIES AND REVIEW

used instead of varactor diodes. The impedance of an antenna is also controlled through chip capacitors which is a moderate technique. In [98], a patch antenna was designed with a U-slot and by using PIN diodes. The PIN diodes are utilized to switch the slots ON and OFF for different frequency bands. But, it provides tri-band response in the reported frequency range. Another patch antenna was designed by incorporating two slots on both sides of the patch which are controlled by two switches. The status of these two switches changes the resonant frequencies which affects the frequency bands. In [99], a microstrip patch antenna was presented for wireless applications which work from 0.9 GHz to 5.35 GHz. A multiband response was achieved by designing a modified ground plane. It has a unique structure of comb shape on both sides of the patch. This technique also assists to increase the gain and bandwidth of an antenna. A wideband microstrip patch antenna which also allowed multiband properties by designing an array was presented in [100]. This technique gives better efficiency and gain, operating at different frequency bands viz. 2.4 GHz, 5.5 GHz and 9 GHz, respectively. To reduce the effective permittivity of substrate, a technique of Photonic Band-Gap (PBG) structure was introduced in [101]. The suggested multiband microstrip antenna resonates at six frequency bands covering a frequency range of 1-5.35 GHz. These bands cover most of the commercial communication applications. The designing of PBG structure on ground plane degrades the efficiency of an antenna. Multiple patches with a slot-coupled technique were also used to get multiband results [102]. Three patches were used and a slot was etched in the middle of patch to couple upper and lower patches. This design worked at different bands in frequency range 0.7-1.7 GHz and it covered GPS, PCS and GSM frequency bands. Various multiband MPAs having different design configurations and come under the category of slot loaded multiband microstrip antennas are elaborated in the following [103-107].

In this chapter, various practical methods will be examined for designing multi-frequency wideband microstrip antennas that merge/unite all the properties referred above which formulate them desirable for contemporary communication applications. Peculiar examples will also be demonstrated for every case.

2.5.1. Slot Loaded Multiband Microstrip Antennas

In addition to bandwidth enhancement, a practical method of slot cutting the surface of printed antenna has been evidenced to be very impressive in obtaining the dual and multi-frequency

operation of patch [81-87]. Different shapes of slots have been intended for the texturing of the patch; a few significant outcomes are demonstrated in Figures 2.16 to 2.18. When a rectangular patch is cut or loaded with a folded slit or L-shape slit as presented in Figures 2.16(a) & (b), then the entire antenna configuration so formed is regarded to be comprised of two coupled resonators of distinct sizes [82].

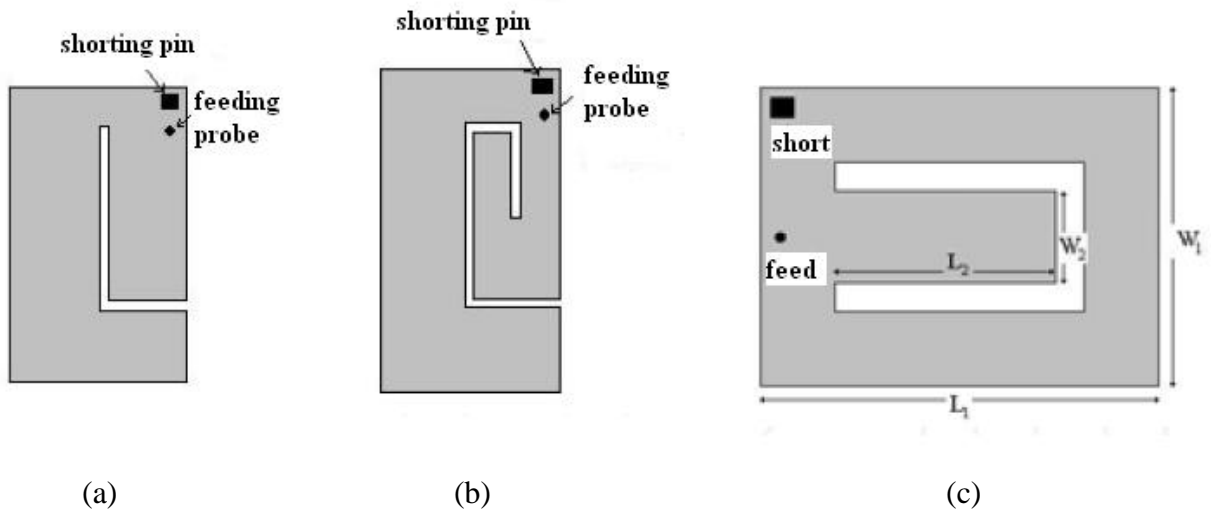


Figure 2.16: Geometries of shorted rectangular patch antenna for dual frequency operation with (a) an L-shape slit (b) a folded slit and (c) U-slot, [82]

A significant amount of size reduction has been achieved by appending shorting pins at the edge of radiating patch thus devising this type of compressed dual-band antenna fit for mobile and wireless communication applications. The magnitudes of the smaller and larger sub-patches in a particular direction in Figure 2.16(a) can be contrived to approximately resonate as quarter-wavelength resonating structures at the pre-specified frequencies. The secondary configuration of Figure 2.16(b) shows that the smaller sub-patch that resonates at a higher frequency, starts/begins from the feed point and expands into the center portion of rectangular patch. Thus, using this strategy it is surrounded by the slit on all sides and is enclosed by the outer larger sub-patch that resonates at the lower frequency. In lieu of utilizing an L-shape slit or a folded slit to attain two individual sub-patches, an integrated and embedded U-slot can be utilized as depicted in Figure 2.16(c). The smaller rectangle of dimensions $L_2 \times W_2$ in this configuration resonates at the higher of pre-specified frequencies and resides in the central portion of primary rectangular patch of dimensions $L_1 \times W_1$ that resonates at the lower frequency. The lower and upper

CHAPTER-2 PRELIMINARIES AND REVIEW

operating frequencies, f_L and f_H of this design can be roughly ascertained from prelisted frequencies [82].

$$f_L \cong \frac{c}{4(L_1 + W_1)}, \quad (2.29)$$

$$f_H \cong \frac{c}{4(L_2 + W_2)}, \quad (2.30)$$

where c is the speed of light in free space.

The non radiating edges of basic rectangular patch are altered by T-shape notches urging the patch to comparable operational characteristics as demonstrated in Figure 2.17(a). Another alteration of the patch by two pairs of smaller T-notches with appropriate size presented in Figure 2.17(b) outcomes in triple frequency band operation [84].

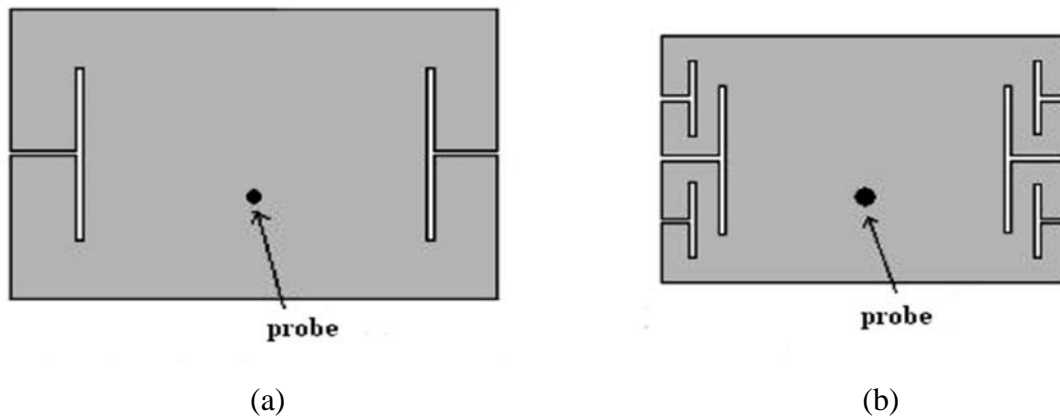


Figure 2.17: Microstrip elements coated with (a) single and (b) multiple T-notches [84]

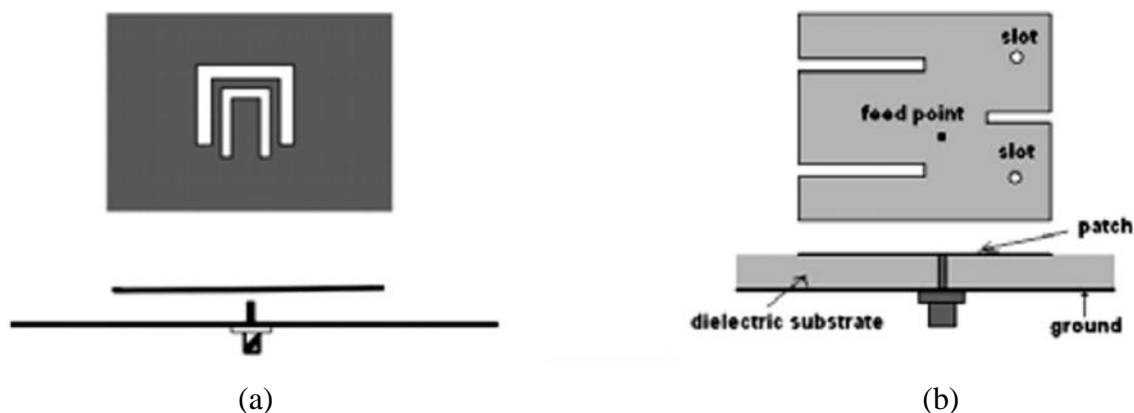


Figure 2.18: Configurations of MPAs (a) dual U-slot loaded patch [85] (b) patch loaded with unequal slits and tiny circular slots [87]

The approach of coating the surface of the patch by U-slots could adequately advance a wide band operation. It could be capable in urging the radiating patch element to multi-frequency operation as well. Two U-slots [85], of distinct size shown in Figure 2.18(a) or unequal slits united with circular slots that are extremely small in size are presented in Figure 2.18(b) that can ensure triple band operation [87].

A different composition of MPA, loaded with slits is presented in [86]. The patch having annular ring shape shown in Figure 2.19(a) is cut over a two layered dielectric substrate and is covered by a dielectric superstrate as illustrated in Figure 2.19(b).

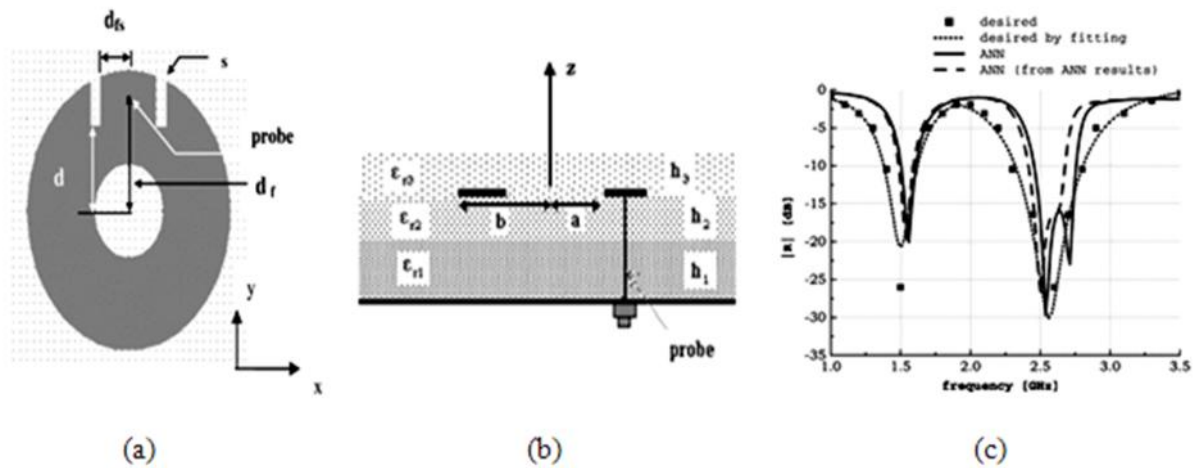


Figure 2.19: Dual-band microstrip antenna with multilayered substrate [86]

(a) Top view (b) Side view (c) Reflection coefficient

The fundamental benefit of a ring antenna is the characteristic to resonate for a diameter less than $\lambda_g/2$ where, λ_g is the guiding wavelength of the equivalent linear microstrip line occupying width equal to that of the ring. This distinct feature renders an overall size smaller as compared to the size of the corresponding circular disc resonating at the same frequency. Also, the total height of the substrate is large in the suggested layout that assures the broadband characteristics of frequency bands as depicted in Figure 2.19(c). Also the slits introduced in the proximity of the location of the probe nullify the huge inductive input impedance effectively that results from the thickness of the substrate in an unavoidable manner.

Another antenna design for multi-frequency operation proposed in [103] uses a U-Slot Gap-Coupled Rectangular Microstrip Array Antenna (USGRMAA) using corporate feed arrangement that has been verified to be very effective in urging the element to triple-band operation. This

CHAPTER-2

PRELIMINARIES AND REVIEW

antenna provides triple bands at 8.24, 8.86 and 11.02 GHz of frequencies. The overall impedance bandwidth has been found to be 8.8%. The effect of change in impedance bandwidth and gain has been studied experimentally by replacing U-slot with V and H slots in the parasitic element of USGRMAA. The H-slot antenna yields maximum impedance bandwidth and gain among the proposed antennas. Most importantly, this antenna also shows sum and difference radiation pattern in its operating bands.

Furthermore, a compact, single feed, multi-frequency design of reconfigurable MPA with various slots proposed in [104] has been illustrated in Figure 2.20. As shown, a rectangular patch loaded with horizontal slots occupying extended slot arms forms the fundamental structure of the antenna.

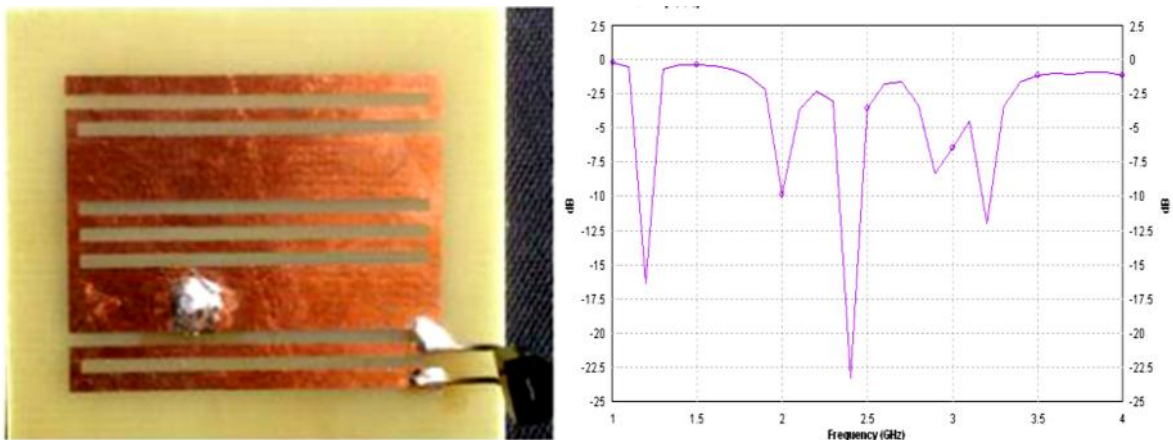


Figure 2.20: Reconfigured slotted antenna and its reflection coefficient [104]

The tuning of the multi resonant frequencies is noticed by altering the effective electrical length of the slots by loading varactor diodes over the slots. In comparison with conventional rectangular microstrip, a patch size reduction of 84% for the lower operating frequency is obtained. Also, the suggested antenna is extremely useful for multi-band wireless applications like GSM1800, IMT2000, and WLAN etc. operating over a wide range of bands.

Furthermore, a novel miniaturized design of a multi-frequency rectangular microstrip patch antenna proposed for WLAN, HYPERLAN and SATELLITE applications [105] has been demonstrated in Figure 2.21. The proposed antenna uses a pi-shape slot made into the ground. The proposed antenna has multi-frequency bandwidth of about 385 MHz (3.282-3.672GHz), 517MHz (5.114- 5.631GHz) and 1111 MHz (5.917-7.028GHz) at -10 dB return loss that is adequate enough to make the antenna helpful for WLAN/HIPERLAN/SATELLITE operation.

The maximum obtainable gain over the whole frequency band is close to 5 dBi. In this antenna design, the resonance frequencies were adjusted by altering the dimensions of the ground plane.

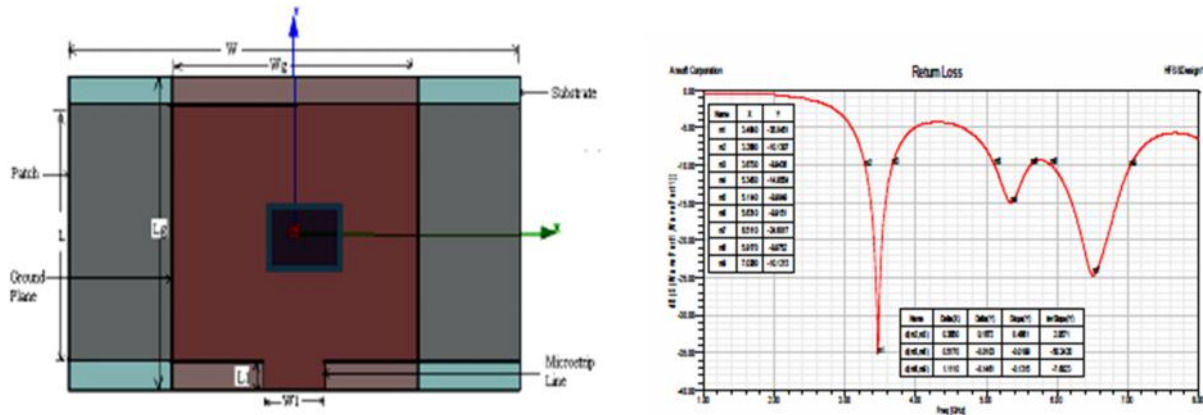


Figure 2.21: Multi-frequency RMPA with its return loss curve [105]

2.5.2. Dual Port Excited Multiband Microstrip Antennas

A novel compact size two-port E-shape microstrip single-layer patch antenna depicted in Figure 2.22 can be utilized for multiband applications. It has been designed, analyzed, and fabricated for multiband wireless applications in [106]. This E-shape antenna is designed to function at three sub-bands, namely 5 GHz, 10 GHz and 20 GHz with about 8% bandwidth at each frequency. It incorporates two ports excited with microstrip line feed mechanism. Dual feed has the benefit of easing the utilization of multi-polarization consequently it draws the attention many researchers. The suggested antenna is extremely encouraging for different modern communication applications.

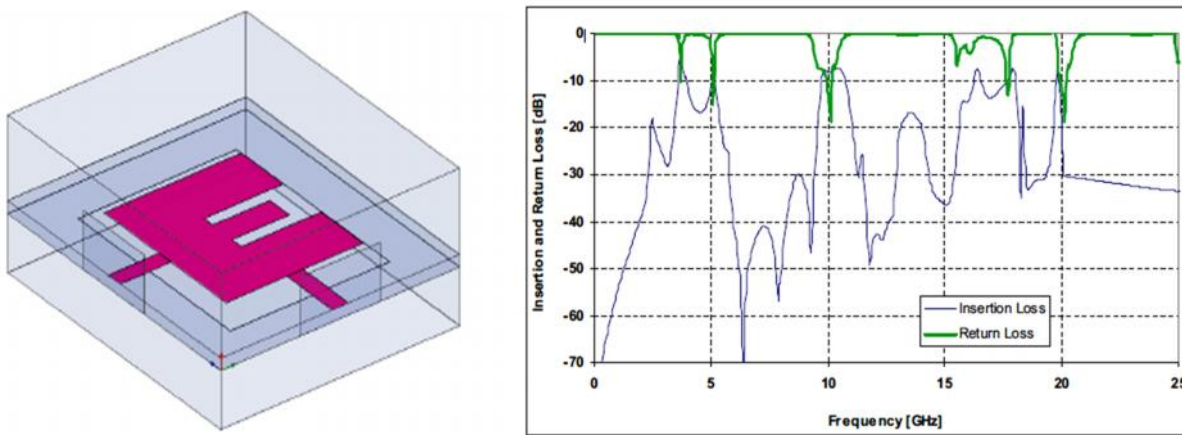


Figure 2.22: 3D model of the proposed E-shape MPA with its insertion & return loss [106]

CHAPTER-2

PRELIMINARIES AND REVIEW

2.5.3. Corner Excited Multiband Microstrip Antennas

Multi-frequency operation can be obtained by joining two MPAs at corner with corner excitation [107]. In the proposed configuration shown in Figure 2.23, two rectangular MPAs are designed with center frequencies 9 GHz and 5.67 GHz. Different parameters such as width, dielectric constant & effective length are calculated. Subsequently the antenna impedance is matched to 50-ohm of coaxial feed for maximum power transfer. The designed structure is then reorganized for multi-frequency operation by joining two MPAs at corner with corner excitation as aforesaid. The simulation confirms operation at 5.77GHz, 7.32GHz and 7.80GHz with constancy of radiation patterns. The antenna shall be acceptable for wireless communication system applications.

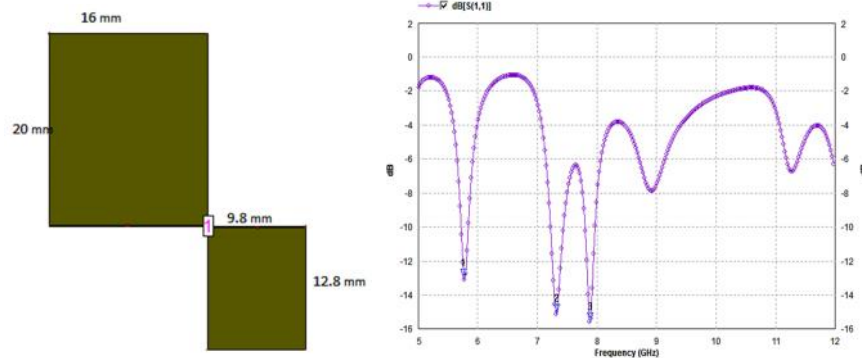


Figure 2.23: Reflection coefficient of the proposed MPA having two single frequency antennas joined at the corner and fed at the connecting point [107]

2.5.4. Multiple Patches

For designing a printed multiband antenna, another approach is to employ more than one element having distinct sizes that resonate at distinct frequencies. As displayed in Figure 2.24, the antenna is an array of microstrip annular rings having a common center impressed over a double dielectric layer. A multi-frequency operation is obtained from the resonances of the individual rings and from the alterations made to the rings [88]. Two inherent advantages are exhibited by this entire layout as i) each annular ring resonates possessing diameter less than $g/2$ and ii) a ring shape printed element permits other rings of smaller radius to resonate at distinct frequencies, thus promising multi-frequency operational characteristics and compactness are obtained at the same time. To discover the resonating frequencies of each ring it is essential to elucidate the electromagnetic problem of printed annular ring antennas fed by probes. An

exhaustive and fundamental method for this solution, in spatial domain, is to decide the corresponding Green function [2] [108]. The components of the radiated field do not alter by more than 5 dB on both principal planes in all frequency bands on account of the annular ring shape of the elements of the antenna. Besides, the use of probes provides a good prospect to enhance the level of gain employing a correct phase shift between the probes.

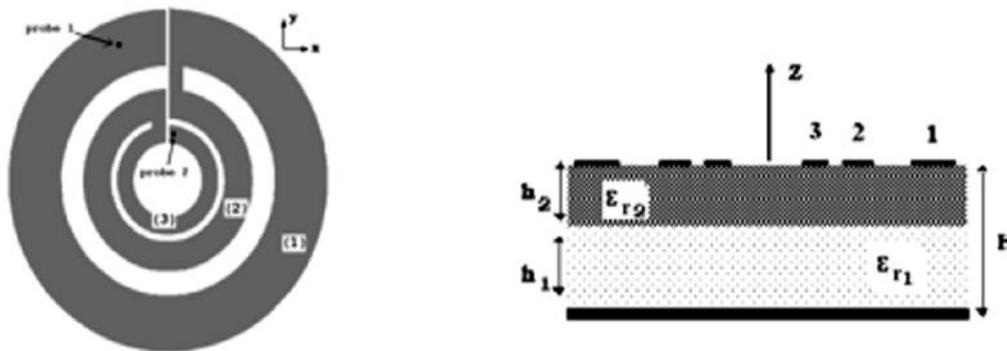


Figure 2.24: Top and side-view of a multi-frequency MPA with three conductively connected rings [88]

2.5.5. Bowtie Patches Loaded with Slots

Bowtie patch shape is an additional configuration that permits the antenna to exhibit multi-frequency operation. Bowtie MPAs are emerging as an attractive choice nowadays in communication systems because of their compact size in comparison to a traditional rectangular patch in spite of the fact that both of them have identical characteristics and performance at the similar frequency. The basic design of a bowtie MPA is demonstrated in Figure 2.25. Basically, a printed bowtie object is obtained from a rectangular patch by making few amendments and the equations for calculation of the resonance frequency f_r are derived in terms of material and geometrical parametric values [109]. The key rule of producing slots on the top of an impressed antenna so as to impinge it into multi-frequency operation can be implemented to bowtie patches as well. The different configurations of bowtie MPAs with modified patch shapes are depicted in Figure 2.26 [90].

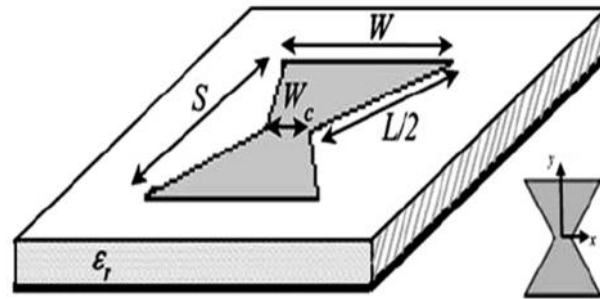


Figure 2.25: Geometry of the bowtie MPA [109]

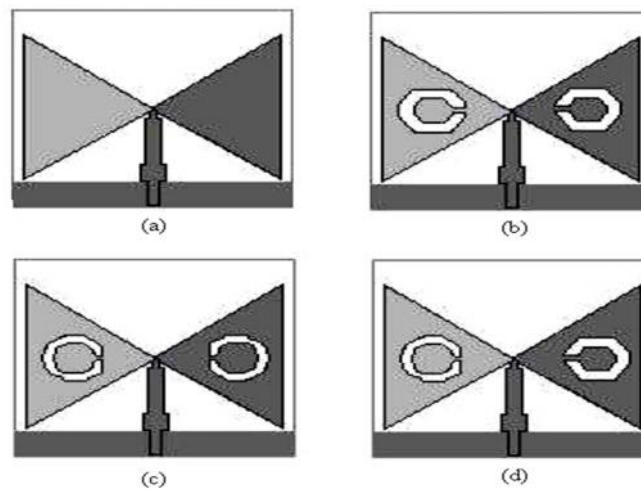


Figure 2.26: Bowtie MPAs (a) the ordinary configuration, (b)-(d) patches modified by loading slots of various shapes for multiband operation [90]

The first step of the design procedure is to select proper attributes of the arms of the bowtie to confirm the first frequency band which is then followed by the addition of circular or polygon slots to the bow patch antenna designs. This arrangement causes the antenna to accomplish dual-frequency operation in which the initial frequency can be attained by the first step of design and a later desired one can be achieved by selecting the suitable size of the slots as demonstrated in Figures 2.26(b) and 2.26(c). A tri-band antenna can be obtained by cutting slots of changed shape or size in the two parts of the antenna, as illustrated in Figure 2.26(d).

In all the designs realized in [90], the printed radiating elements are constructed with one on the lower side and the other on the upper side of the dielectric substrate. Method of feeding is contingent upon on the chosen bow-tie design. Moreover, the high frequency transmission

microstrip line theory could be implemented for calculating the parameter values of feeding network.

2.5.6. Spiral Antennas

Multi-frequency function could be obtained by utilizing spiral printed antennas. An appropriate amendment of general shape of the printed spirals, mainly the rectangular shape, has been reported to be adequate for multi-band operation. Figure 2.27 indicates three design structures that are based on an altered spiral line method and shorting-pin method [91-92].

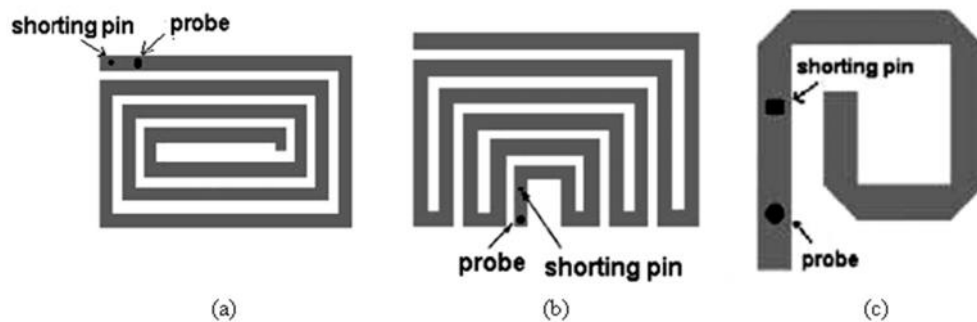


Figure 2.27: Microstrip spiral configurations (a) the ordinary shape (b) conductor folded back onto itself (c) small number of bends and truncated corners [91-92]

These antennas are capable to resonate at frequencies much smaller than multiband antennas with compact size. The extended length of the current path because of the spiral structure along the conductor area is the groundwork or basis for this operation. Figures 2.27(a) and 2.27(b) demonstrate two ways of folding the conductor to maximize its length. First is the standard rectangular folding and second is folding the conductor back onto it in two dimensions. For a constant antenna area, three dependent variables include the conductor width, number of bends in the conductor and gap between the conductors. The thickness of the conductor should be set according to the diameter of shorting pins and probe. Making use of these structures dual band function was obtained at frequencies both being less than 1 GHz [91]. By the design of Figure 2.27(c), a multiband operation could be attained. To accomplish this, a small number of bends for the spiral structure are utilized and the corners are shortened for the streamlined flow of current. The resonating frequencies, proportional bandwidths and impedance matching characteristics are restrained by the width and length of line, the gaps within the lines and the location of feed point and shorting pin. By utilizing a dual slab substrate, the lower slab being of air or foam, the bandwidth may be increased. Thus, for higher frequency operations, a spiral

CHAPTER-2

PRELIMINARIES AND REVIEW

shape antenna because of the comparatively small length of conductor is suggested. By proper selection of the parameters, a dual band phenomenon was obtained [92], one from 2.37 GHz to 2.47 GHz and other one of large width, from 5 GHz to 6.3 GHz.

2.5.7. Fractal Antennas

The antennas based on fractal technique have been implemented to numerous domains of science along with fractal electrodynamics. Basically, fractal concepts are incorporated with electromagnetic theory for examining radiation, propagation and scattering problems scientifically. The fractal antenna technology emphasize on two auspicious research fields: the first relates to the study and modeling of radiating fractal elements with the other one focusing on the utilization of the fractal approach for modeling arrays of antennas [2] [110-113]. These types of antennas have properties that are very preferable in military and commercial spheres. Most elements of fractal antennas have printed conformations, short profile, compact size, cheap, multi-band functionality and simple feed mechanism. The working of fractal antennas could be improved potentially by the appropriate alterations in their design. Furthermore, the use of fractals for the designing of an antenna array may result in radiating systems having huge size, relatively more gain accompanying multi-band or frequency-independent function and radiation patterns with low level of side lobes. Further, the antenna array elements when fed in succession function as Direct Radiating Antennas (DRAs) and operate as phased arrays [114-116]. Fractals can be categorized in two groups: deterministic and random. Deterministic fractals are those which are rendered from various scaled and revolved transcripts of themselves applying an algorithm relating to a recursion. Random fractals incorporate components of haphazardness that permit simulation of normal working. Various algorithms have been established for obtaining both deterministic and random fractals whereas most of the suggested fractal antennas have been modeled with a deterministic fractal mechanism. The fractal approach is supported by the concept of recognition of the functional attributes of an antenna by the repetition of a radiating architecture occurring at the beginning in regular or arbitrary scales. A generator is the key feature of a fractal developed antenna which is also termed as pioneering radiating element. Specifically, the whole antenna can be created recurrently through iterative application of the pioneering radiating element under a determined scaling factor that is one of the specifications of the problem. Potentially, this phenomenon is obtained by making use of two different schemes:

Using first one, the generating antenna is repeated in such a manner that its whole physical magnitude gets bigger from stage to stage of fractal building. Using other method, the whole area is defined a priori, which the concluding antenna is permitted to use up. After the proper repetition of the generating element, the usable area is occupied by the scaled copies of generator. Such type of space filling results in antenna structures with electrically large lengths though they are compact hence, comprising considerably a miniaturization technique generating elements effectively packed into minute areas, thus feasible and appropriate for installation in portable telecommunication devices. The realization and theoretical analysis of the process of a fractal microstrip antenna are settled upon the rudimentary relation within a MPA and a fractal resonator. The most suitable fractal configurations, reported in literature, that were verified to be effective in antenna design are the Koch fractal, the Sierpinski gasket or carpet fractal, the Hilbert fractal, the Minkowski and the Square Curve fractals. Each of these were established to give printed antennas, conformal or planar, with multi-frequency operation and simple feeding, satisfactory gain and polarization characteristics, whereas they are compact in size. Because of all these characteristics, they are an improved and comparatively good option for portable telecommunication devices.

Koch: Direct and Inverse Fractal Islands

The basic geometry of the Koch fractal curve and Koch Fractal Island is demonstrated in Figure 2.28. The Koch fractal microstrip patches are often utilized because of their appealing properties like compact size, single feeding port and directive radiation patterns [117-119]. The basic configuration of the Koch island could be achieved by substituting the sides of an equilateral triangle by a Koch curve. An equilateral triangle is a generator and the higher stages of fractal development accompany or play along the respective stages of Koch fractal curve as presented above in Figure 2.28. A major benefit of Koch patch is that it could resonate effectively at frequencies lower than that of a regular patch having identical size as been substantiated by electromagnetic simulation and through experimental studies as well. Further, equivalence among their sizes is necessary to understand the high quality of Koch fractal to a conventional triangular patch.

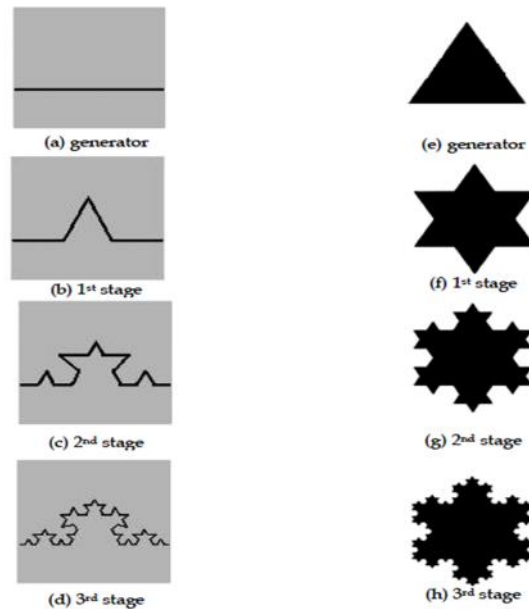


Figure 2.28: The generator and first three stages of the Koch fractal curve (a)-(d), and Koch fractal island antenna (e)-(h) [117]

Sierpinski Fractals

Sierpinski fractal is another fractal concept that is commonly used to model MPAs [120-128]. Many Sierpinski fractals have been suggested: The Sierpinski Gasket (or triangle), the Sierpinski Carpet (or rectangle), the Sierpinski Pentagon and the Sierpinski Hexagon. Making a close reference to the available literature, the most impressive configurations for antenna applications are the carpet and particularly the gasket. Dipole or monopole gasket fractal microstrip contours have been responsible for yielding multi-frequency antennas. Although, different geometrical conformations support the Sierpinski objects, they have one construction principle in common. Figure 2.29(a) demonstrates the geometrical scheming of Sierpinski gasket that initiates with an equilateral triangle that is also regarded as a generator. In the scheming procedure, the next measure is to obviate the middlemost triangle, the one with vertices that are demonstrated at the midpoints of the sides of the original triangle. Three equal triangles persist in the configuration by the elimination of central triangle, each one being half of the size of the original one as demonstrated in Figure 2.29(b). A similar process is carried out for the three remaining triangles etc. as depicted in Figure 2.29(c) and Figure 2.29(d).

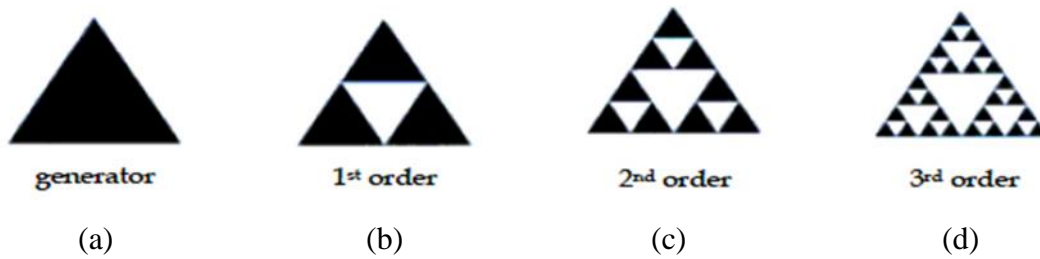


Figure 2.29: The generator and first three stages of Sierpinski fractal gasket (a)-(d) [120]

When the iteration is accomplished an infinite number of times, a perfect fractal Sierpinski gasket is achieved. All of the three chief parts of the structure created are perfectly similar to the whole object, merely scaled by a factor in each stage of the fractal building. Hence, the Sierpinski gaskets, along with other Sierpinski fractal objects are suitable illustrations of autonomously complementary strategies. From an engineering viewpoint in antenna domain, it may be ascertained that the triangular black areas exemplify a conductor made of metal while the triangular white areas represent the metal eliminated regions.

Hilbert Fractals

In the modeling of fractal microstrip antennas, Hilbert fractal curve is a quite better option to use [129-133]. Despite of being autonomously complementary, these curves have the added outcome of almost occupying a plane and this aspect is employed in operating a ‘small’ resonant antenna. Hilbert fractals with size much smaller than $\lambda/10$ are susceptible to resonate, with operation identical to that of a dipole whose resonant length is nearby $\lambda/2$.

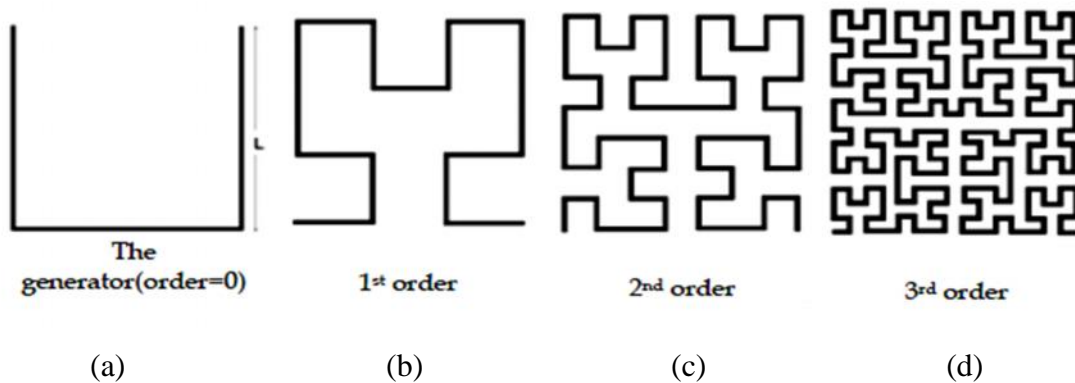


Figure 2.30: The generator and first three stages of Hilbert fractal antennas (a)-(d) [129]

Figure 2.30(a) illustrates the generator or initiator of Hilbert curve having a rectangular U-shape. Further, Figures 2.30(b)-2.30(d) present the Hilbert fractal printed curves for the various

CHAPTER-2

PRELIMINARIES AND REVIEW

iterations. The fractal structure of antenna at each stage is achieved by suitable conforming four replicas of the immediately past iteration linked by one or more line segments.

Square Curve Fractals

By incorporating a square curve fractal algorithm in the configuration of MPAs, radiating designs with multiband function can be rendered [134]. In such type of fractal phenomena, the generator is a rectangular ring and consequently the curves of various other stages are closed curves. Square curve fractals do not adjunct to the family of space filling curves. Moreover, an increase in their entire length is not noteworthy from stage to stage, hence allowing the antenna systems to fulfill the demand of compact physical magnitude with increased and appreciable gain in virtue of their incremented linear dimension. Figure 2.31(a) illustrates the initiating point of building process. The choice of size of the generator is a rectangular ring with side length L . After wards, the four corners of the square ring are utilized as the center of four smaller squares each having side half than the side of main square. The areas that coincide or imbricate partially or wholly are polished away. Figure 2.31(b) presents the curve generated by this first iteration. Using the similar algorithmic procedure, the following stage of fractal antenna can be incurred as demonstrated in Figure 2.31(c).

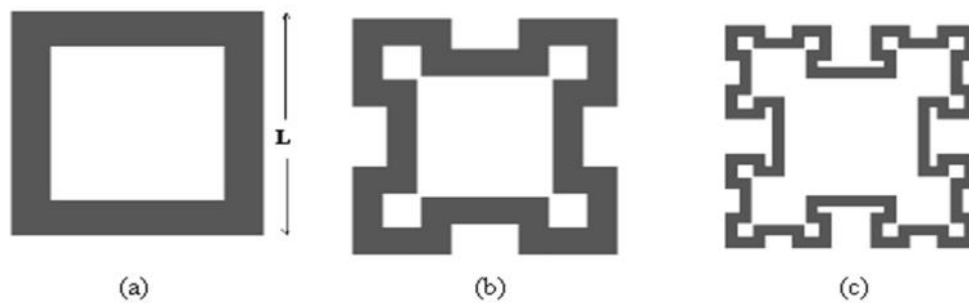


Figure 2.31: The generator and two lower stages of Square Curve fractal (a)-(c) [134]

2.5.8. Reduced Ground Plane

The process of alteration in the ground plane dimensions and feed line position shown in Figure 2.32 can be selected for the modeling of multi-frequency wideband square patch antenna for ISM and Wireless Medical Telemetry Service (WMTS) applications as proposed in [135]. The betterment of their impedance matching was ratified and discussed. A short size was also achieved by enhancing the overall geometry of the antennas, when in fact a broadband performance was attained mainly by using an asymmetrical feed and a limited ground plane. The

large impedance bandwidth, proportionally high gain, fair radiation quality, less assembling cost, simple integration and easy feeding make this antenna a suitable choice for various communication systems, especially biotelemetry.

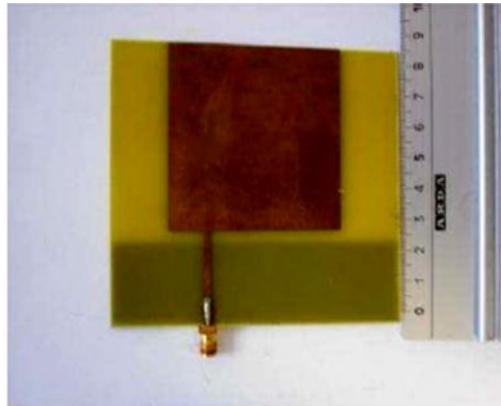


Figure 2.32: Proposed antenna with reduced ground plane [135]

2.5.9. Stacked Multiband Microstrip Antennas

Probe/Coaxial feeding, inverted patch and multiple slotted stacked patches are the new additional design methods that are proposed following present day techniques [136].

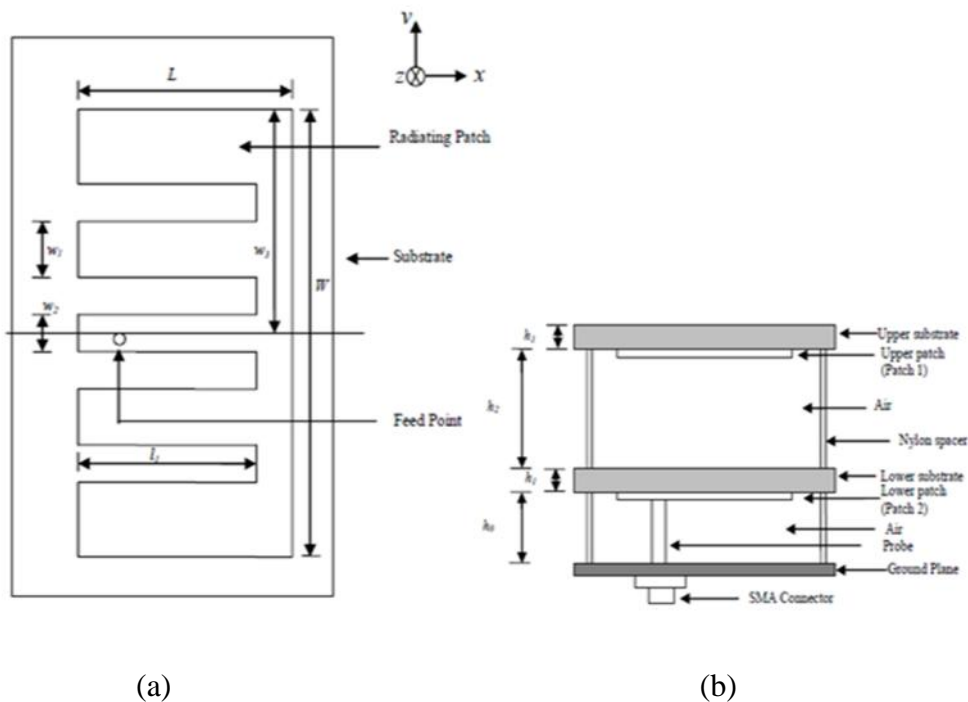


Figure 2.33: Geometry of proposed stacked patch antenna (a) Top view, (b) Side view [136]

CHAPTER-2 PRELIMINARIES AND REVIEW

The compound response of incorporating these all these methods and by using the novel multiple slotted patch as shown in Figure 2.33, some fascinating features such as a low profile, high gain, and small size of multi-frequency/multi-standard antenna element are offered. The outcome showed good working with utmost obtainable gain of about 12.35 dBi and an impedance bandwidth of 21.48% covering array applications commonly for base station. Moreover, because of its huge gain and enhanced bandwidth, numerous applications can be intercepted.

Moreover, a structure of single-feed dual-frequency patch antennas with various polarizations and radiation patterns is considered [137]. The antenna design is built of two stacked patches, in which the head is a square patch and the base is a corner truncated square-ring patch. Figure 2.34 demonstrates two patches that are joined together with four conducting strips. Two driving frequencies can be obtained in this antenna structure. The radiations at the higher and lower frequencies are a conical pattern with linear polarization and a wide pattern with circular polarization respectively. The suggested prototype antenna functioning at 1575 and 2400 MHz bands is built and measured. Both the simulated and measured outcomes signify that the present prototype has satisfactory functioning and is well suited for WLAN and GPS purposes.

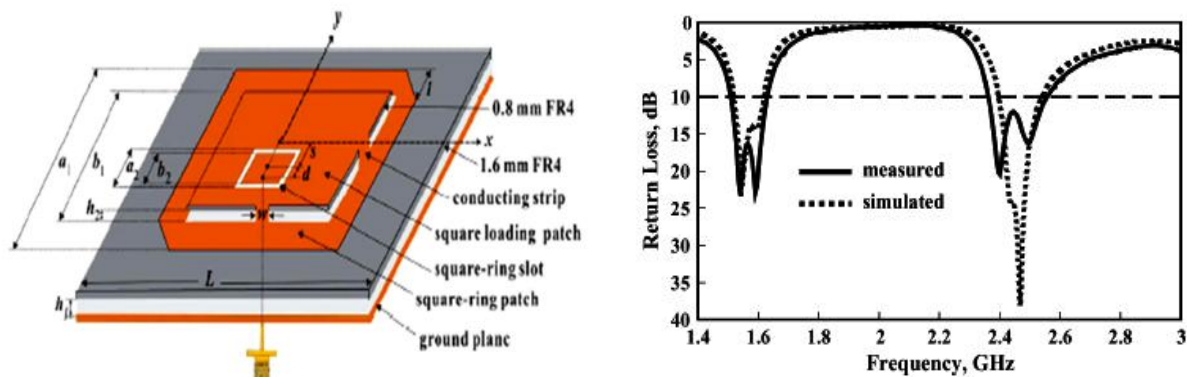


Figure 2.34: Proposed dual frequency patch antenna and its reflection coefficient [137]

2.5.10. Multiband Microstrip Antennas using DGS

In [138], we define a recent way to make the antenna size small and exhibit multiband phenomena. Electromagnetic Band Gap (EBG) structure is used as DGS to minimize size and attain multiband resonant frequencies. Two cells of spiral-shape DGS are utilized in the design demonstrated above in Figure 2.35. As evident from the simulated results, more than 50% size reduction was achieved with five resonant frequencies following as a consequence from the new design. The fundamental patch antenna resulted in one resonance while the other four ensued

from each of the spiral arms. Appreciable E-plane and H-plane radiation patterns with an antenna gain of nearly 4 dB were obtained.

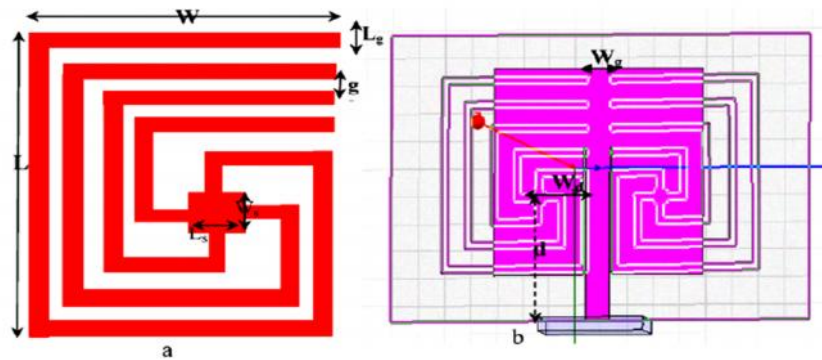


Figure 2.35: Multiband MPA using DGS (a) The schematic of a spiral cell used in DGS (b) the cell design for optimized antenna size reduction [138]

2.6. Some Relevant Developments in Multi-frequency Microstrip Antennas

Due to the integration of different wireless applications satisfying different bands on a single device, multi-band microstrip patch antenna is the best solution keeping the overall size of the device small. In this section, a brief summary has been provided on some recent developments in MPAs along with their design configurations and resonating frequency bands.

S. Das et al. (2014) proposed a compact single layer microstrip patch antenna with single feed for multi-frequency operation. A T-shape slot which is open ended had been innovated at right-side radiating edge of the patch with an aim to reduce the antenna size and to obtain multiple resonant frequencies. The measured results indicated 61% reduction in the size of antenna with an enhanced frequency ratio. The proposed antenna was simulated and fabricated for operating at 3.6, 5.2, 6.1, and 7.3 GHz frequency bands [139].

T. H. Chang and J. F. Kiang (2013) proposed a compact triple-band H-shape slot antenna fed by microstrip coupling. Four resonant modes were excited, including a monopole mode, a slot mode, and their higher-order modes, to cover GPS (1.575 GHz) and Wi-Fi (2.4–2.485 GHz and 5.15–5.85 GHz), respectively. Sensitivity study of the slot geometry upon the resonant modes had been conducted. The measured gains at these four resonant frequencies were 0.2 dBi, 3.5 dBi, 2.37 dBi, and 3.7 dBi, respectively, and the total efficiencies were 2.5 dB, 1.07 dB, 3.06 dB, and 2.7 dB, respectively. The size of this suggested slot antenna was only $0.24\lambda_0 \times 0.034\lambda_0$,

CHAPTER-2

PRELIMINARIES AND REVIEW

where λ_0 is the free-space wavelength at 1.575 GHz is is, hence is suitable to install on notebook PC's and handheld devices [140].

S. A. Ali et al. (2012) presented a patch antenna for multiband operations based on a fractal shape slot. The fractal shape slot was prototyped on the rectangular patch and the feed to the resulting antenna was provided through a microstrip line. The suggested antenna design permitted the antenna for multi-band operations in the frequency range of 1-20 GHz. The simulated results indicated VSWR ≤ 2 over the entire resonating frequency band. The proposed design exhibited a higher gain as compared to the conventional patch antenna [141].

W. Cao et al. (2012) presented a multi-frequency microstrip patch antenna with dual-mode behavior. The meta-material substrate composed of modified mushroom-type Electromagnetic Band Gap (EBG) structure when introduced enabled multi-function behavior of proposed antenna. Various theories like composite right/left-handed transmission line (CRLHTL) theory and multi-conductor transmission line (MTL) theory were presented to examine this kind of antenna. Three radiation patterns including two patch-like radiation patterns and one monopole radiation pattern were analyzed for accessing different parameters of EBG structure of dual polarized antenna [142].

J. Malik and M. V. Kartikeyan (2012) proposed a metamaterial-inspired antenna for WiMAX/WLAN applications. Design studies, analysis of parameters, results obtained on simulation along with measurements for a L-shape slotted ground microstrip patch antenna with CSRR (Complementary Split Ring Resonator) embedded on patch structure operating simultaneously at WiMAX (3.5 GHz) and WLAN (5.8 GHz) were presented. The metamaterial-inspired loading was utilized to create resonance for upper WLAN band while an L-shape slot on the ground plane was responsible for a resonance at the WiMAX band, maintaining the antenna's overall small form-factor. The measured *S*-parameter and radiation patterns of fabricated prototype reveal that the design so proposed is suitable for emerging WiMAX/WLAN applications [143].

N. Ramli et al. (2012) presented a novel Frequency Reconfigurable Stacked Patch Microstrip Antenna (FRSPMA) employing an aperture coupler as the feeding technique with stacked technology. The antenna was able to accommodate S/X band separately by using the same antenna. Two patches at different substrates were operated sequentially to attain frequency

reconfigurability by modifying the switch mode at the feed line. Both patches and feed line were coupled electromagnetically via two small electrical apertures in the ground plane. This design was simulated utilizing CST MWS to be operational from 2 GHz to 8 GHz [144].

S. Arianoz et al. (2012) presented two designs of multi-band antennas for automotive communication application. Both antennas were designed for operating in four frequency bands (GSM, E-GSM, DCS and PCS). They were made to be integrated into a PCB that was placed inside a plastic box and mounted underneath the dashboard of the vehicle. The first design was a planar printed antenna which was fully integrated into the PCB, thus minimizing the cost virtually to zero; the second design was a three dimensional antenna, which did not need any dedicated space on the PCB. The simulated reflection coefficients and radiation patterns of both antennas were reported to be in good agreement with the prototype measurements [145].

F. Mirzamohammadi et al. (2012) presented a dual band microstrip monopole antenna for mobile communication applications. The radiating patch was modified by the inclusion of a complex form of slot and ground plane was considerably adjusted by the addition of a pair of modified U-shape slots. By employing these modifications, two frequency wide bands of 1.38–3.98 GHz (97%) and 5.15–6.2 GHz (18%) were obtained. In another design of the antenna, a very small slot as a switch was employed in the special positions on the ground plane to vary and control the frequency response to cover multiple and single bands along with narrow and wide bands between 1.5 and 6 GHz frequencies. The entire size of the antennas was reported to be 20 × 34 mm [146].

J. Cao et al. (2012) presented a planar triple-band monopole antenna with a U-shape strip line and a L slot. The antenna proposed was very concise with a size of 20 × 30 × 1.5 mm³ and fed by a 50-ohm microstrip line with a defected ground. The measured -10 dB impedance bandwidth of the proposed antenna covered 2.33-2.51 GHz, 3.25-3.82 GHz, and 4.83-8.4 GHz, respectively, which satisfied the specifications of WLAN 2.4/5.2/5.8 GHz and WiMAX 3.5/5.5 GHz. The radiation characteristics showed a monopole-like pattern, and the measured results were in agreements with the simulated ones [147].

F. C. Ren et al. (2012) presented a compact microstrip-fed slot antenna with triple-frequency operation. The proposed antenna structure consisted of a cross-shape microstrip feed line and multiple open-ended slots on the ground plane. By the proper selection of shapes and dimensions

CHAPTER-2

PRELIMINARIES AND REVIEW

of these embedded slots, the triple-resonance situations at 2.4/3.5/5.8 GHz were obtained. Meanwhile, the cross-shape feed line with shorting pin made a joint benefit to adjust the matching condition and impedance bandwidth. The numerical and experimental results exhibited the designed antenna to be operational over triple frequency ranges and covered a number of useful frequency bands for present wireless communication systems. In addition, acceptable radiation characteristics were achieved over the operating bands [148].

X. Q. Zhang et al. (2012) presented a miniature single-layer CPW-fed monopole antenna with triple-band operation for WLAN and WiMAX applications. The proposed antenna comprising a planar rectangular patch element embedded with dual U-shape slot was capable of producing three distinct operating bands, 2.37-2.53, 3.34-3.82, and 4.23-6.88 GHz spreading over the 2.4/5.5/5.8 GHz WLAN bands and the 3.5/5.5 GHz WiMAX bands. The designed antenna had a simple uniplanar structure and a compact size along with the finite ground CPW feeding mechanism. Moreover, the proposed antenna demonstrated good monopole-like radiation patterns with small cross-polarization and stable antenna gains across the three operating bands [149].

J. Pei et al. (2011) proposed a miniaturized multi-frequency antenna comprising a circular ring, a Y-shape-like strip and a defected ground plane that can yield three separate impedance bandwidths to spread over 2.4/5.2/5.8 GHz WLAN operating bands and 2.5/3.5/5.5 GHz WiMAX bands. Introduction of a Y-shape like strip in the circular ring of antenna excited two resonant modes. By the addition of a cambered ground plane accompanied by an isosceles triangle-defect, the third wide band with improved impedance matching was achieved. The measured results of the prototype antenna demonstrated good radiation patterns and sufficient gain covering the operational bands [150].

E. Ebrahimi et al. (2011) described an integration concept for multi-standard antennas. The technique was based on using a relatively large antenna that was printed on the top side of a substrate, acting as a ground for a smaller antenna. The smaller antenna was printed onto the bottom side of the substrate. The antenna comprised of a shorted microstrip patch integrated with a CPW fed ultra wideband (UWB) antenna. A prototype of the integrated antenna was fabricated and its performance was validated. This arrangement was a confirmed candidate for applications where some level of reconfigurability was requisite. A set of external tuning circuits were

designed to reveal the potential of the suggested configuration for desired applications. For enhancing the isolation between the wideband and narrowband ports various modified arrangements were presented and investigated [151].

N.F.F. Areed (2011) proposed a microstrip patch antenna incorporating a C-shape slot implemented on a thin substrate that resulted in a size reduction of 40% in comparison to an ordinary microstrip patch antenna working for the same resonant frequency band. However, size reduction resulted at the cost of bandwidth and the gain which were then incremented to an appreciable level by utilizing transmission-lines-feed and annular ring slots. The combined effect of integrating these techniques yielded a low profile, broadband, and multiband antenna capable to work in the WiMAX (3.27-3.4GHz and 6.9-7.8GHz) frequency bands [152].

K. F. Lee et al. (2011) described the method of employing U-slots to design dual- and triple-band patch antennas. When a U-slot was engraved in one of the patches, a notch was presented into the matching band, and the antenna turned to be a dual-band antenna. If another U-slot was engraved in the same patch or another patch, the outcome was a triple-band antenna. This method is put to L-probe-fed patch and M-probe-fed patch along with the coaxially fed and aperture-coupled stacked patches. The radiation patterns and gains of the dual-and triple-band antennas were reported to be similar to those of the original broadband antenna. As the band notches introduced by the U-slots appeared within the bandwidth of the antenna lacking slots, this method was acceptable when the frequency ratios of the adjacent bands were small, usually less than 1.5 [153].

K. Jhamb et al. (2011) introduced a frequency-tunable dual-band microstrip annular ring patch antenna design for 2.45 GHz/3.5 GHz/5.5 GHz applications. The suggested antenna rendered realizable gain higher than 5 dBi and return loss improved by 10 dB for the proposed applications. The antenna design comprised of an annular ring patch loaded with a slot or gap. The loaded ring excited higher-order modes around the dominant mode (TM₁₁) of the annular ring thereby making this design capable of dual-band operation. The prototype was realized on a 1.57 mm thick polytetrafluoroethylene substrate utilizing a coaxial probe feed. In this study, a novel technique for independent frequency tuning had also been introduced by cutting grooves on the periphery of the ring at the desired locations [154].

CHAPTER-2

PRELIMINARIES AND REVIEW

K. Song et al. (2011) implemented an open L-slot antenna with triple-band operation for WLAN and WiMAX applications that had been designed incorporating a slit and a strip, and could be used to generate two band-rejected characteristics. Both the strip and the slit played a very important role in suppressing the dispensable bands. By altering the dimensions of the slit and strip, the proposed antenna showed three separated operating frequencies with a bandwidth of 14% from 2.24 to 2.58 GHz, a bandwidth of 19% from 3.02 to 3.66 GHz, and a bandwidth of 10% from 5.62 to 6.21 GHz, respectively [155].

J. Malik and M. V. Kartikeyan (2011) proposed a modified Sierpinski fractalized microstrip antenna using multilayer structure to attain dual band behavior for WLAN applications. Due to the space filling properties of fractal geometry, the suggested antenna was smaller in size as compared to conventional Euclidean-type. An equilateral triangular patch antenna having Sierpinski Gasket fractal shape had been designed and studied. An electromagnetic coupled stacked structure of two different patches operating at two distinct frequencies (2.4 GHz Bluetooth and 5.8 GHz Wireless LAN) had been prototyped for dual band WLAN applications [156].

A. K. Arya et al. (2011) used a DGS in MPAs for dual band operation at microwave frequencies. The soft nature of the DGS facilitates improvement in the performance of MPAs. A design study on microstrip patch antenna with specific DGS slot had been presented in the proposed work. A stacked microstrip patch antenna (SMPA) had been designed for broadband behavior, and then skew-F shape DGS had been integrated with a detailed study of possible DGS slots in a small area for dual band operation. The design and optimization of both the SMPA and DGS structures along with the parametric study were carried out using CST MWS V9.0. Further, the dual band antenna, i.e., the SMPA with skew-F shape DGS, had been fabricated, and the experimental results had shown a good agreement with the simulation ones [157].

D. Yadav (2011) presented a compact MPA feasible for dual-band operations. Rightly arranged slots were loaded on a rectangular microstrip patch for dual frequency and broadband operations of a single feed rectangular patch. Dual frequency operation was attained by loading two pairs of narrow slots onto a rectangular patch parallel to the non radiating edge. Moreover, better impedance bandwidth of 130 MHz and 1.45 GHz was obtained by incorporating two dielectric materials Rohacell RO3003 in combination with foam [158].

K. J. Babul et al. (2010) proposed a compact E-shape patch antenna that could be employed in MIMO systems. The modified antenna was reported to possess improved directivity, bandwidth, and return loss characteristics compared to normal E-shape antenna. The antenna system was found to exhibit the resonances at 5.36 GHz and 5.89 GHz for VSWR 2 which could be employed for WiMAX applications [159].

W. Swelam (2010) presented a triple-band T-shape microstrip patch antenna to be employed in multi-standard mobile communication systems viz. PCS, UMTS and Bluetooth. The suggested antenna element was designed and analyzed utilizing the method of moment (MoM) technique with the help of the Zeland-IE3D electromagnetic simulator. The return loss at the feeding port (S_{11}) improved by -15 dB had been revealed within the frequency bands of the triple wireless communication systems. The radiation pattern revealed the broad-side donut-shape that was suitable for MMIC applications such as active antennas for satellite communication systems [160].

N. Mohammadian et al. (2010) proposed a compact UWB printed slot antenna fed by CPW and microstrip line with multi-band-rejection characteristics for different UWB applications. The proposed antenna fed by CPW and microstrip line had an overall volume of $40 \times 22 \times 0.8 \text{ mm}^3$. Multiband rejection characteristics were obtained by adding an inverted U-shape slot on the tapered radiating patch. The centre frequencies of the notched bands at 2.4, 3.5 and 5.5 GHz could be altered by modifying the length of the inserted slot. A very wide impedance bandwidth from 2 to 12 GHz was measured with voltage standing wave ratio 2, excluding the rejection bands. The omni-directional radiation patterns of the fabricated antenna fed by CPW and microstrip line had been demonstrated with peak gain variation less than 4 dB over the entire operating frequency band [161].

F. Y. Kuo et al. (2010) presented the design of an aperture-coupled patch antenna for applications in RFID system operating at Ultra High frequency (UHF) (915 MHz) and microwave (2.4 GHz) bands. The novelty of the proposed structure resided in the fact that the coupling aperture for the patch antenna was designed as the slot antenna radiating at UHF frequency. The front-to-back ratio at UHF band was improved through the implementation of a non-radiating parasitic ring director in the structure. The measurement results of the prototype

CHAPTER-2

PRELIMINARIES AND REVIEW

revealed that the suggested antenna was absolutely suitable for dual-band RFID mobile terminal applications [162].

Pankhuri and M. V. Kartikeyan (2010) presented a generalized ψ -shape antenna structure for dual-band WLAN application. The Particle Swarm Optimization (PSO) Algorithm had been exploited to facilitate the design optimization of the full- ψ antenna for dual-band operation. Moreover, a novel half- ψ structure had also been found to present dual-frequency behavior. A dual-band half- ψ patch corresponding to the full- ψ patch optimized for dual-band WLAN had been presented with indistinguishable bandwidth characteristics. Both the antennas were fabricated employing dry-etching technique and the measurement results rendered a good antenna performance [163].

H. Tiwari and M. V. Kartikeyan (2010) presented a novel type of stacked microstrip patch antenna in which fractal shape defects had been abraded from the patch surfaces. The antenna had been 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 achieved due to the use of fractal shape defects. The antenna was simulated using CST MWS 2010 and optimized using Particle Swarm Optimization (inbuilt in CST). The measurement results for the fabricated antenna were found to be in good agreement with the simulated results [164].

F. Li et al. (2010) proposed a novel CPW-fed triple-band monopole antenna designed by embedding an S-shape meander strip into a C-shape strip for WLAN and WiMAX applications. The antenna with simple and compact structure was easy to be fabricated, and the prototype of the proposed antenna had been designed and measured. The triple operating bands with 10- dB return-loss bandwidths of about 110MHz centered at 2.45 GHz, 310MHz centered at 3.55 GHz, and 39% ranging from 4.1 to 6.2 GHz, spreading over the desired bandwidths of 2.4/5.2/5.8 GHz WLAN and 3.5/5.5 GHz WiMAX standards, were obtained. In addition, good radiation performance and antenna gain across the three frequency ranges had been obtained [165].

I. Sarkar et al. (2010) proposed a single layer, single feed, multi frequency, compact rectangular MPA. Resonant frequency had been decreased immensely by etching unequal rectangular slots at the edge of the patch beside two tiny circular slots constructed inside the patch to enhance return loss. Antenna size had been lowered by 64% with an increased frequency ratio (the ratio of second or higher resonant frequency to the first resonant frequency [166].

W. Hu et al. (2010) proposed a wide open slot antenna accompanied by a pair of symmetrical L-strips for dual-band WLAN applications. A T-shape monopole was used to cover 5.15 ~ 5.825 GHz. To achieve dual-band characteristic, a pair of symmetrical L-strips was embedded in the wide open U-slot to yield another band covering 2.4 ~ 2.48 GHz. The two bands were relatively independent from each other. The suggested antenna had an advantage of simple structure and excellent performance on the WLAN 2.4/5.2/5.8 GHz bands. The measured results of the fabricated antenna showed that the impedance bandwidths are 150MHz from 2.37 to 2.52 GHz and 1270MHz from 4.83 to 6.10 GHz, which spread over the desired operating bands [167].

N. Kulkarni et al. (2010) presented the design and development of a simple and cheap rectangular MPA for multiband operation. Inclusion of U-slot of optimum geometry and open stubs at opposite corners on the rectangular radiating patch motivated the antenna to operate between 1.815 to 9.01 GHz frequencies with an overall reduction in size of 44.84%. Broadside radiation characteristics at each operating band were obtained for the suggested antenna. The incorporated U-slot and open stubs at the corners reduced the copper area of the patch to 8.50%, in comparison to the copper area of conventional rectangular MPA designed for the same frequency. The proposed antenna could be used in mobile, WLAN, WiMAX and SAR applications [168].

L. Peng et al. (2010) proposed compact dual/triple-band MPAs with an asymmetric M-shape patch. The antenna designs employ vias on the longer arm of the patch for compactness and separation of the operational bands. A prototype of antenna having low profile and concise patch size operating at 2.44 and 5.77 GHz was fabricated and measured. The antenna also rendered low cross polarization and symmetrical patterns in both E-and H-planes. Finally, a triple-band antenna with enlarged bandwidth was designed [169].

J. Anguera et al. (2009) presented a dual-band enhanced-bandwidth MPA with a frequency separation of $f_2/f_1 = 1.33$. In order to attain the dual-frequency operation, a rectangular patch was loaded with a stub at one of its radiating edges. To improve bandwidth at each band, two parasitic patches were coupled to the driven element [170].

M. A. S. Alkanhal (2009) presented two new triple band small size composite-resonator MPA configurations each composed of three resonating elements that are suitable for wireless communication. Two types of compact short-circuited resonators were utilized; stepped

CHAPTER-2

PRELIMINARIES AND REVIEW

impedance and quarter-wave resonators. The design procedure based on constituting the antenna resonators was simple and could be employed to design any triple band antenna at three pre-specified bands using basic relations and design curves. The resonator integration had been carried out to preserve single feed, minimize the overall antenna size, and maintain the quality-performance at each band. The two designed antennas were simulated, optimized, and realized on RT/Duroid substrate to validate the concept. Simulation and experimental results were found to be in good agreement and revealed the appreciable performance of both triple band compact antennas [171].

S. S. Natarajamani et al. (2009) proposed the design of a low profile, single feed, dual band and multi-slot microstrip antenna operating at Wi-Fi/WiMAX communication system. By etching slots into radiating edges of microstrip patch antenna, a dual frequency response could be obtained. The antenna was investigated by means of numerical simulation. The return losses at 2.45 GHz and 3.4 GHz were reported to be -21.5dB and -13.2 dB respectively [172].

A. Pal et al. (2009) proposed a feed arrangement which was electromagnetically coupled for simultaneously exciting multiple concentric ring antennas for operating at multi-frequencies. The proposed antenna had a multi-layer dielectric configuration in which a transmission line was inserted under the layer accommodating radiating rings. Energy coupled to these rings from the line underneath was optimized by appropriately modifying the location and dimensions of stubs on the line. Moreover, it was demonstrated that the resonant frequencies of these rings do not alter as several of these single frequency antennas were integrated to form a multi-resonant antenna. Furthermore, all radiators were imposed to operate at their primary mode and some harmonics of the lower resonant frequency rings seeming within the frequency range were suppressed when combined. The experimental antenna design was reported to exhibit three resonant frequencies and possessed good radiation characteristics [173].

K. G. Thomas. & M. Sreenivasan (2009) presented a low profile printed antenna accompanied by triple band operation for simultaneous use in WLAN and WiMAX applications. The antenna comprised of a rectangular radiating element fed asymmetrically by a 50-ohm microstrip line and a trapezoidal shaped ground plane. Rectangular horizontal strips were joined to the radiation element to form different current paths in order to make the antenna to resonate in WLAN and WiMAX frequency bands [174].

I. Sarkar et al. (2009) proposed a single layer, single feed, multi-frequency, compact rectangular microstrip patch antenna. Resonant frequency had been reported to decrease drastically by cutting unequal rectangular slots at the edge of the patch beside two tiny circular slots that were created inside the patch helped to improve the return loss. Antenna size had been decreased by 64% with an enhanced frequency ratio (the ratio of second or higher resonant frequency to the first resonant frequency) [175].

Y. C. Lee and J. S. Sun (2009) presented design of a printed antenna incorporating a radiator element of simple shape for multi-operating bands of the wireless communication systems. The proposed antenna could be utilized in multiband wireless operations, spreading over GSM (880–960 MHz), DCS (1710–1880 MHz), PCS (1850–1990 MHz), UMTS (1920–2170 MHz), 2.4 GHz WLAN(2400–2484 MHz), WiMAX (2500–2690 MHz) and 5 GHz WLAN (5150–5350/5725–5825 MHz) bands. Various properties of the suggested printed antenna in multiband operation, such as impedance bandwidth, radiation pattern and measured gain were numerically and experimentally explored [176].

K. H. Chiang and K. W. Tam (2008) proposed a double U-shape DGS to widen impedance bandwidth of a monopole antenna fed by microstrip line. The antenna structure comprised of a simple trapezoid monopole incorporating a DGS microstrip feed line for excitation and impedance bandwidth widening. Results showed that the antenna had a -10 dB down return loss from 790 to 2060 MHz, resulting 112.4% impedance bandwidth improvement in comparison to traditional design [177].

C. Y. Pan et al. (2007) presented a novel printed monopole antenna having dual wide bands for simultaneously satisfying WLAN and WiMAX applications. The antenna structure comprised of a rectangular monopole accompanied by a microstrip feed line for excitation and a trapezoid conductor-backed plane for band widening. The analyzed 10 dB bandwidth for return loss was from 2.01 to 4.27 GHz and 5.06 to 6.79 GHz spreading over the 2.4/5.2/5.8 GHz WLAN bands and 2.5/3.5/5.5 GHz WiMAX bands [178].

W. C. Liu (2007) presented a dual band CPW-fed planar monopole antenna appropriate for WLAN application. The “G” shaped antenna designed by exploiting the PSO algorithm could yield dual resonant modes and a much broader impedance bandwidth for the higher band. Prototypes of the optimized antenna were designed and tested. The measured results showed

CHAPTER-2

PRELIMINARIES AND REVIEW

good dual band operation with -10 dB impedance bandwidths of 9.7% and 62.8% at bands of 2.43 and 4.3 GHz, respectively, which spread over the 2.4/5.2/5.8 GHz WLAN operating bands [179].

Y. Song et al. (2007) proposed a multiband CPW-fed triangle-shape monopole antenna for wireless applications spreading over 2.4 and 5 GHz WLAN bands and 3.4 GHz WiMAX band in IEEE 802.16. Prototype of the proposed antenna was constructed and tested. The experimental results showed that the antenna could yield two separate impedance bandwidths of 140MHz (about 5.8% centered at 2.43 GHz) and 3100 MHz (about 61.4% centered at 4.91 GHz), that fulfill the required bandwidths specification of 2.4/5 GHz WLAN and 3.4 GHz WiMAX standard. Good omni-directional radiation patterns over the desired frequency bands had been reported and the suggested antenna was found to be extremely appropriate for multiband wireless applications [180].

G. Khunead et al. (2007) presented a rectangular slot antenna incorporating microstrip line feeding that had been designed for standard of IEEE 802.11b/g (2.4-2.4835 GHz), IEEE 802.11a (5.15-5.35 GHz), and IEEE 802.16d (5.7-5.9 GHz). A rectangular slot antenna comprising two conductor strips located in a slot cut in the ground plane was investigated for dual frequency. The frequency range covered at -10 dB return loss was 2.26-2.61 GHz for low frequency and was 5.05-8.18 GHz for high frequency for the proposed antenna [181].

J. Antoniuk et al. (2005) presented an integration procedure of low profile microstrip planar antennas into laptop computers. An antenna system had been designed which was to be put up in the space accessible behind the LCD matrix of a 14" screen size laptop. A prototype of a multi-element antenna arrangement incorporating a total of 19 elements was designed, fabricated and tested. It could be employed in the GSM1800, UMTS, IEEE802.11b/Bluetooth and HIPERLAN2 standards. The radiation pattern, the input reflection coefficient and the mutual coupling between elements demonstrated that such system could be used for multi-standard operation [182].

D. U. Sim et al. (2004) presented a novel planar-type meander-line antenna that could be used as a triple-band internal antenna incorporating microstrip line feeding for PCS/IMT-2000/Bluetooth mobile handsets applications. By employing the two branches of meander line, the desired resonant frequencies could be attained. By tuning the parts of radiating patch and size of each strip line segment, a broadband characteristic for each band was optimized. The suggested

antenna was compact enough to be built in a mobile handset for operating at multiple frequencies [183].

J. Anguera et al. (2004) presented a Sierpinski fractal based dual-frequency antenna with two parasitic patches for increasing the impedance bandwidth. An electrical circuit model constituted of *RLC* resonators was employed for attaining the dual band operation and reducing a trial-and-error numerical/measurement proofs. The antenna was designed employing method of moment commercial code and was experimentally tested, acquiring two bands with enlarged bandwidth and similar radiation patterns [184].

J. Guterman et al. (2004) proposed a novel microstrip patch antenna accompanied by a Koch pre-fractal edge and a U-shape slot for multi-standard use in GSM1800, UMTS, and HIPERLAN2. Size reduction of the proposed antenna was achieved by employing a Planar Inverted-F antenna (PIFA) structure. The multi-band behavior was acquired by widening the lower frequency resonance of the fractal patch to encrust GSM1800 and UMTS, and putting a U-slot dimensioned for the HIPERLAN2 band. Experimental results had proved the accuracy of the design procedure and confirmed the attainment of the requirements for multi-standard mobile terminal applications [185].

Y. L. Kuo and K. L. Wong (2003) proposed a simple printed double-T monopole antenna having dual-band. The antenna consisted of two stacked T-shape monopoles of different sizes that produced two separate resonant modes for the required dual-band operation. The antenna with a low profile could be conveniently fed by using a 50-ohm microstrip line. Prototypes of the proposed antenna designed for WLAN operations in the 2.4 and 5.2 GHz bands were fabricated and tested with good radiation pattern characteristics. The consequences of varying the monopole dimensions and the ground-plane size on the performance of antenna were also studied [186].

J. Anguera et al. (2003) proposed a multi-frequency microstrip patch antenna comprised of a driven patch and a multiplicity of parasitic elements settled beneath a driven patch. The antenna featured a multi-frequency behavior (five operating band) with similar gain [187].

J. Anguera et al. (2003) proposed a MPA comprising of two stacked patches for dual-frequency and broad-band performance. Different E-plane and H-plane arrangements were analyzed to

CHAPTER-2

PRELIMINARIES AND REVIEW

achieve isolation better than 30 dB between the operating bands. A prototype working at 1.8 and 3.5 GHz bands was simulated and tested [188].

M. Clenet and L. Shafai (1999) discussed multiple resonances and polarization of a single layer wideband microstrip U-slot patch antenna fed by probe. It was reported that the radiation characteristics like polarization and gain were adjusted within the bandwidth due to the excitation of resonant modes orthogonal to each other. MPA composed of parallel dipole resonators of various lengths fed by a rectangular slot etched in the ground plane of a microstrip line was studied utilizing an integral equation technique solved in the spectral domain exploiting the Galerkin method of moments [189].

F. Croq and D. M. Pozar (1992) demonstrated the multi-frequency operation of MPAs using parallel dipoles of different length, aperture-coupled to a microstrip line. Triple frequency band antennas had been studied theoretically and experimentally to achieve a frequency ratio of more than 1.35:1, using two different configurations with different characteristics in frequency ratio and bandwidth. The fundamental parameters effecting the realization of multi-frequency operation, along with impedance matching of the different resonances were explored. Moreover, the radiation patterns of the antenna at different frequencies and relative contribution of the dipoles to the radiation were also studied [190].

Chapter 3
Dual Band
Multistrip Monopole
Antenna with
DGS

In this chapter, a novel multistrip monopole antenna fed by a cross-shaped stripline comprising one vertical and two horizontal strips has been proposed for WLAN/ISM/IMT/BLUETOOTH/WiMAX applications. The designed antenna has a small overall size of $20 \times 30 \text{ mm}^2$. The goal of this chapter is to use DGS in the proposed antenna design to achieve dual band operation with appreciable impedance bandwidth at the two operating modes satisfying several communication standards simultaneously. The antenna was simulated using CST MWS V9.0 based on the finite integration technique with perfect boundary approximation (PBA). Finally, the proposed antenna was fabricated and some performance parameters were measured to validate against simulation results. The design procedure, parametric analysis, simulation results along with measurements for this multistrip monopole antenna using DGS operating simultaneously at WLAN (2.4/5.8 GHz), IMT (2.35 GHz), BLUETOOTH (2.45 GHz) and WiMAX (5.5 GHz) are presented.

3.1. Introduction

The rapid developments in the wireless communications industry demand novel micro designs that can be used in more than one frequency band. The most widely used antenna on existing mobile telecommunication applications is probably the standard monopole antenna [191]. In recent years, the dual-band or multi-band antennas have received much attention for applications to multimode communication systems as these antennas are vital for integrating more than one communication standards in a single compact system to effectively promote the portability of a modern personal communication system [192-193]. The currently popular antenna designs suitable for the applications of WLAN and WiMAX have been reported [143] [156] [165] [186] [194] [195]. The traditional monopole antenna is inherently a narrow-band structure. To enhance the impedance bandwidth, the monopole with different shapes is used. As reported in [36], a simple microstrip stub served as the impedance matching element and provided around 13% bandwidth enhancement when compared with the traditional design. To realize much wider bandwidth, additional stub could be added but the feed line becomes lengthy. In order to achieve multi-band operation, the traditional approach is to use multi-resonator elements [196], which generally leads to a large volume [197-199] or requires a large ground-plane [200]. In [186], Kuo et al. proposed a dual-band double T-monopole antenna, which achieves a certain miniaturization factor but with a narrow bandwidth at the upper WLAN band.

CHAPTER-3

DUAL BAND MULTISTRIP MONOPOLE ANTENNA WITH DGS

In the present work, we proposed a new technique for enhancing the impedance bandwidth of a multi-frequency dual band microstrip patch antenna. The proposed antenna employs a multistrip based geometry fed by a cross-shaped stripline comprising one vertical and two horizontal strips and a notable ground structure named DGS. Defected ground structures or slotted ground planes have been used to provide multiband performance in handset antennas [201-205]. The usage of DGS with double microstrip stub feedline for size reduction, bandwidth enhancement, and resonance mode increment has not been addressed for antenna's application yet. Parametric analysis and optimization of the design parameters of proposed structure was conducted using commercial software CST MWS V9.0. A prototype of the proposed antenna design was fabricated and tested for its performance in terms of bandwidth, gain and radiation pattern. The details of obtained simulated and measured results are presented, analyzed and discussed.

3.2. Monopole Antenna Design and Simulated Results

The antenna configuration of the proposed resonator structure with DGS having dual band operation covering several frequency bands is shown in Figure 3.1. For designing the proposed antenna, the radiator and ground plane were etched on the opposite sides of a PCB with a dielectric constant of 4.4 and substrate thickness of 1.524 mm. A cross-shaped stripline, which comprises a vertical strip with dimensions of L_1 W_1 and two horizontal strips with dimensions of L_2 W_2 and L_3 W_3 , placed at distances from the feed point of d_1 and d_2 , respectively, is used for feeding the radiator. Horizontal strips were used to enhance the available bandwidth for the upper band having a resonance at 5.4 GHz. The rectangular patch which is the basic radiator having the dimensions of L_4 W_4 was protruded with three vertical arms from the patch's upper side. Each of these three arms which make the monopole patch resemble like rotated E (\sqcap) have dimensions L_5 W_5 . The solid rectangular ground plane was made defected with slots of equal dimensions, which were appropriately cut from the ground's left and right sides. These slots were introduced to improve the impedance matching condition and radiation characteristics of the proposed antenna. The overall size of ground plane was taken to be L W and each of the slots had a vertical section of L_{g1} W_{g1} as well as a horizontal section of L_{g2} W_{g2} . The slot was etched with a distance of d_3 from the bottom of the ground and its vertical section has a distance of W_{g3} from the ground side edge. A substrate of dimension 20 mm \times 30 mm was used. A 50-ohm line was used to feed the patch for impedance matching.

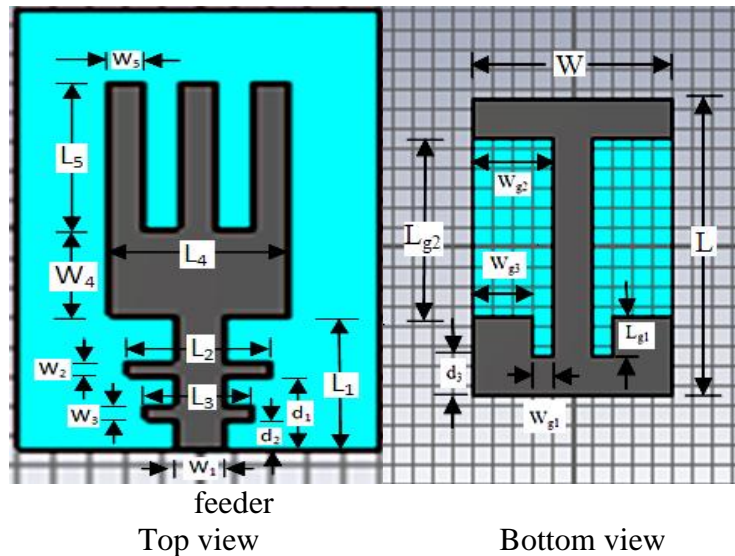


Figure 3.1: Configuration of the proposed antenna with defected ground structure

3.2.1. Reflection coefficient and Voltage Standing Wave Ratio

To investigate the performance of the proposed antenna configuration, the commercially available simulation software, CST MWS V9.0 based on FIT was used for the required numerical analysis and to obtain the proper geometrical parameters. To simulate the antenna transient solver was chosen. During simulation hexahedral mesh cell with 20 lines per lambda was selected. The geometrical parameters were adjusted carefully by running numerous parameter sweeps and finally the optimal parameters for proposed configuration were obtained as depicted in Table 3.1 in tabular form.

Table 3.1: Optimal design parameters of the proposed MPA

Parameter	L	W	L ₁	W ₁	L ₂	W ₂	L ₃	W ₃	L ₄	W ₄	L ₅	W ₅	L _{g1}	W _{g1}	L _{g2}	W _{g2}	W _{g3}	d ₁	d ₂	d ₃
Unit (mm)	30	20	9	2.8	8	1	6	1	10	6	10	2	4	2	18	8	6	5	2	4

Figure 3.2 shows the simulated reflection coefficient (S_{11}) of proposed antenna with the optimized parameters which confirms dual band operation at desired bands with reasonable bandwidth. Two resonant bands at frequencies 2.385 GHz and 5.4 GHz with bandwidths, defined for 10-dB reflection coefficient, of about 327 MHz (2.27-2.60 GHz) and 604 MHz (5.24-5.85 GHz) respectively are obtained.

CHAPTER-3

DUAL BAND MULTISTRIP MONOPOLE ANTENNA WITH DGS

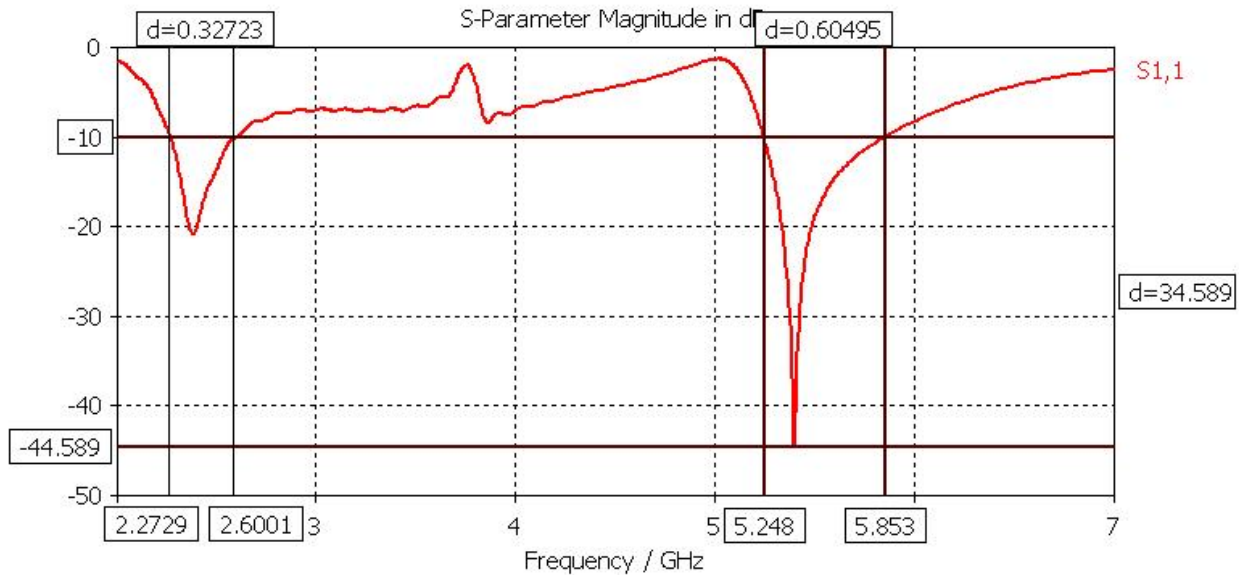


Figure 3.2: Simulated reflection coefficient of proposed antenna showing bandwidths of 327 MHz and 604 MHz at respective resonating frequencies of 2.385 and 5.4 GHz

The multistrip based geometry of a microstrip-fed monopole antenna with a cross-shaped stripline was responsible for the resonance at 5.4 GHz with a reflection coefficient of -44.4 dB covering the wide upper band from 5.24 GHz-5.85 GHz and a notable DGS created a resonance at 2.385 GHz with a reflection coefficient of -20.8 dB covering the lower band from 2.27 GHz - 2.60 GHz. During the simulation a dip in the reflection coefficient pattern at around 3.85 GHz was observed. This could be ascribed to numerical convergence problem. Apparently, the above obtained bandwidths simultaneously cover the 2.4/5.8 GHz WLAN, 2.35 GHz IMT, 2.45 GHz BLUETOOTH and 5.5 GHz WiMAX IEEE standards.

Figure 3.3 represents the VSWR of the proposed antenna at 2.385 GHz and 5.4 GHz frequencies. For an ideal match the VSWR should be 1 which means no reflections. In our present case, VSWR turns out to be 1.19 and 1.012 and the impedance transformations ratio are 1:1.19 and 1:1.012 at 2.385 GHz and 5.4 GHz which indicate that the antenna is very well matched to a 50-ohm line allowing maximum power to be coupled through the line to antenna allowing for best results.

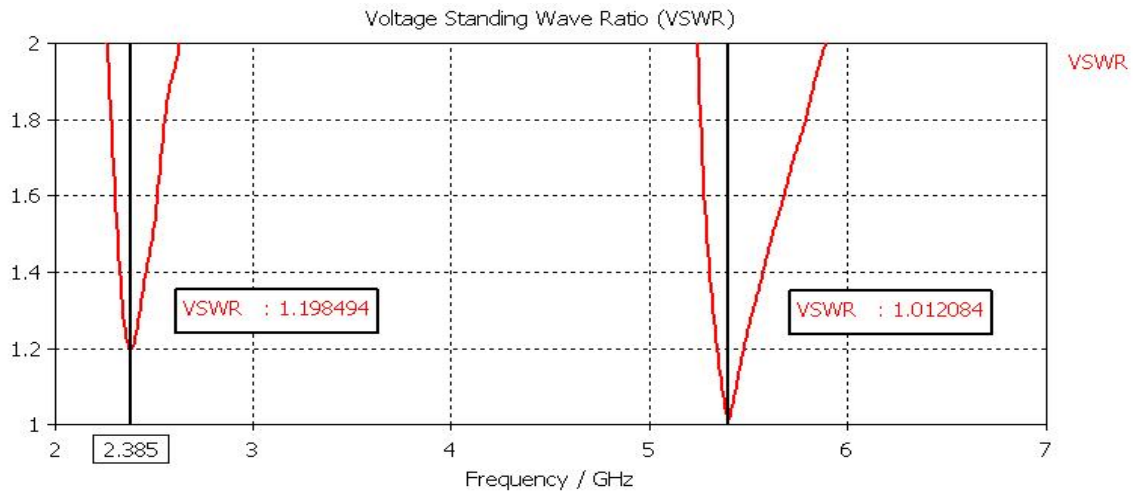
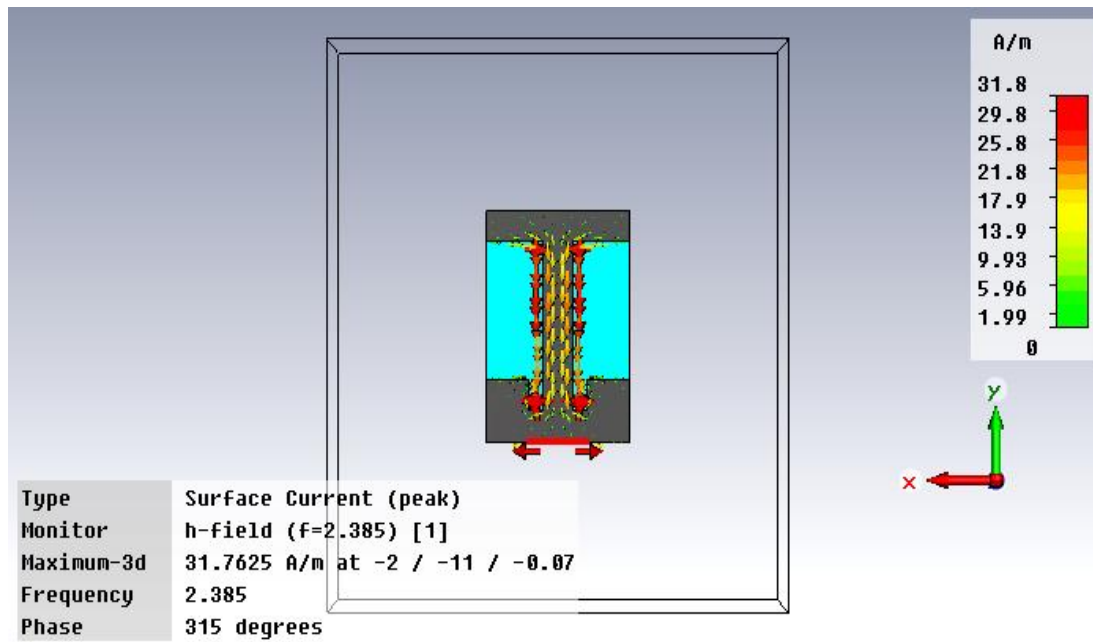


Figure 3.3: VSWR of the proposed antenna at 2.385 GHz and 5.4 GHz

3.2.2. Current Distribution Results

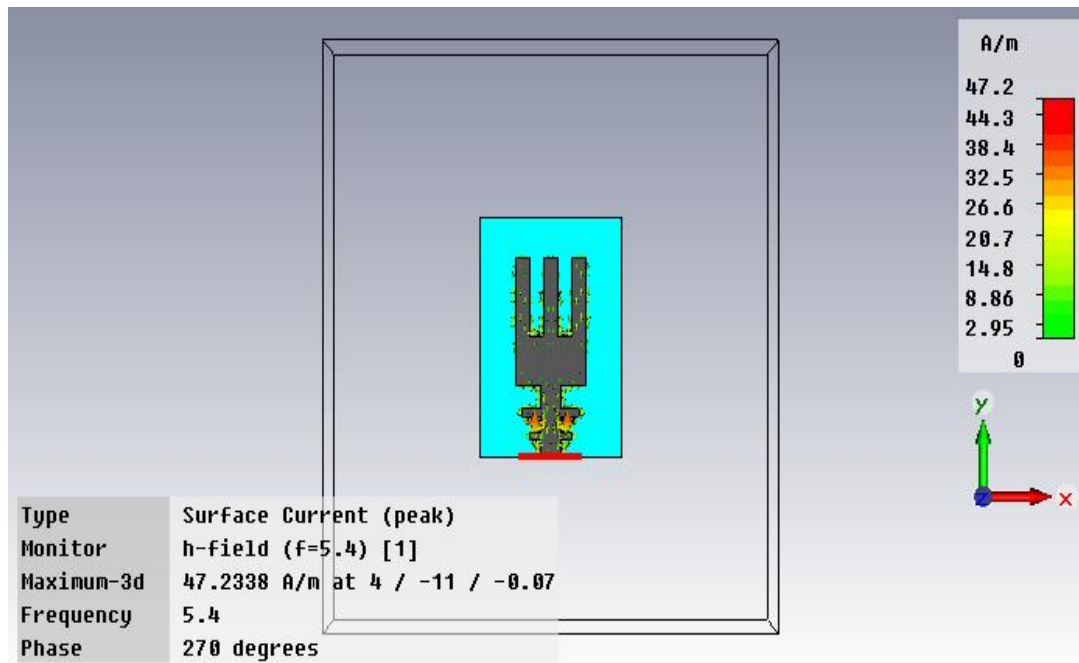
To explain more details on the excited resonant modes of the proposed antenna, the simulated current distributions at two resonant frequencies of 2.385 GHz and 5.4 GHz are shown in Figures 3.4(a) and (b).



(a)

CHAPTER-3

DUAL BAND MULTISTRIP MONOPOLE ANTENNA WITH DGS



(b)

**Figure 3.4: Surface current distributions of the proposed antenna at
(a) 2.385 GHz and (b) 5.4 GHz bands**

Figures 3.4(a) and (b) indicate that the DGS was responsible for the resonance at 2.385 GHz and microstrip fed monopole antenna was responsible for resonance at 5.4 GHz. Further, a cross shaped stripline comprising one vertical and two horizontal strips presented in Figure 3.4(b) worked for enhancing the impedance bandwidth for the upper band at 5.4 GHz covering various WLAN/WiMAX standards.

3.2.3. Simulated Reflection coefficient without DGS

Figure 3.5 shows the simulated reflection coefficient (S_{11}) antenna without DGS. Two resonant bands at frequencies 2.385 GHz and 5.4 GHz with bandwidths, defined for 10 dB reflection coefficient, of about 190 MHz and 200 MHz respectively are obtained. These bandwidths are sufficiently less than those attained with DGS. This clearly shows the advantage of using DGS in the proposed antenna design that how it is responsible for bandwidth enhancement and resonance mode increment at the two desired bands.

In addition, harmonic radiation is a drawback of active integrated microstrip antennas, and DGS structures are suggested to reduce higher-order harmonics in microstrip antennas. A defected ground structure in microstrip antennas is used to reduce the cross-polarized (XP) radiation. The

dumb-bell shaped DGS is successfully used for mutual coupling reduction of a two-element microstrip antenna array. Surface waves are undesired because when a patch antenna radiates, a portion of total available radiated power becomes trapped along the surface of the substrate. It can extract total available power for radiation to space wave. Therefore, surface wave can reduce the antenna efficiency, gain and bandwidth. For arrays, surface waves have a significant impact on the mutual coupling between array elements. One solution to reduce surface waves is using DGS. The comparative performance analysis of antenna configurations in terms of bandwidth with and without DGS is illustrated in Table 3.2.

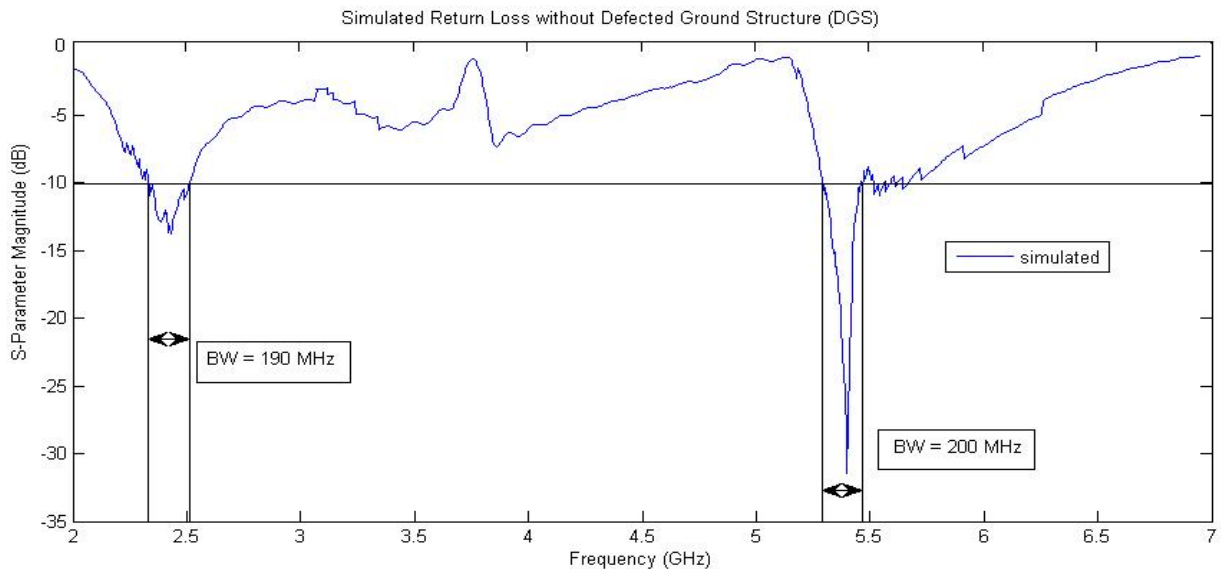


Figure 3.5: Simulated reflection coefficient of antenna without the DGS showing bandwidths of 190 MHz and 200 MHz at respective resonating frequencies of 2.385 GHz and 5.4 GHz

Table 3.2: Comparative analysis of bandwidth with and without DGS

Antenna configuration	With DGS	Without DGS
Bandwidth for lower band	327 MHz	190 MHz
Bandwidth for upper band	604 MHz	200 MHz

CHAPTER-3

DUAL BAND MULTISTRIP MONOPOLE ANTENNA WITH DGS

3.3. Fabrication and Measurement Results

The simulated antenna after detailed parametric analysis and optimization was fabricated on a dielectric substrate named Epoxy Glass-FR4 ($\epsilon_r = 4.4$, $\tan \delta = 0.0024$, $h = 1.524$ mm) and was studied experimentally. Available photolithography method with wet etching facility was adopted for fabrication of the prototype antenna and its photograph is shown in Figure 3.6. After fabrication, the reflection coefficient of the antenna was tested on Agilent E5071C vector network analyzer at Microwave and Antenna Laboratory, Thapar University, Patiala. The radiation performance was measured in the Anechoic Chamber at Millimeter Wave Laboratory, I.I.T-Roorkee, India. The measured reflection coefficient against frequency plot for this dual band proposed antenna design covering multiple frequency bands is presented in Figure 3.7.



Figure 3.6: Photograph of the proposed antenna

The measured reflection coefficient of proposed MPA indicates that two resonant modes at frequencies of 2.385 GHz and 5.4 GHz were obtained with reflection coefficient as -20.4 dB and -43.2 dB respectively. The measured impedance bandwidths of the two distinct operating bands with 10 dB reflection coefficient were about 240 MHz (2.3-2.54 GHz) and 590 MHz (5.26-5.85 GHz). They are wide enough to cover the required bandwidths of 2300-2400 MHz for IMT, 2400-2484 MHz for WLAN/ISM, 2400-2500 MHz for BLUETOOTH, 2484-2491 MHz for GLOBALSTAR SATELLITE PHONE UPLINK, 5250-5850 MHz for WiMAX band and 5725-5825 MHz for WLAN/ITS working in the 5.8 GHz frequency band. The multistrip monopole antenna fed by a cross-shaped strip line was responsible for the resonance at 5.4 GHz and a

notable DGS created a resonance at 2.385 GHz. Two slots which were appropriately distracted from the ground's left and right sides improved the impedance matching condition and radiation characteristics of the proposed antenna.

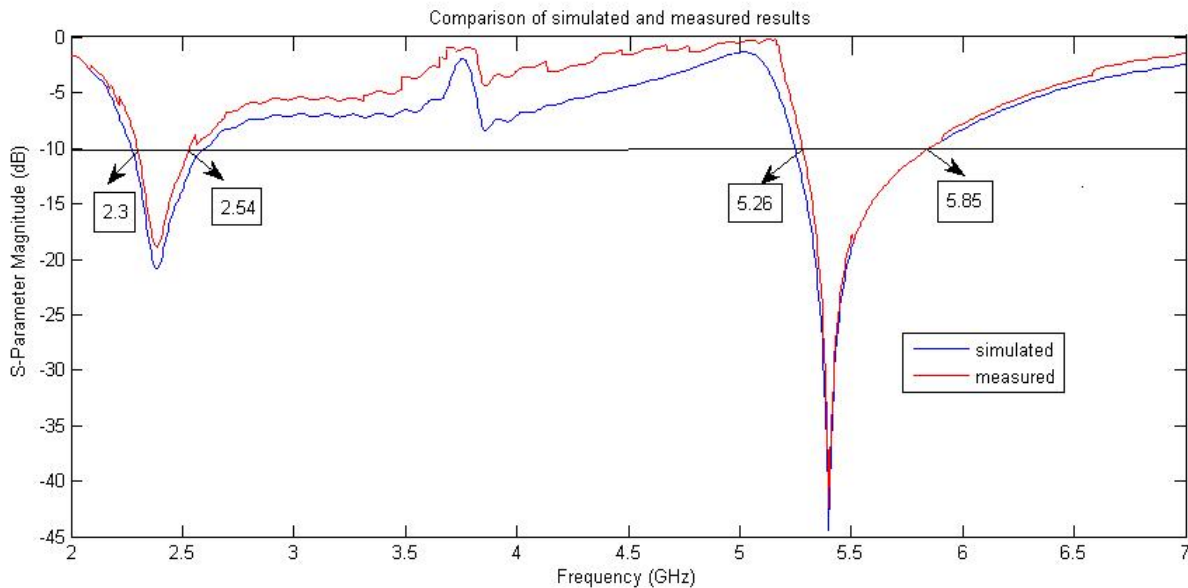


Figure 3.7: Measured reflection coefficient of the proposed antenna

A quite good agreement was seen between the simulated and measured results for the proposed antenna. A little shift in both the resonating bands was observed during measurement which could be attributed to mismatching between the connector and the antenna feeder, fabrication errors, interference and noise.

Figure 3.8 and Figure 3.9 depict the simulated and measured far-field radiation patterns of the proposed antenna in both the E-plane and H-plane at the operating frequency bands of 2.385 GHz and 5.4 GHz. Because of the symmetry in structure, rather symmetrical and very monopole-like radiation patterns are seen in both the planes as depicted in the plots. The simulated and measured radiation patterns in Figures 3.8 and 3.9 were normalized for setting the maxima 0 dB. Reasonable good agreement was found between the simulated and measured values of radiation patterns in two distinct operating frequency bands which validate the proposed design. Some slight differences between the simulated and measured field patterns may be attributed to alignment error and possible presence of interference and noise.

CHAPTER-3

DUAL BAND MULTISTRIP MONOPOLE ANTENNA WITH DGS

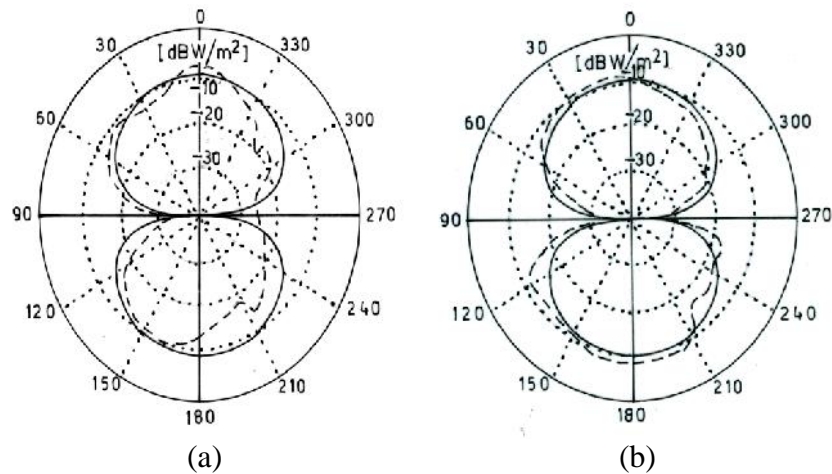


Figure 3.8: Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 2.385 GHz

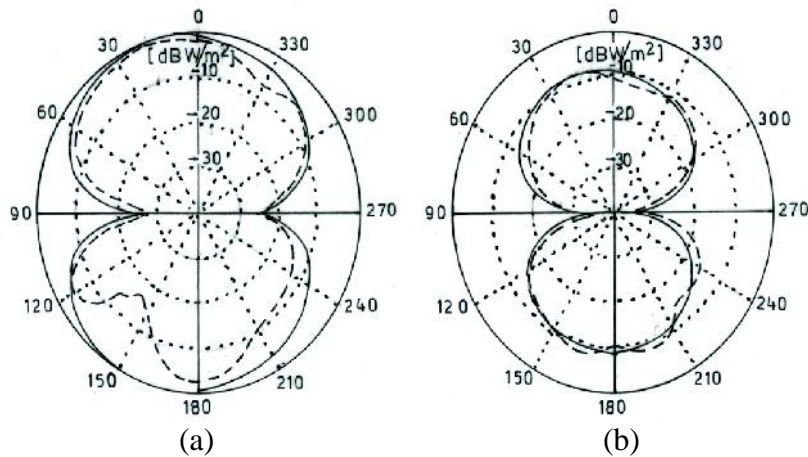


Figure 3.9: Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 5.4 GHz

The simulated and measured gain curves for two operating bands at 2.385 GHz and 5.4 GHz are presented in Figure 3.10. The transmitter antenna was given 15 dBm power from the RF power generator, and the distance between the transmitter and the receiver was kept as 1.5 m. Gain was calculated using the substitution method with the help of the standard calibrated horn antenna (reference antenna) working in the range of 0.9–8 GHz. About 1-2 dB of difference in the simulated and measured gains was observed which could be attributed to fabrication and measurement errors.

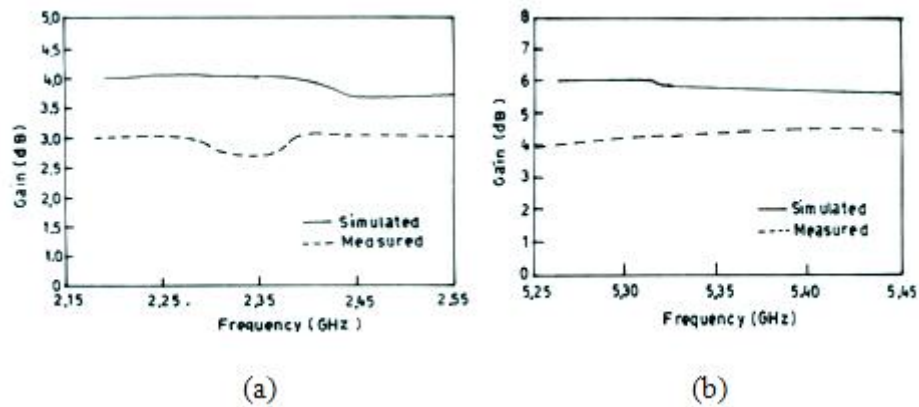


Figure 3.10: Simulated (solid) and Measured (dash) gains of the proposed antenna at (a) 2.385 GHz and (b) 5.4 GHz

3.4. Discussion

In this chapter, dual band operation of a multistrip monopole antenna was presented which could be suitable to cover 2300-2400 MHz for IMT, 2400-2484 MHz for WLAN/ISM, 2400-2500 MHz for BLUETOOTH, 2484-2491 MHz for GLOBALSTAR SATELLITE PHONE UPLINK, 5250-5850 MHz for WiMAX and 5725-5825 MHz for WLAN/ITS working in the 5.8 GHz frequency band. The microstrip line feeding method used in our design enabled direct feeding of the structure without using complicated impedance transformer or microstrip taper. The monopole antenna fed by a cross-shaped stripline comprising one vertical and two horizontal strips was responsible for the resonance at 5.4 GHz and a notable DGS created a resonance at 2.385 GHz. Obviously, both the multistrip based geometry of patch and DGS play a vital role in generating these two strong resonating frequency bands. The fabricated prototype upon measurement shows reasonable impedance bandwidths of around 240 MHz (2.3-2.54 GHz) and 590 MHz (5.26-5.85 GHz) in two operating bands which actually exceed the requirements of any WLAN/WiMAX application. Thus, in the present study it was observed that using such a new technique of incorporating a multistrip patch and DGS in antenna design, two distinct operating bands with an impedance bandwidth of 10% from 2.3 to 2.54 GHz and a bandwidth of 11% from 5.26 to 5.85 GHz can be achieved. Also, appreciable gain and radiation characteristics have been observed over the entire operating range. Hence, the proposed design can be easily integrated to microwave circuits and compatible with MMIC technology for practical applications.

Chapter 4

Triple Band

O-Shape

MPA

with Modified

Ground Plane

In this chapter, a triple-band patch antenna for wireless communication applications has been proposed. For designing an antenna with suitable resonance characteristics to cover many frequency bands simultaneously, a strip is coupled on the right side of an O-shaped patch element and ground plane has been modified with an inverted L-slot and two unequal slits. The proposed design resonates in three different bands viz. 2.35-2.86 GHz, 3.0-4.3 GHz and 5.64-6.85 GHz with respective bandwidths of 510 MHz, 1.3 GHz and 1.21 GHz. Obviously, the achieved bands are suitable to cover WLAN/ISM/Bluetooth/WiMAX/IMT/ITS/Satellite communication standards. The overall size of the proposed antenna is 35×30 mm². The fabrication and measurement of parameters of proposed structure was carried out to verify the simulated results. Finally, complete geometrical method for the design of O-shaped MPA with modified ground plane is presented.

4.1. Introduction

In electromagnetic history, the MPA design is gaining interest due to its advantages such as low fabrication and production cost, conformal nature, compact size and low weight, ease of integration with other devices and remarkably good radiation characteristics. The geometry and substrate characteristics of the MPA control its operation and performance [2] [17]. The integration of various communication standards into one antenna is gaining hot demand for portable wireless communication device. Therefore, a multiband antenna operating at different frequency bands is an attractive and a useful feature, as it avoids the use of multiple antennas. Many promising dual and multiband planar antenna designs have been studied and investigated suitable for WLAN/WiMAX operation. Printed double-T monopole [186], G-shape monopole [206], multistrip monopole [207] and complementary Sierpinski gasket fractal antenna [208] were used to generate two resonances for dual-band applications. Some tri-band and quad-band multi-frequency antennas like meander monopole [209], monopole using defected ground structure (DGS) [194], compact size triple-band antenna [210], coplanar waveguide (CPW) fed miniature slotted multi-frequency wideband MPA [211], Y-shape monopole [212], triangle-shape monopole [180], composite meta-material resonators [213], a flower-like monopole [214], a fractal monopole [215], a parasitic C-shape strip [216], multi-frequency wideband [217] and co-axial fed microstrip patch antenna with Pi slot under T-slot [218] have been reported in literature. All these reported antennas are having good multiband characteristics but large size or

CHAPTER-4

TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

complicated structure restricts their applicability. A wide open U-slot antenna with a pair of symmetrical L-strips [167], triple-band open L-slot antenna with a slit and a strip [155], non-symmetric ground $\lambda/4$ open slot antenna [219], broadband single layer rectangular MPA [220] and band-rejected design of the printed open slot antenna [221] have been reported for wideband applications. To cover the UWB frequency range, a bandwidth enhancement scheme was applied to improve the limited operation band greatly but unfortunately, this novel broadband antenna had higher cost as it used a filter to reject the undesired bands [222].

In the present work, we propose a compact triple-band microstrip-fed O-shaped patch antenna for wireless applications. The patch antenna is simply constructed by coupling a strip on the right side of resonator and by etching an inverted L-slot and two slits of different lengths in the ground plane. The design approach is introduced to have triple-band antenna with stable radiation characteristics over all bands of operation. A strip coupled on the right side of radiating patch and two slits etched in the ground plane play a very important role in suppressing the dispensable bands for better band-rejected performance in two undesired bands. The detailed parametric study of proposed antenna based on various design parameters was conducted to find the optimum parameters using “parameter sweep” option and “optimize” option available in transient solver window of electromagnetic simulator CST MWS V9.0. Lastly, the prototype of the antenna is manufactured and measured. The details of simulated and measured results of proposed antenna design are presented and discussed.

4.2. Antenna Design and Simulated Results

The geometrical configuration of proposed antenna suitable for triple-band operation is illustrated in Figure 4.1. The antenna was etched on double sides of FR4 (Epoxy Glass) substrate with relative dielectric constant 4.4, thickness 1.6 mm, $\tan \delta = 0.0024$ with a total dimension $L_s \times W_s$ (35×30) mm². A 0.07 mm thick metal was used to fabricate the antenna. A rectangular O-shaped patch with a size of $L_p \times W_p$ (8.5×6) mm² was fed by a 50-ohm microstrip line on the top side of the substrate. The thickness of O-shaped patch on the radiating and non-radiating edges was 1 mm and 1.75 mm respectively. A strip of length L_2 (7.6) mm was coupled to the patch. An inverted L-slot consisting of two rectangles of size $S_1 \times S_2$ (18×6) mm² and $S_3 \times S_4$ (19.25×6) mm² and two slits of lengths L_3 (16) mm and L_4 (10) mm were etched in the ground plane. For good band notched characteristics, both the strip and two slits in the ground plane were set with the

CHAPTER-4 TRIPLE BAND O-SHAPE MPA WITH MODIFIED GROUND PLANE

same width of d_1 (0.5) mm and their positions were also adjusted carefully. Two appropriate band-rejected features were achieved after an exhaustive iterative analysis by varying the length of strip and slits. Figures 4.1(a) and (b) illustrate the patch side and ground side view of designed triple-band MPA respectively.

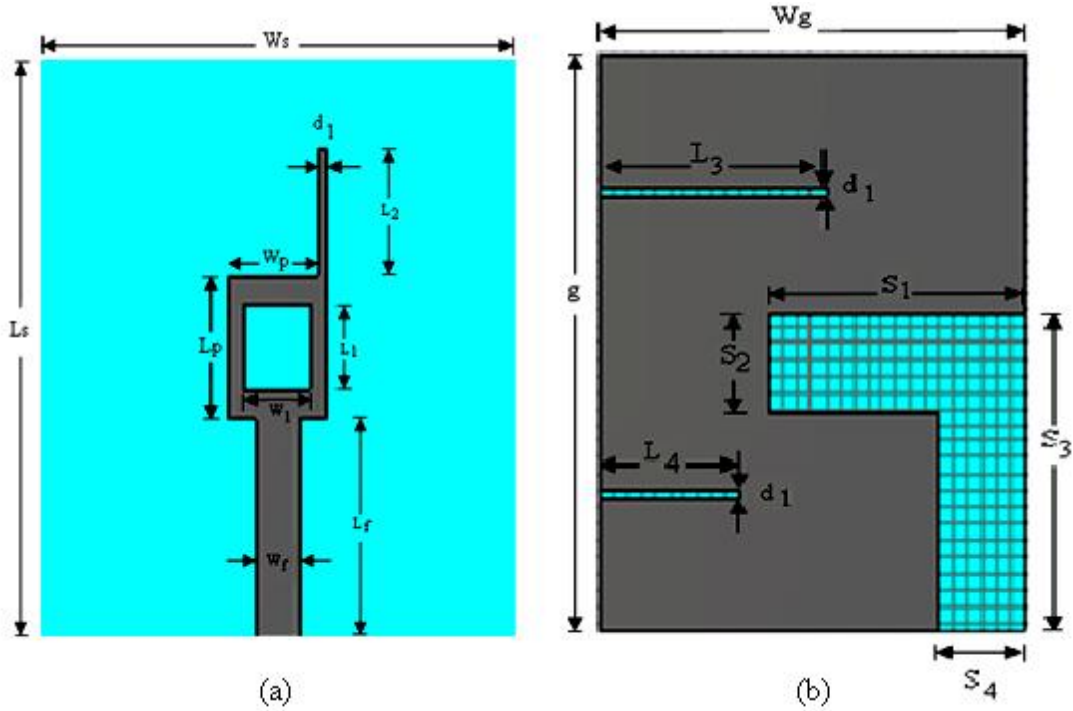


Figure 4.1: Antenna configuration of the proposed antenna
(a) Patch side (Front view) (b) Ground side (Back view)

4.2.1. Reflection coefficient and Voltage Standing Wave Ratio

The design and simulation study of proposed triple-band antenna was carried out using commercially available electromagnetic simulation software CST MWS V9.0. The optimized parameters of the final structure were obtained using PSO which is an in-built optimization technique in CST MWS. They were found to be: $L_s=35\text{mm}$, $W_s=30\text{mm}$, $L_g=35\text{mm}$, $W_g=30\text{mm}$, $L_p=8.5\text{mm}$, $W_p=6\text{mm}$, $L_1=5\text{mm}$, $W_1=4\text{mm}$, $L_2=7.6\text{mm}$, $L_3=16\text{mm}$, $L_4=10\text{mm}$, $d_1=0.5\text{mm}$, $S_1=18\text{mm}$, $S_2=6\text{mm}$, $S_3=19.25\text{mm}$, $S_4=6\text{mm}$, $L_f=13.25\text{mm}$ and $W_f=2.6\text{mm}$. Transient solver was chosen to simulate the proposed antenna with port impedance adjusted to 50-ohm. In CST, hexahedral mesh cell consisting of 20 lines per wavelength and an accuracy of -30 dB was set up. The optimal parameters of proposed antenna configuration are tabulated clearly as can be seen from Table 4.1.

CHAPTER-4

TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

Table 4.1: Optimal design parameters of the proposed antenna configuration

Parameter	L_s	W_s	L_g	W_g	L_p	W_p	L_1	W_1	L_2	L_3	L_4	d_1	S_1	S_2	S_3	S_4	L_f	W_f
Unit (mm)	35	30	35	30	8.5	6	5	4	7.6	16	10	0.5	18	6	19.25	6	13.25	2.6

Figure 4.2 depicts the simulated S_{11} curve of the optimized antenna, that clearly show triple-band operation at designated bands with sufficient bandwidth. The antenna showed a reflection coefficient of -25.5 dB, -19.8 dB and -20.2 dB with strong resonances at 2.24 GHz, 3.12 GHz, and 5.92 GHz respectively. For proper impedance matching, the feeding of the patch was done with 50-ohm microstrip line.

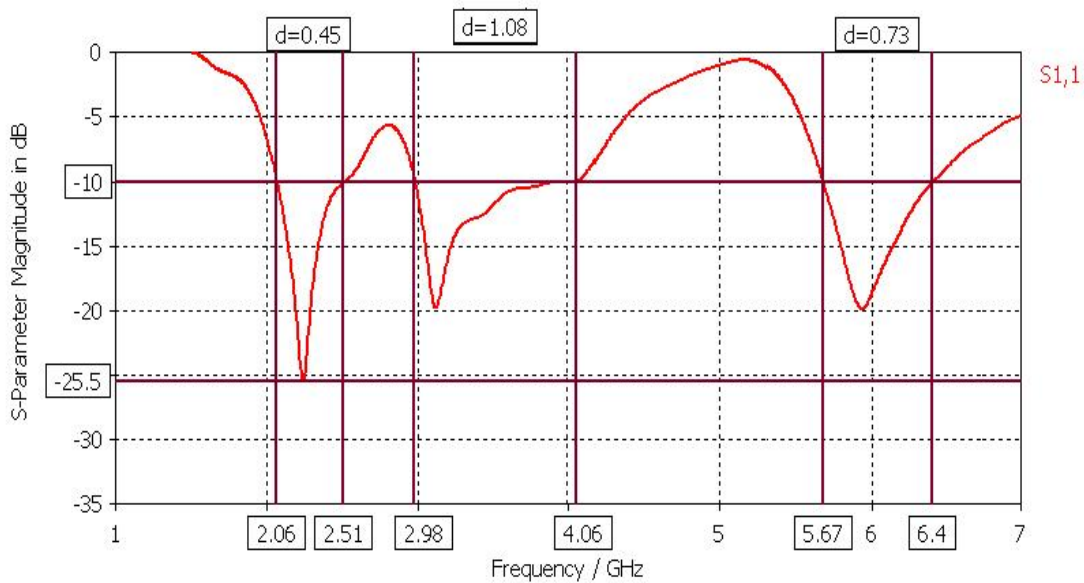


Figure 4.2: Simulated reflection coefficient curve of proposed triple-band antenna at three different resonating frequency bands

The simulated 10 dB down impedance bandwidth of the three operating bands was found to be 448.43 MHz (2.06-2.51 GHz), 1.07 GHz (2.98-4.06 GHz) and 730.32 MHz (5.67-6.40 GHz). The analysis of the proposed MPA using VSWR curve was also done as shown in Figure 4.3.

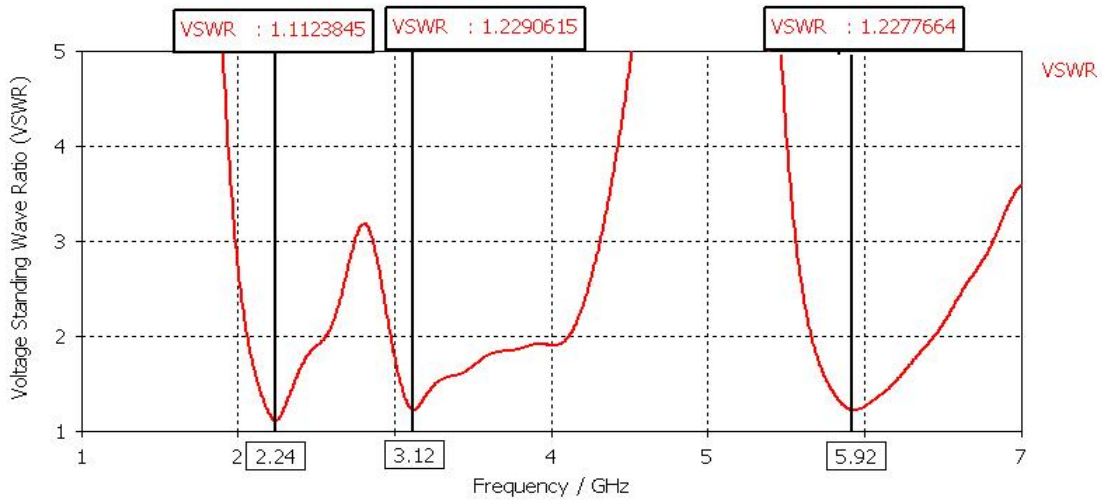


Figure 4.3: VSWR of the designed antenna at 2.24 GHz, 3.12 GHz and 5.92 GHz

From Figure 4.3, the VSWR was found 1.11, 1.22 and 1.22 i.e. less than 2 for all the three operating bands and the impedance transformation ratios were 1:1.11, 1:1.22 and 1:1.22 at 2.24 GHz, 3.12 GHz and 5.92 GHz respectively, which demonstrate good matching of proposed antenna to a 50-ohm line, thereby transferring maximum power from line to antenna.

4.2.2. Parametric Study of Antenna

A complete parametric study for the designed antenna structure was carried out in order to demonstrate the effects of two slits of different lengths etched in ground and a strip coupled on the right side of radiating patch for generating the respective lower and higher band-rejected features. Slots can be modeled in terms of L-C resonator circuits as illustrated in Figure 4.4 which can be extracted from the S-parameters of simulated antenna results as far as the literatures are reported [223-225].

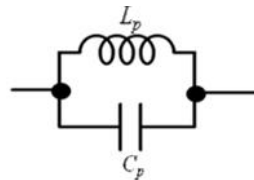


Figure 4.4: L-C resonator circuit

The mathematical expressions are given below for calculating L and C.

CHAPTER-4 TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

$$C_p = \frac{5f_c}{\pi[f_0^2 - f_c^2]} \text{ pF} \quad (5.1)$$

$$L_p = \frac{250}{C_p (\pi f_0)^2} \text{ nH} \quad (5.2)$$

The responses of the designed antenna with various values of strip length (L_2) and longer slit length (L_3) in ground are presented in Figure 4.5 and Figure 4.6 respectively.

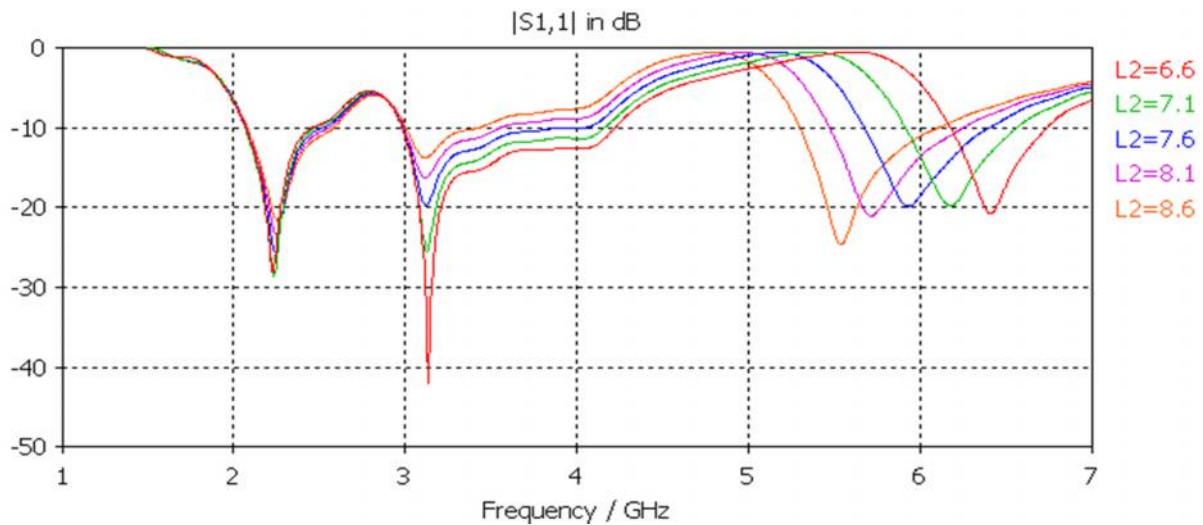


Figure 4.5: Simulated reflection coefficients with different values of lengths of L_2 ($L_3 = 16$ mm and $L_4 = 10$ mm)

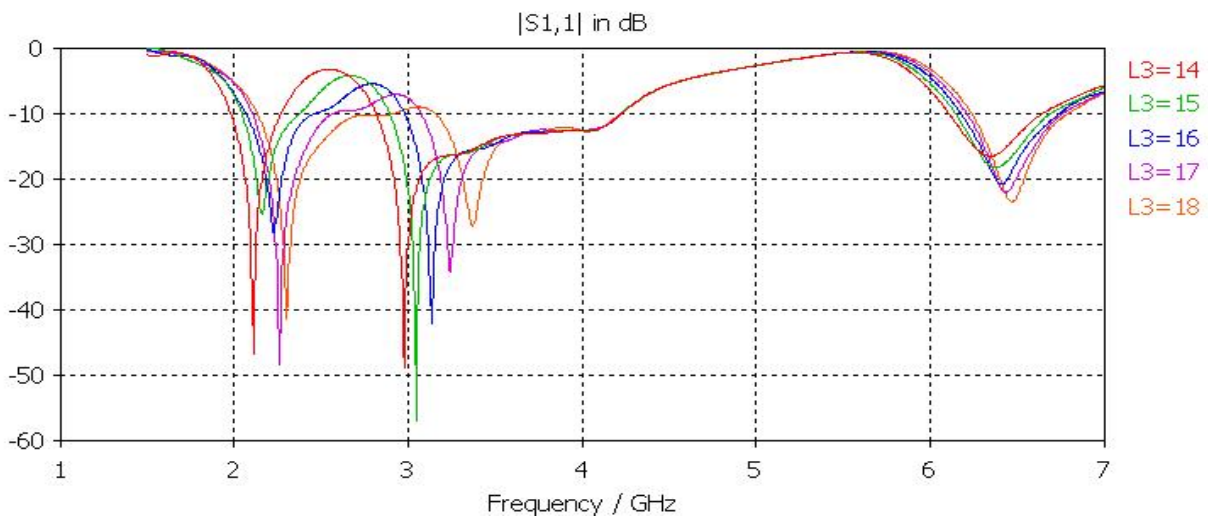


Figure 4.6: Simulated reflection coefficients with different values of lengths of L_3 ($L_2 = 7.6$ mm and $L_4 = 10$ mm)

CHAPTER-4

TRIPLE BAND O-SHAPE MPA WITH MODIFIED GROUND PLANE

Either the strip or the longer slit can generate a rejected band to form dual-band operation. With the strip only, the band-rejected feature at the higher band of 5.16 GHz can be obtained. Similarly, when the longer slit is individually presented, a band-rejected feature at lower band of 2.8 GHz can be excited. Thus, it is observed/noticed that the two notched bands are adjusted by adjusting lengths of longer slit and strip. The change in input impedance causes a shift in the reflection coefficient level for the cases shown in Figures 4.4 and Figure 4.5. With suitable dimensions of the coupled strip and longer slit, three separated bands for various wireless communication applications can be obtained. In addition, the effect of removing a ground plane's shorter slit (L_4) of size $10 \times 0.5 \text{ mm}^2$ on the performance of designed triple-band antenna is presented in Figure 4.7.

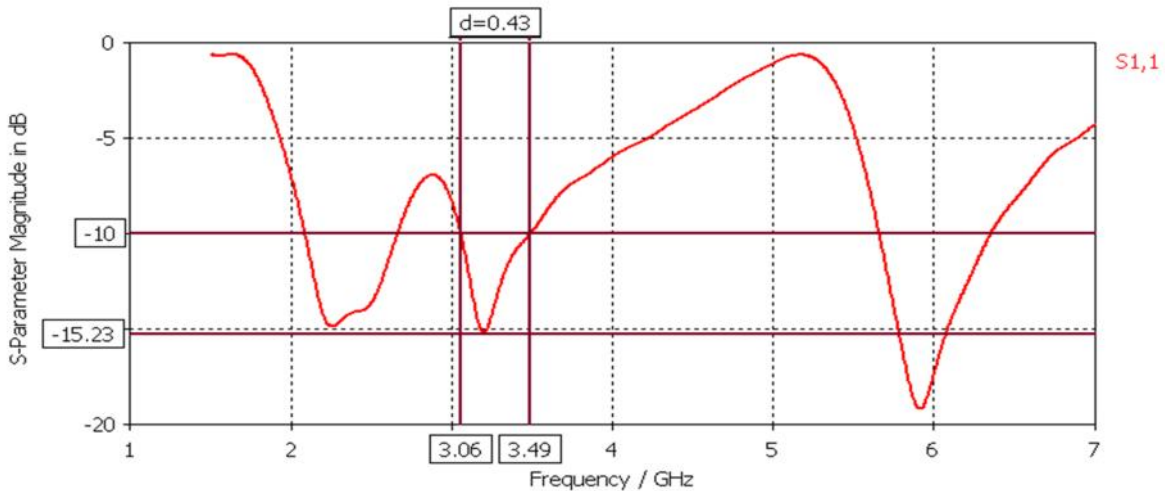


Figure 4.7: Simulated reflection coefficient against frequency for the proposed antenna without shorter slit of length $L_4 = 10 \text{ mm}$ ($L_2 = 7.6 \text{ mm}$ and $L_3 = 16 \text{ mm}$)

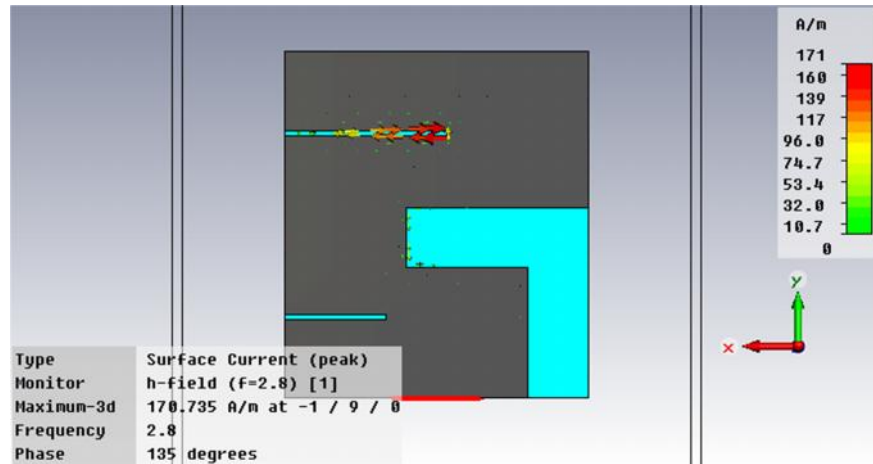
As the figure conveys, the impedance bandwidth of middle band reduces. It limits to 429 MHz from 1.07 GHz (reported in simulated result of reflection coefficient in Figure 4.2). The decrease in impedance bandwidth for the middle band can be ascribed to coupling effects between the longer and shorter slits etched in the back side of MPA, which significantly influence the S_{11} for the proposed antenna.

CHAPTER-4

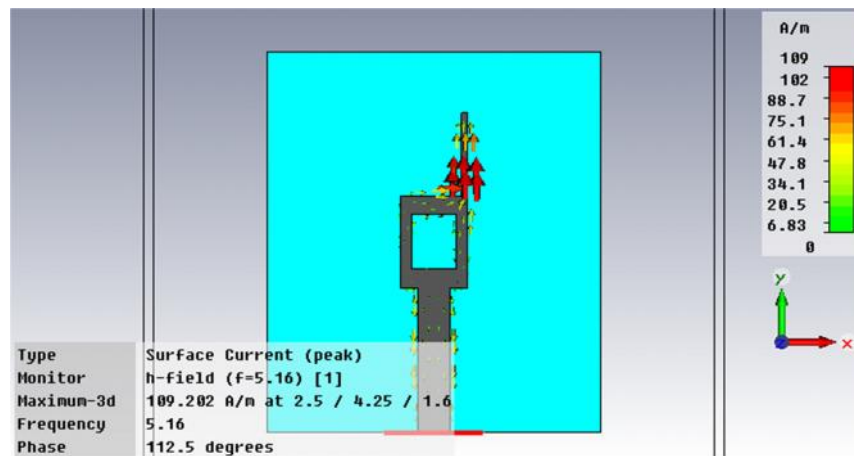
TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

4.2.3. Current Distribution Results

In order to better understand the electromagnetic radiation pattern of the band rejected frequencies, the surface current distributions at the notched frequencies were studied and they are displayed in Figures 4.8(a) and (b).



(a)



(b)

Figure 4.8: Simulated surface current distributions of the proposed antenna at two stop-bands (a) 2.8 GHz (b) 5.16 GHz

When the proposed antenna was operated at lower rejected frequency of 2.8 GHz, a large surface current density was observed along the longer slit etched in the ground structure i.e. it acts as a good resonating structure to generate the lower notched band and also provides the electrical current path for producing 2.8 GHz rejected band effectively as depicted in Figure 4.8(a). At the

CHAPTER-4

TRIPLE BAND O-SHAPE MPA WITH MODIFIED GROUND PLANE

upper rejected frequency of 5.16 GHz, the surface currents showed in Figure 4.8(b) clearly indicate that the strip of length 7.6 mm coupled to the patch yields a strong band rejected characteristic and it is wholly responsible for generating the stop-band. Hence, the related geometrical mechanism of proposed antenna on the resonance situation could be presented from the frequency response and surface current distributions. Thus, the antenna can generate three distinct bands to cover various wireless communication standards.

4.3. Fabrication and Measurement Results

After detailed parametric study and with optimized design parameters (L_2 , L_3 and L_4), the simulated antenna was printed on a substrate FR4 ($\epsilon_r = 4.4$, $\tan \delta = 0.0024$, $h = 1.6$ mm) and experimentally analyzed. The final antenna was fabricated using wet etch based conventional photolithography technique. Its photograph is shown in Figure 4.9. The Agilent E5071C vector network analyzer was used for measuring the reflection coefficient of this triple-band MPA covering multiple frequency bands. All reflection coefficient and radiation pattern measurements were carried out at Microwave and Antenna Laboratory, T.U., Patiala and at Advanced Microwave Laboratory, I.I.T, Roorkee respectively. The pictorial view of measured reflection coefficient is shown in Figure 4.10.



Figure 4.9: Photograph of the proposed antenna

CHAPTER-4

TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

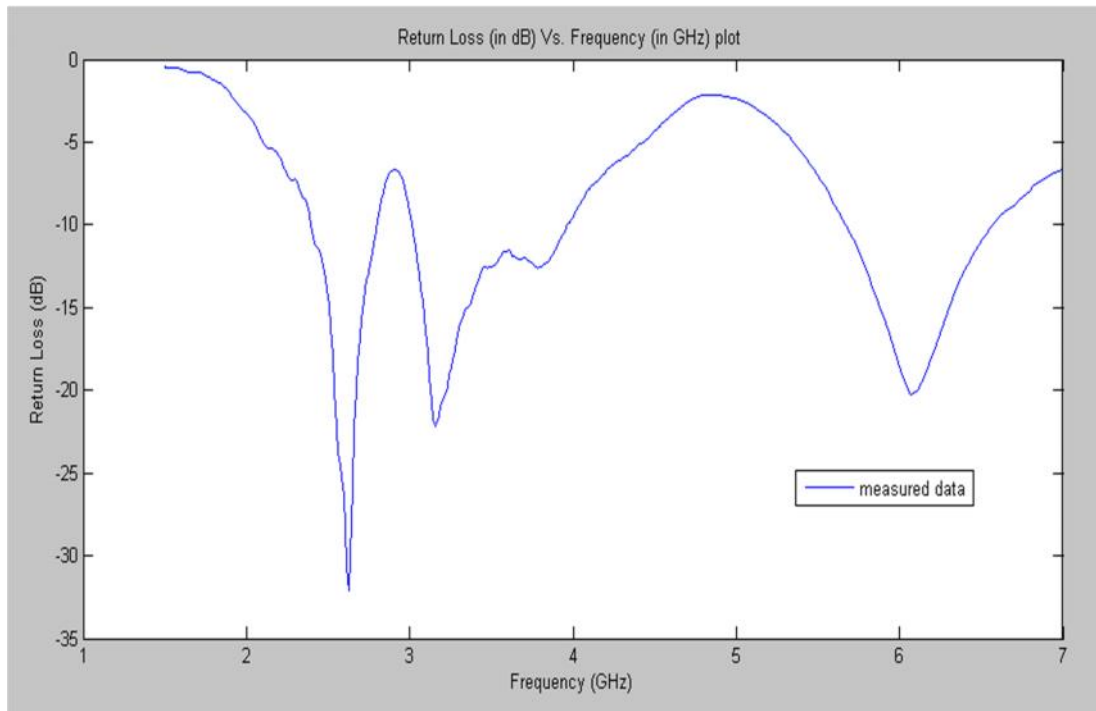


Figure 4.10: Measured reflection coefficient curve of the proposed antenna

The measured reflection coefficient results of fabricated MPA indicate that three resonant modes at frequencies of 2.65 GHz, 3.12 GHz and 6.0 GHz were obtained with the values of reflection coefficient as -33.2 dB, -21.4 dB and -20.2 dB respectively. The measured 10 dB down bandwidths of the three different resonating bands are approximately 510 MHz (2.35-2.86 GHz), 1.3 GHz (3.0-4.3 GHz) and 1.21 GHz (5.64-6.85 GHz), which are covering the required bandwidths of WLAN/Bluetooth/ISM/WiMAX/IMT/ITS/Satellite. Thus, using both the strip coupled on the right side of radiating patch and two unequal slits etched in ground plane, three distinct resonating bands having bandwidth of 20% from 2.35 to 2.86 GHz, 37% from 3.0 to 4.3 GHz, and 19% from 5.62 to 6.21 GHz, respectively, are attained. Obviously, both the strip in patch and slits in ground have a strong mutual effect on generating these two rejected bands. A little difference between measured and simulated results was observed for two higher bands which may be because of errors in fabrication process. Such frequency shifts over the middle and higher resonating bands could not be improved and may be present due to mismatch between the antenna feeder and connector. The lower band (2.65 GHz) obtained during measurement shows somewhat greater disagreement from its simulated result (2.24 GHz) which may be due to the

fact that low power levels were received by the antenna at this particular frequency. So, finally we can say that the shift in three resonating frequency bands obtained during measurement could be attributed to fabrication errors, interference and noise. The comparison of simulated and measured reflection coefficient curve of the proposed antenna is presented in Figure 4.11.

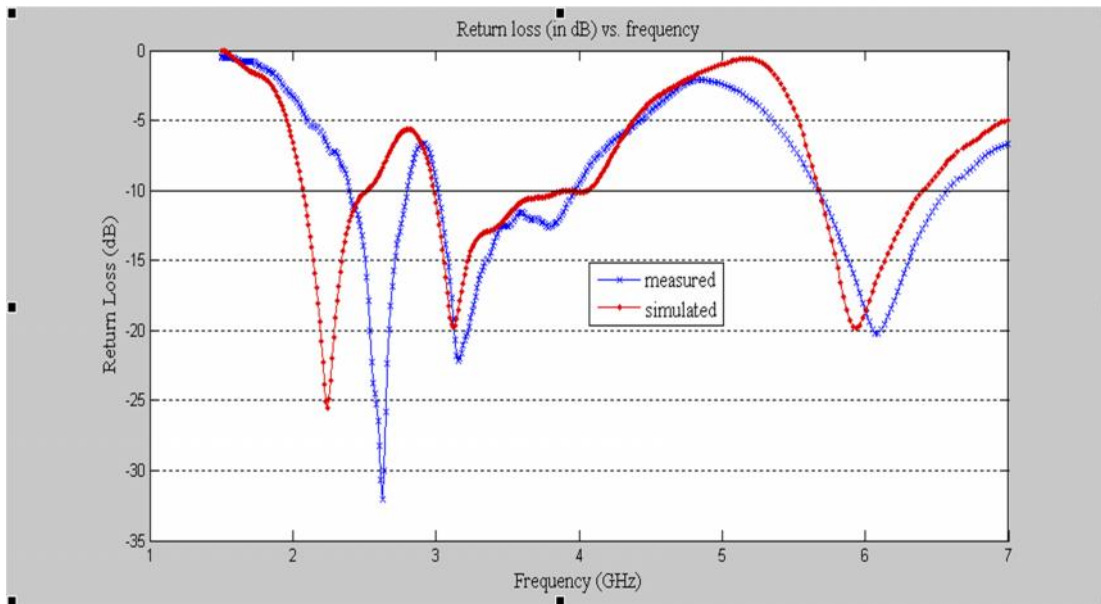


Figure 4.11: Simulated and measured reflection coefficient curves of the designed antenna

The measured and simulated E-plane and H-plane radiation patterns of designed antenna are shown in Figures 4.12, 4.13 & 4.14. These measurements are carried out at resonating frequency bands of 2.45 GHz, 3.5 GHz and 5.8 GHz. In H-plane, an approximately omni-directional and in E plane, dipole like radiation pattern is observed. Normalization to 0 dB has been performed for all the simulated and measured values of radiation patterns. The validation of the proposed design is observed from good agreement between the simulated and measured radiation patterns in three different resonating bands. Interference and noise may be the reason of minor differences between the simulated and measured field patterns.

CHAPTER-4

TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

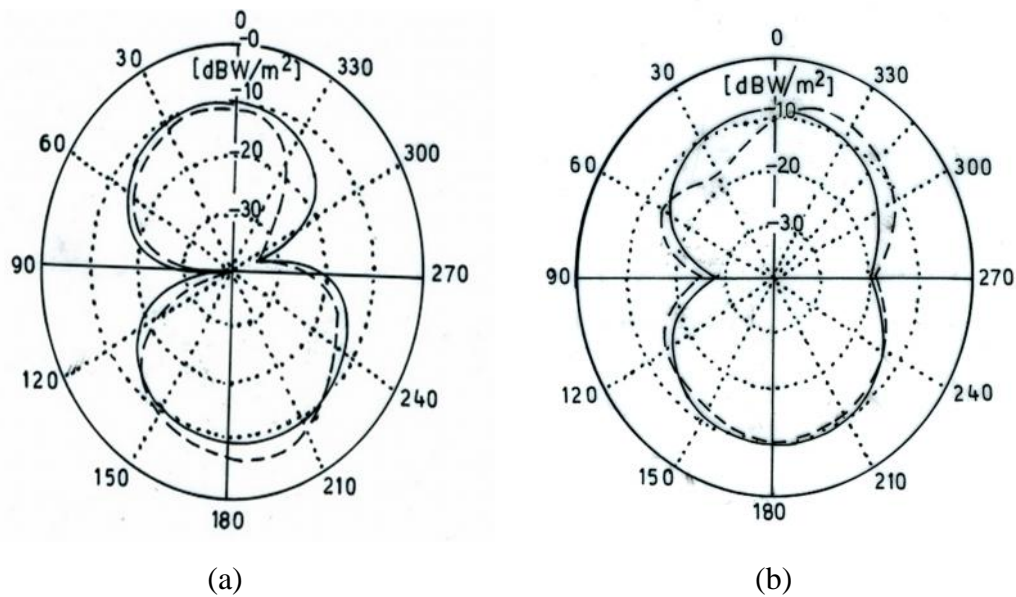


Figure 4.12: Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 2.45 GHz

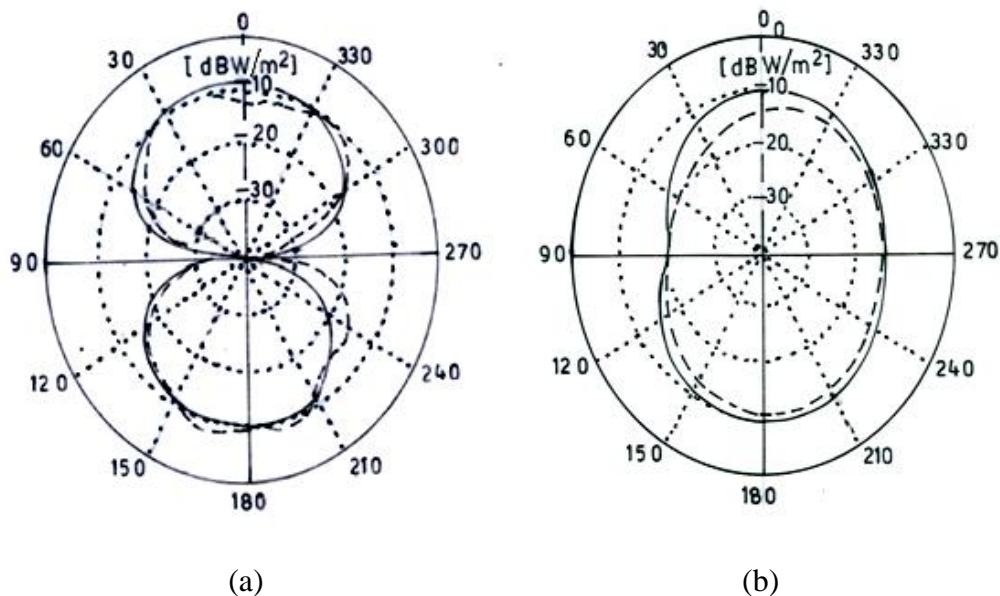


Figure 4.13: Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 3.5 GHz

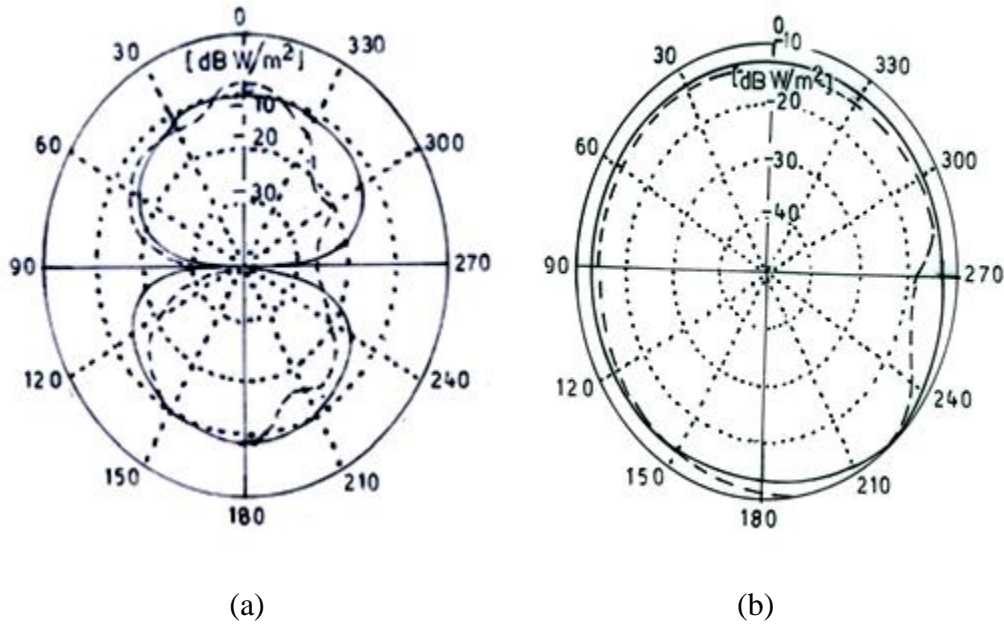


Figure 4.14: Simulated (solid) and measured (dash) (a) E-plane radiation pattern, (b) H-plane radiation pattern at 5.8 GHz

The gain for three resonating bands at 2.45 GHz, 3.5 GHz and 5.8 GHz was also simulated and measured as shown in Figure 4.15. The RF power generator was made to provide 15 dBm power to the transmitter antenna with a receiver located 1.5 m away from transmitter. A standard calibrated horn antenna (0.9–8 GHz) along with available substitution method was used for the calculation of gain. The approximated simulated gain values are 4 dB, 6 dB and 7 dB for three operating frequency bands and similarly the measured gain values are 3 dB, 5 dB and 5.5 dB at the respective frequencies of 2.45 GHz, 3.5 GHz and 5.8 GHz.

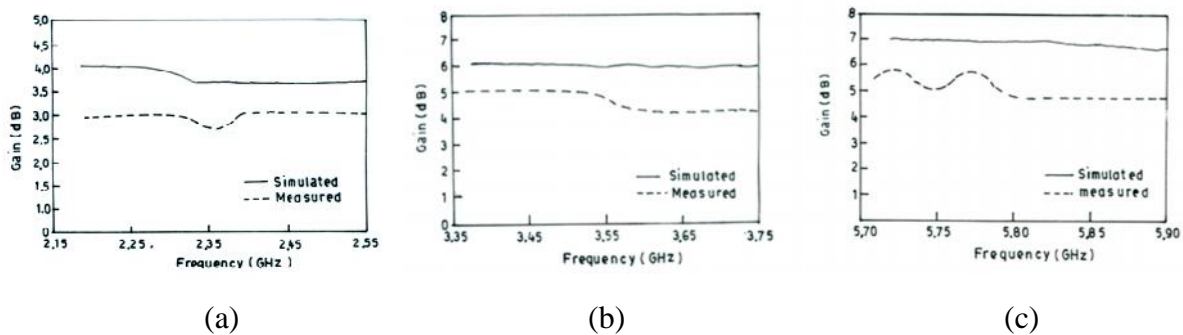


Figure 4.15: Gain plots of the proposed antenna at (a) 2.45 GHz, (b) 3.5 GHz and (c) 5.8 GHz frequency bands

CHAPTER-4

TRIPLE BAND O-SHAPE MSA WITH MODIFIED GROUND PLANE

The measured gain is 1-2 dB lower than the simulated gain that can be attributed to errors during fabrication and measurements.

4.4. Discussion

In this chapter, a triple-band O-shaped MPA was presented which could be used for multiple frequency bands simultaneously covering WLAN/Bluetooth/ISM/WiMAX/IMT/ITS/Satellite standards. A strip coupled on the right side of patch was responsible for a band rejected characteristic at the higher frequency of 5.12 GHz. An inverted L-slot and two rectangular slits of different lengths were also etched in ground plane. The longer slit was responsible for a notched band at lower frequency of 2.8 GHz and the shorter slit enlarged the impedance bandwidth of middle band from 429 MHz to 1.07 GHz during simulation. Both the strip coupled on the patch and two unequal slits etched in ground are responsible for rejection of the interfering bands in selected frequency regions. The measured impedance bandwidths of the fabricated antenna structure were found to be 510 MHz (2.35-2.86 GHz), 1.3 GHz (3.0-4.3 GHz) and 1.21 GHz (5.64-6.85 GHz) in three resonating bands, respectively that is clearly more than bandwidth required for WLAN/WiMAX standards. Therefore, in the proposed design it is seen that using a new technique of incorporating a strip on the right side of O-shaped MPA and an inverted L-slot with two unequal slits in ground, three different resonating bands having bandwidths of 20% from 2.35 to 2.86 GHz, 37% from 3.0 to 4.3 GHz, and 19% from 5.62 to 6.21 GHz, respectively, are obtained. This large impedance bandwidth obtained at all the three frequency bands is quite appreciable and not yet reported by using such a simple and compact design. Also, gain performance and radiation pattern characteristics are acceptable at all the three resonating frequency bands. Hence, the proposed triple-band antenna design can be used successfully in microwave and millimeter-wave integrated circuits for practical purposes and can be used for commercial wireless applications after being patented.

Chapter 5
Simulation Studies
of
Some New
MPAs

In this chapter, four new antenna design configurations are presented that have been designed and simulated using the commercially available electromagnetic simulator CST-MWS V9.0. Antenna Designs I & II are impressed on a promptly accessible and inexpensive substrate material FR-4 with relative permittivity 4.4 as already used while discussing antenna designs in chapters three and four, while Antenna Designs III & IV are projected on substrates with relative permittivity 2.33 and 2.2 respectively.

5.1. Design I - Multi-Frequency Wideband MPA for 5.2/5.5/5.8 GHz

The present antenna design demonstrates a novel rectangular single layer MPA accompanying wideband characteristics for WLAN and WiMAX applications. The suggested antenna has a 10 dB down frequency bandwidth of almost 885 MHz (4.969-5.854 GHz) at that is adequate enough to stimulate the antenna functional and effective for 5.2/5.5/5.8 GHz WLAN and 5.5 GHz WiMAX communication standards. This multi-standard wide/broad band behavior thus incurred is because of the pi-shaped slot integrated into the ground. This designed antenna has one more band below -10 dB ranging from 6.19-6.562 GHz which is feasible for satellite applications covering a bandwidth of 372 MHz. The best possible realizable gain across the whole frequency band is 4.7 dBi. The feed line is located such so as to match with its 50-ohm characteristic impedance. Various simulated results are presented and directions for further study are discussed.

5.1.1. Introduction

During recent trends, broadband antennas are increasing in demand for utilization in high-speed and high frequency data communication; therefore today's major requirement is enlarging the frequency bandwidth of the antennas. Thus the design of an efficient, wideband, compact and high gain antenna, for recent wireless applications is a great challenge. MPAs have a wide scope of applications initiating from communication system field and stepping towards biomedical systems, because of their different irresistible and appealing features such as light weight, low-cost fabrication, small size, robustness, ease of installation and integration with feed networks, low profile, simplicity, conformability to planar and non-planar surfaces and ease of production [22]. However, despite of all these advantageous properties, two most critical restrictions of the MPAs are their limited bandwidth and degraded gain as these limit the range of frequencies across which the antenna can execute in a satisfactory manner. Poor radiation efficiency resulting

CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

from surface waves and spurious feed radiation, conductive and dielectric losses are also among their ill points. Nowadays bandwidth and gain enhancement together with size diminution are turning out to be the leading design conditions for most practical wireless communication applications of microstrip antennas [226-227]. The bandwidth can be improved by various methods like increasing the substrate height, adding slots into the patch, introducing a capacitive coupling among the ground plane and the radiating element, decreasing ϵ_r of substrate [26], colligating various patch elements to constitute an antenna array [228], altering the configuration of radiating element and appending a shorting pin [229-231]. Moreover, the appropriate designed smaller scale antenna will ameliorate transmission and reception, scale down power ingestion, last longer and ameliorate the likelihood of communication device for being sold in market.

5.1.2. Antenna Geometry

The front view geometrical configuration of suggested MPA design is demonstrated in Figure 5.1. The antenna is printed on PCB with the dimensions of patch L_p W_p as 18.4 mm 45 mm. Radiating and non-radiating edges are the respective edges diverged along the width and length of patch antenna. The substrate with an overall size of L_s W_s as 22.83 mm 45 mm and having a dielectric constant 4.4 with a loss tangent 0.0024 and thickness 1.524 mm has been utilized. The height of the ground and the patch which are perfect electric conductors are 0.07 mm each. The proposed antenna is excited by a microstrip feed line (2.215 mm 6 mm) which is made of PEC material having the same thickness of the patch. As the microstrip line feed generates quasi-TEM mode so the dimensions of port from which the patch is excited are extended in all directions.

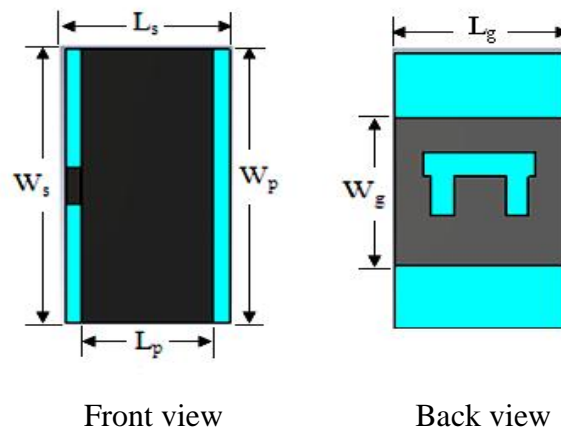


Figure 5.1: Front & Back view of proposed MSA

For the designing of proposed rectangular MPA, the transmission line model is used to calculate the dimensions of MPA [63]. From the Figure 5.1 of the antenna design, it is clearly shown that the width of patch and substrate are the same whereas the width of ground plane has been reduced for getting optimum results with enhanced bandwidth. The feed line of the proposed antenna is only 2.215 mm long and 6 mm thick where the best matching for 50-ohm characteristic impedance is achieved. Proper impedance matching always yields the best desired results.

The dimensions of the patch and feed line placement for suggested antenna have been made optimal so as to acquire the incomparable impedance match to the antenna. For design purpose of proposed antenna, the parameters considered are presented as following:

Substrate permittivity = 4.4, Thickness of substrate (h) = 1.524 mm, Loss tangent of substrate ($\tan \delta$) = 0.0024, Length of patch (L) = 18.4 mm, Width of patch (W) = 45 mm, Length of substrate (L_s) = 22.83 mm, Width of substrate (W_s) = 45 mm, Length of Ground (L_g) = 22.83 mm, Width of Ground (W_g) = 24 mm.

5.1.3. Simulated Results

Reflection coefficient

The optimization of the resonant characteristics of the suggested MPA has been carried out by utilizing the in-built optimizer in transient solver window of CST-MWS V9.0 software. The reflection coefficient parametric results for the intentional antenna were deliberated and the simulated reflection coefficient solutions are demonstrated in Figure 5.2. The S_{11} parameter should be less than -10 dB for acceptable operation. The simulated impedance bandwidths of 885 MHz from 4.969 GHz to 5.854 GHz with VSWR = 1.0 and 372 MHz from 6.19 GHz to 6.562 GHz with VSWR = 1.2 are attained at -10 dB reflection coefficient which give the measure of the broadband property of the patch antenna structure. The reflection coefficient that is achieved at the resonant frequencies 5.551 GHz and 6.4 GHz is equal to -47 dB and -20 dB respectively. This reflection coefficient value proposes that there is an acceptable level of matching at the frequency point beneath the -10 dB region. The bands thus obtained cover 5.2/5.8 GHz WLAN, 5.5 GHz WiMAX and 6.34 GHz satellite applications. The accomplished value of reflection coefficient is limited enough in magnitude and frequency is close enough to the explicitly stated

CHAPTER-5 SIMULATION STUDIES OF SOME NEW MPAs

frequency band for 5.2/5.8 GHz WLAN and 5.5 GHz WiMAX and 6.34 GHz satellite applications. The achieved antenna impedance is approximately equal to 50-ohm.

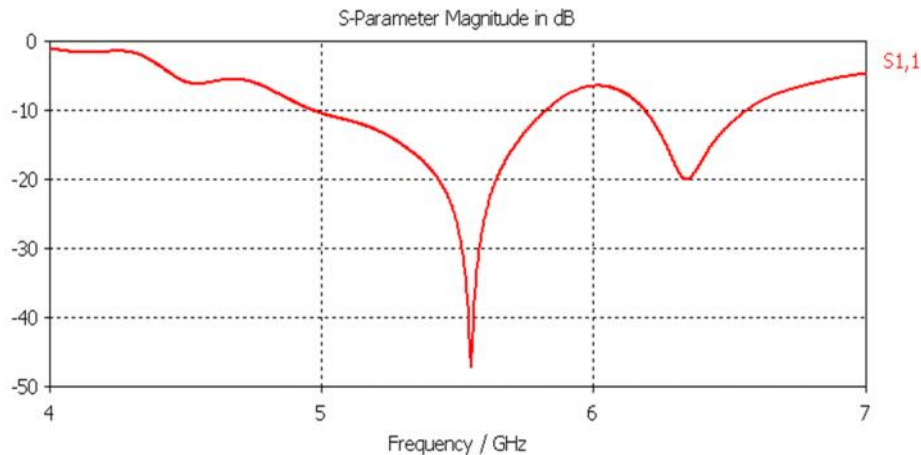
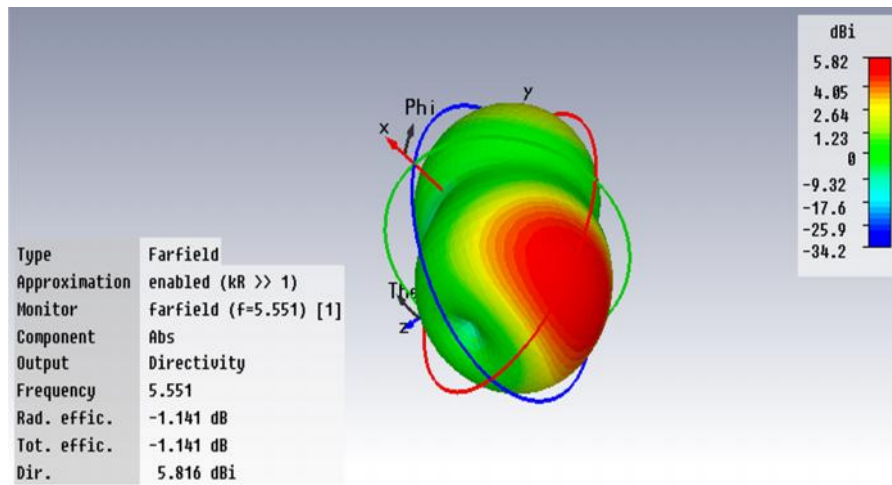


Figure 5.2: Simulated reflection coefficient of the proposed patch antenna

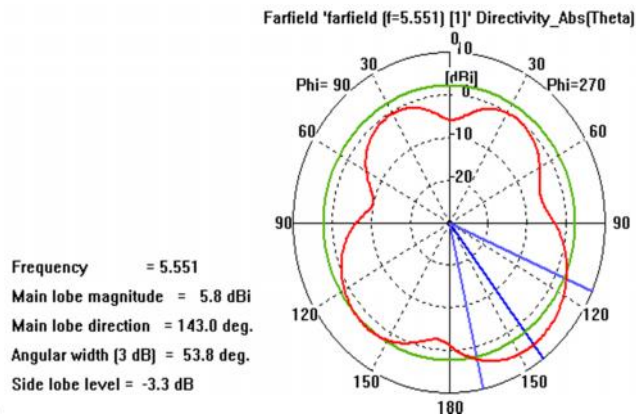
Radiation pattern

The radiation pattern of an antenna is characterized as the comparative dispersion of radiated power which is associated with the spatial directional coordinates. These coordinates are expressed in terms of the azimuth angle and the elevation angle. Generally, it is a diagram of the radiated power from the antenna per unit solid angle.

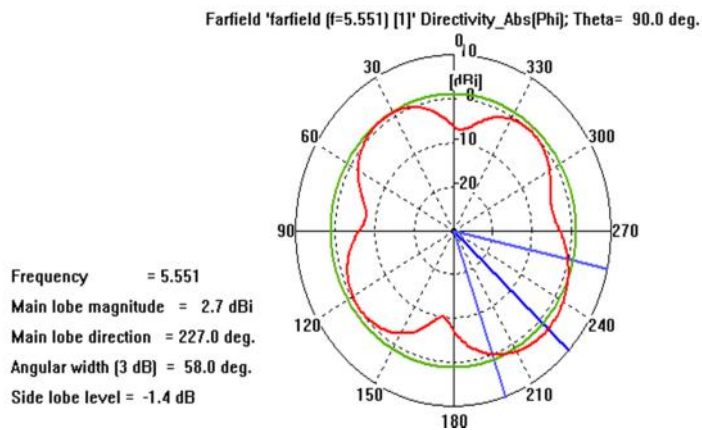
Figure 5.3(a) and Figure 5.4(a) demonstrate the simulated 3-D radiation patterns at the frequencies of 5.551 GHz and 6.34 GHz respectively. These figures display that the intended antenna radiates nearly in omni-directional nature. Moreover, it displays that the directivity of suggested antenna is 5.816 dBi and 5.823 dBi at the respective resonating frequencies of 5.551 GHz and 6.34 GHz. Figures 5.3(b) and (c) show the elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 5.551 GHz and Figures 5.4(b) and (c) show the elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 6.34 GHz. The utmost manageable gain across the whole frequency band is 4.7 dB.



(a)



(b)

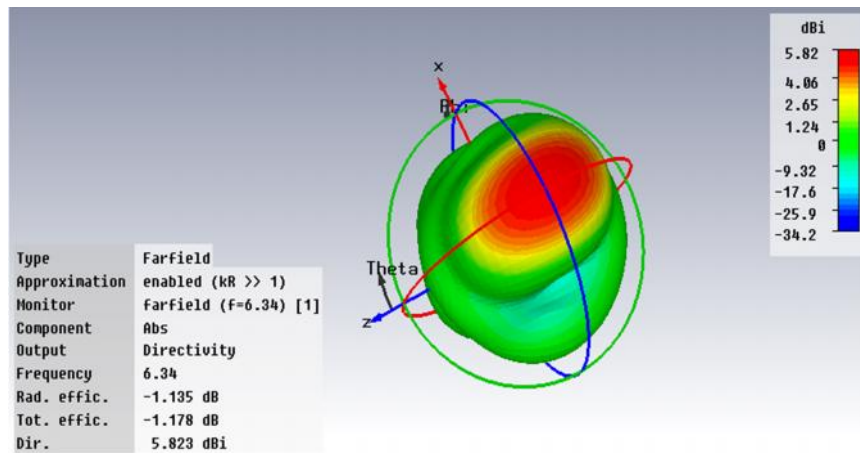


(c)

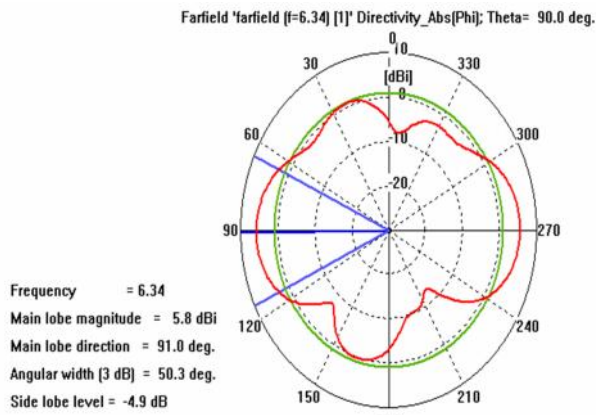
Figure 5.3: Radiation pattern of proposed patch antenna at 5.551 GHz

(a) 3-D plot (b) E-plane and (c) H-plane

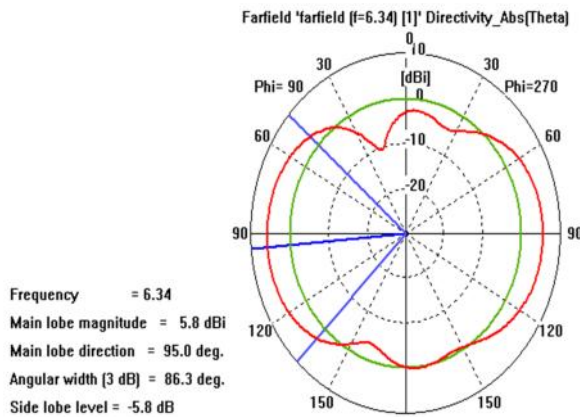
CHAPTER-5 SIMULATION STUDIES OF SOME NEW MPAs



(a)



(b)



(c)

Figure 5.4: Radiation pattern of proposed patch antenna at 6.34 GHz

(a) 3-D plot (b) E-plane and (c) H-plane

5.1.4. Discussion

The proposed antenna design could be suitable to cover WLAN/WiMAX/Satellite communication standards. The simulated impedance bandwidth of the suggested antenna design is around 885 MHz (4.969-5.854 GHz) covering WLAN and WiMAX communication standards. Such a huge and appreciable value of impedance bandwidth of the suggested antenna is more than the demanding bandwidth specification of 600 MHz to cover 5.15-5.85 GHz WiMAX frequency band. The intended antenna structure is feasible for satellite applications as well covering a bandwidth of 372 MHz (6.19-6.562 GHz). The antenna gives a constant and unfluctuating radiation performance with gain above 4.5 dB across the whole frequency band with a good impedance matching of 52-ohm. A nearly omni-directional radiation pattern has been incurred that appears to be appreciably sufficient for the imagined applications. Even though this antenna has been fashioned for WLAN and WiMAX applications, the present design idea concept can be increased in scope or protracted to other frequency bands in concern. Because of the simple feeding technique been used for antenna design in communication, the investigated broadband antenna is a favorable nominee for fabrication to be utilized for many wireless communication applications. Nevertheless, the gain of the microstrip antenna, described here, is not really appreciable. Moreover, the antenna is not compact and thin because of the utilization of high dielectric constant for the substrate material. A large amount of work is still in full swing to attain even improved outcomes with a good gain over a wide impedance bandwidth and a good axial ratio.

5.2. Design II - CPW-Fed Miniature Slotted Multi-Frequency Wideband MPA for WLAN/Wi-Fi/WiMAX/IMT/AMSAT/WAVE Applications

The present antenna design proposes a novel compact MPA comprising two horizontal E-shaped slots fed by a coplanar waveguide. In this design structure, both the slotted patch and symmetrical ground planes are embedded in the same plane. Both the ground plane and radiating patch are PECs that are impressed on a promptly accessible and inexpensive substrate material FR-4 with relative permittivity 4.4, loss tangent 0.0024 and thickness 1.6 mm. The suggested MPA design is susceptible of rendering three different operating bands with -10 dB reflection coefficient viz. 2.40-2.58 GHz, 3.4-4.26 GHz and 4.63-7.30 GHz with a satisfactory bandwidth of 180 MHz, 860 MHz and 2.67 GHz respectively. Obviously, the achieved impedance

CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

bandwidths are as much as necessary to cover the obligatory bandwidths of several communication standards simultaneously i.e. 2.400-2.500 GHz Wi-Fi, 2.400-2.484 GHz/5.150-5.350 GHz/5.725-5.825 GHz WLAN, 3.400-4.200 GHz IMT, 3.400-3.690 GHz/5.250-5.850 GHz WiMAX, 5.650-5.670 GHz AMSAT, 5.900 GHz for WAVE and 6.1-6.85 GHz Satellite communication. Eventually, the design process to accomplish the needed performance is demonstrated and discoursed thereafter.

5.2.1. Introduction

The demands for antennas with multiband operation, small size, low cost, simple configuration and easy fabrication have increased drastically due to the rapid development of modern wireless communication system. WiMAX (2.5-2.69, 3.4-3.69, and 5.25-5.85 GHz) and WLAN (2.4-2.484, 5.15-5.35, and 5.725-5.825 GHz) technologies have been widely applied in mobile devices since the latest decade. To adapt to the diverse and complicated WLAN and WiMAX environments, therefore, the antennas in these devices should provide stable operations at multiple frequency bands, which cover 2.5/3.5/5.5 GHz WiMAX and 2.4/5.2/5.8 GHz WLAN frequency bands. Several promising dual and multiband planar antenna designs have already been proposed for WLAN/WiMAX applications such as a split-ring monopole antenna [232], a symmetrical G-shaped monopole antenna [233], a CPW-fed dual rectangular ring monopole [234], a CPW-fed monopole antenna [235] and a S-shaped monopole antenna [236]. Although the antennas mentioned above are able to satisfy the WLAN or WiMAX standards, some of them either have large overall sizes and complex structures, which make them impractical for mobile devices, or have narrow bandwidths that fail to cover certain required frequency bands. Other available antenna designs such as a double-T shaped monopole [186], double-S shaped [237], C-shaped [238], E-shaped [239], meandered T-shaped [240] and back-to back dipole [241] radiating structures cannot provide a multi-band operation to support WiMAX application. The antennas in [178, 242] can generate wide bands to cover the WLAN and WiMAX bands, however, their wide operating bands cover many other existing narrowband services such as C-band satellite communications. To address this issue, therefore, several triple-band antennas which have better rejections in undesired bands for WLAN/WiMAX applications have been proposed [243-247]. These designs of triple band antenna are either complex in structure or large in size, which limit their availabilities for practical application. In the present work, we

demonstrate a small and slotted multi-frequency wideband MPA based on FR-4 dielectric substrate material and fed by a CPW feed mechanism feasible for wireless applications. FR-4 material is generally used for fabricating microstrip antennas because it is cheap and promptly available. The proposed antenna is limited to a small size of $25 \times 18 \text{ mm}^2$. It simply consists of a slotted monopole and a modified CPW ground plane which is capable of generating three distinct operating bands 2.40-2.58 GHz, 3.4-4.26 GHz and 4.63-7.30 GHz to cover the WLAN/Wi-Fi/WiMAX/IMT/AMSAT/WAVE/Satellite bands. As the feeding of antenna has been done by a CPW structure, therefore a simple single-metallic layer is required that is able to decrease the complexity of the antenna structure. In addition, the antenna can be incorporated into MMICs or active devices without question.

5.2.2. Antenna Geometry

The geometrical structure of the suggested CPW-fed multi-frequency MPA with wideband behavior has been depicted in Figure 5.5. The antenna with a single-layered metallic structure is engraved on one side of an inexpensive substrate material having relative permittivity 4.4, a loss tangent 0.025, a thickness 1.6 mm, and with no metallization present on the other side. A 50-ohm CPW feed line that has a strip width of W_f and a gap distance of G_f between the strip and the coplanar ground plane is utilized to excite an antenna. Two equal modified finite ground planes are situated symmetrically on each side of the CPW feed line. By etching a pair of symmetrical triangles with legs W_3 and L_3 on each side of the ground plane, a smooth transition from one resonant mode to another can be achieved, and good impedance matching is also obtained.

To achieve multi-frequency wideband operation for WLAN/Wi-Fi/WiMAX/IMT/AMSAT/WAVE/Satellite communication applications, two horizontal E-shaped slots, one conventional (top) and the other modified (bottom) are etched into a rectangular patch monopole antenna fed by a co-planar waveguide CPW arrangement. The staircase pattern notched on the bottom of the rectangular patch plays an important role in improving the impedance matching.

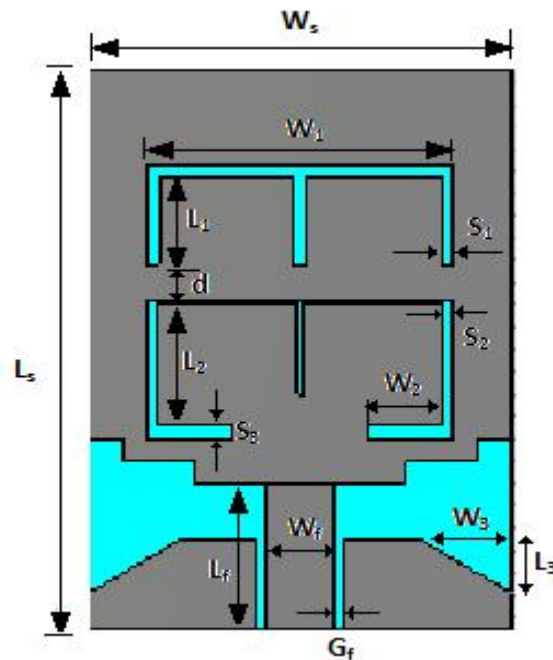


Figure 5.5: Configuration of the proposed antenna with modified ground plane

5.2.3. Simulated Results

Reflection coefficient

Transient solver was selected to simulate an antenna with port impedance adapted to 50-ohm. During simulation, hexahedral mesh cell was set up with 20 lines per wavelength for an accuracy of -30 dB. The optimized parameters of the proposed antenna obtained after using in-built optimizer option in the transient solver window of CST-MWS V9.0 are as follows: $L_s = 25$ mm, $L_1 = 4$ mm, $L_2 = 5.3$ mm, $W_3 = 3.9$ mm, $L_3 = 2.4$ mm, $L_f = 6.5$ mm, $d = 1.6$ mm, $W_s = 18$ mm, $W_1 = 13$ mm, $W_2 = 3.6$ mm, $W_f = 2.8$ mm, $S_1 = 0.5$ mm, $S_2 = 0.4$ mm, $S_3 = 0.7$ mm, $G_f = 0.4$ mm. Figure 5.6 renders the simulated reflection coefficient of suggested/intended antenna with optimum parameters that corroborates or supports multi-frequency wideband operation at coveted bands with moderate bandwidth. The intended MPA design is susceptible of rendering three different operating bands with -10 dB reflection coefficient viz. 2.40-2.58 GHz, 3.4-4.26 GHz and 4.63-7.30 GHz with an adequate respective bandwidth of 180 MHz, 860 MHz and 2.67 GHz. For perfect impedance matching, a 50-ohm CPW line was utilized for feeding the patch.

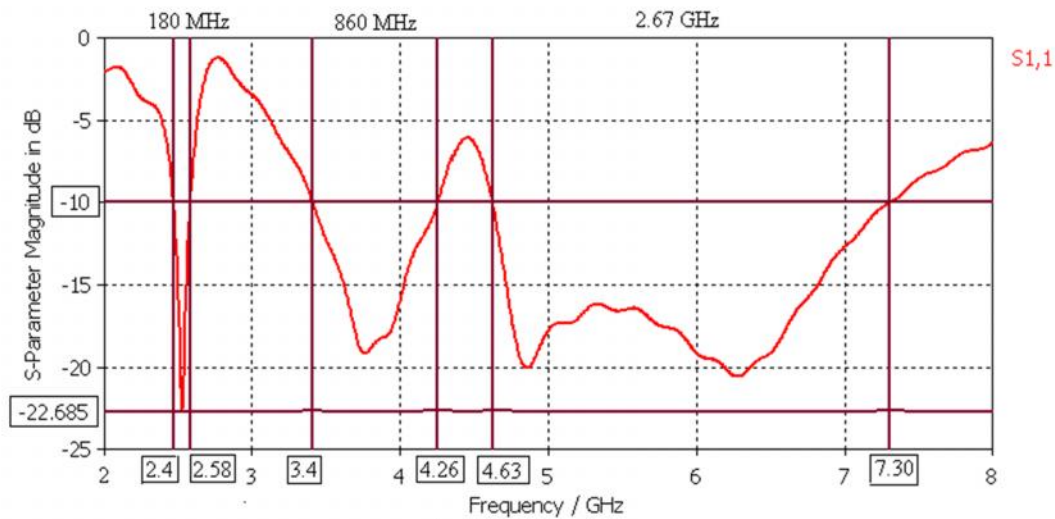


Figure 5.6: Simulated reflection coefficient of proposed antenna

Current Distribution

The simulated surface current distributions at 2.45 GHz and 4 GHz were analyzed and they are exhibited in Figure 5.7 (a) and (b) for better understanding the electromagnetic radiation pattern and excitation mechanism of the proposed MPA. When the suggested antenna was directed at 2.45 GHz, a significant surface current density was ascertained to be concentrated on the modified E-shaped slot at the bottom of rectangular patch monopole i.e. it behaves as a superb and magnificent resonating structure to provide the electrical current path for giving rise to 2.45 GHz resonant mode. The surface currents primarily flow across the conventional E-shaped slot situated at top of the rectangular patch monopole at the rejected frequency of 4 GHz, indicating that it is accountable for rendering/yielding a stop-band at 4 GHz. Therefore, the suggested MPA can yield multiple frequency wide bands to cover assorted wireless communication standards at the same time.

CHAPTER-5 SIMULATION STUDIES OF SOME NEW MPAs

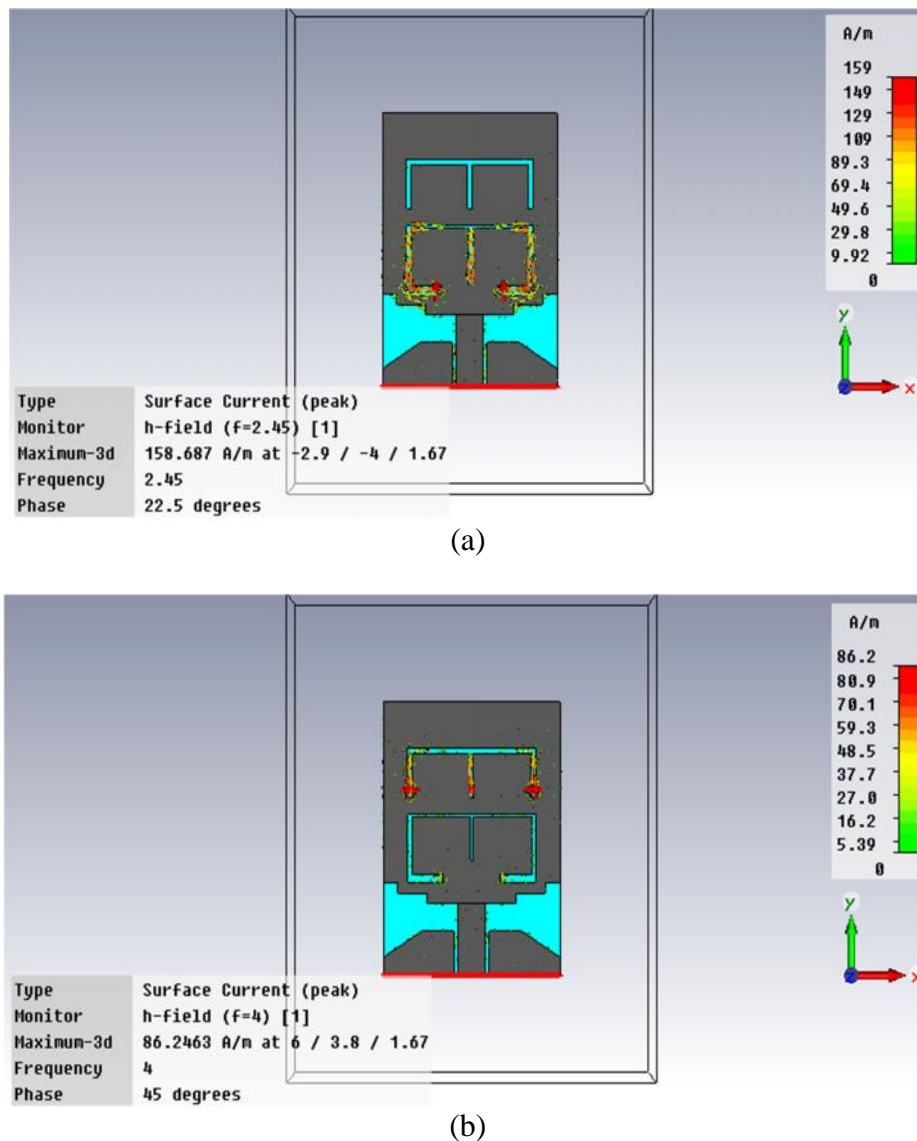


Figure 5.7: Simulated surface current distributions of the proposed antenna at (a) 2.45 GHz (b) 4 GHz

Radiation pattern

Figures 5.8(a), (b) and (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 2.45 GHz.

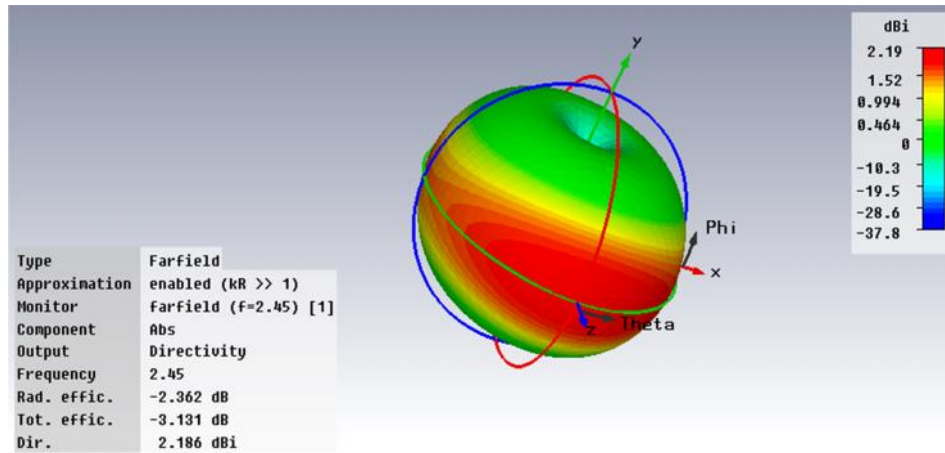
Figures 5.9(a), (b) and (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 3.5 GHz.

Figures 5.10(a), (b) and (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 5.5 GHz.

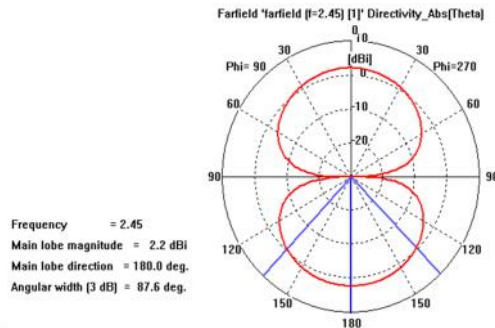
CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

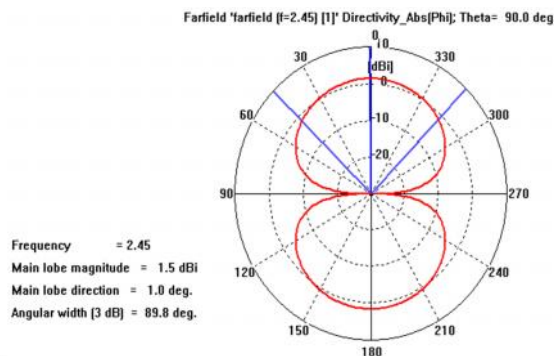
These figures display that the intended antenna radiates nearly in omni-directional nature. Moreover, the directivity of suggested antenna is 2.186 dBi, 2.182 dBi and 2.866 dBi at the respective resonating frequencies of 2.45 GHz, 3.5 GHz and 5.5 GHz. The utmost attainable gain across the whole frequency band is 2.411 dB.



(a)



(b)



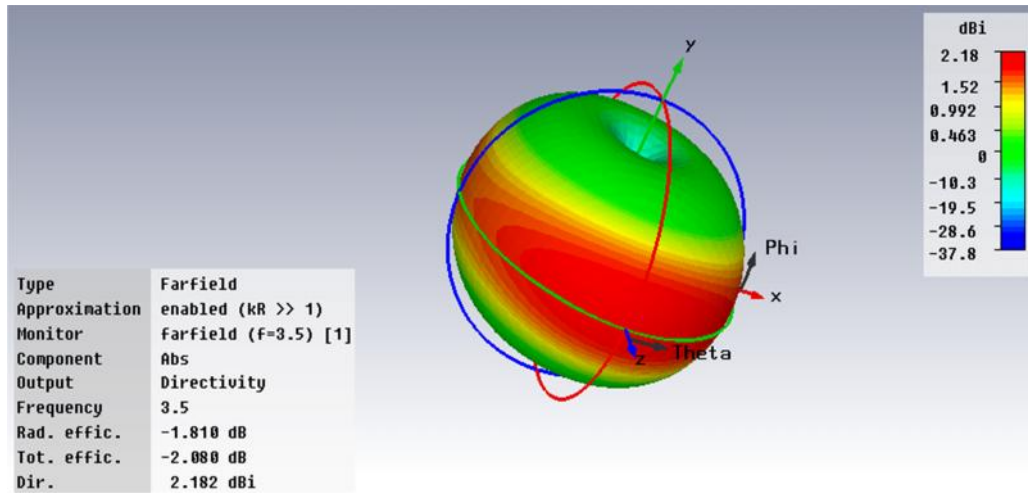
(c)

Figure 5.8: Radiation pattern of proposed patch antenna at 2.45 GHz

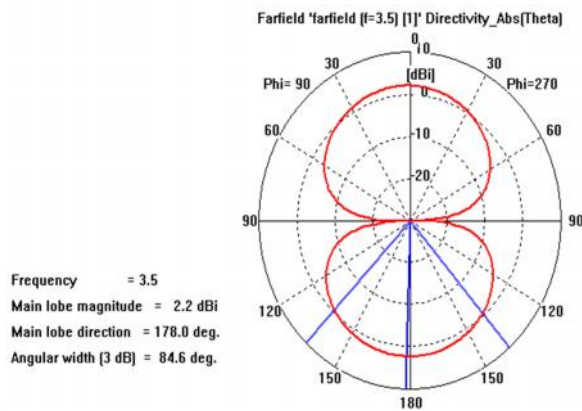
(a) 3-D plot (b) E-plane and (c) H-plane

CHAPTER-5

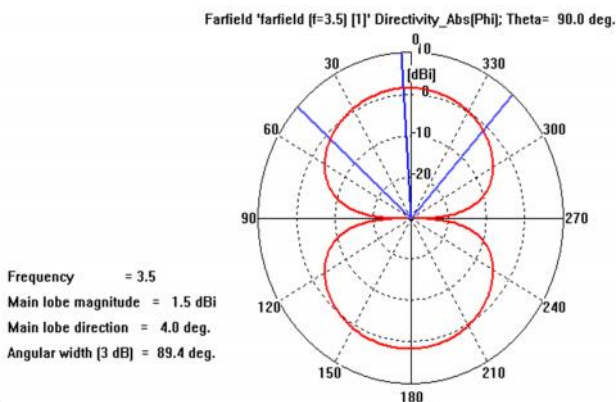
SIMULATION STUDIES OF SOME NEW MPAs



(a)



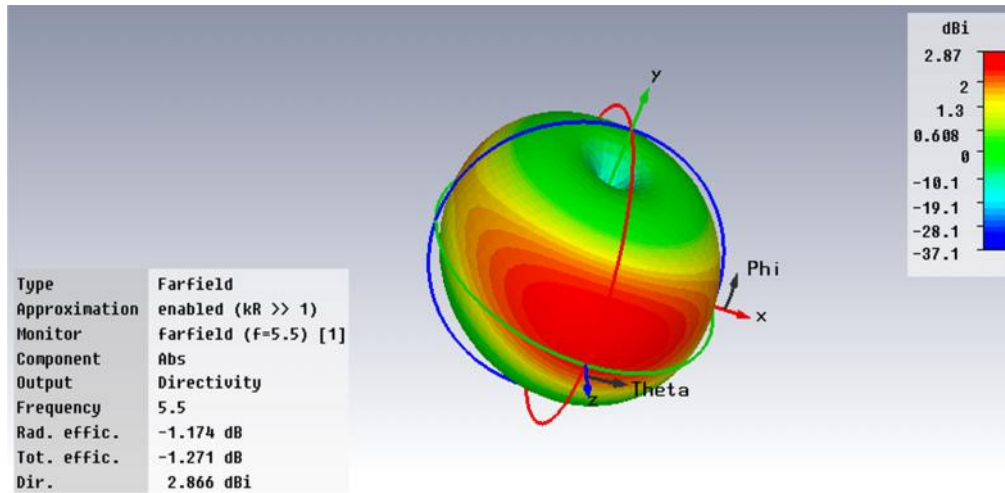
(b)



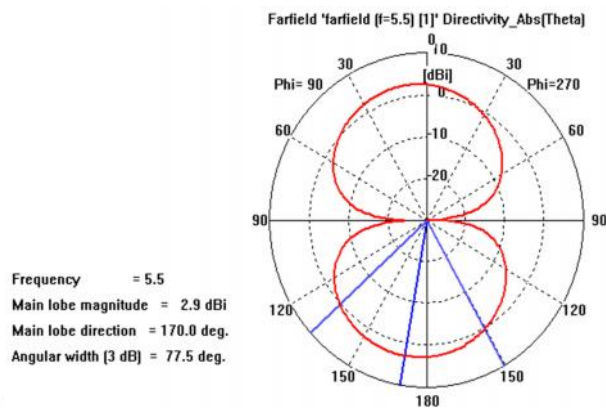
(c)

Figure 5.9: Radiation pattern of proposed patch antenna at 3.5 GHz

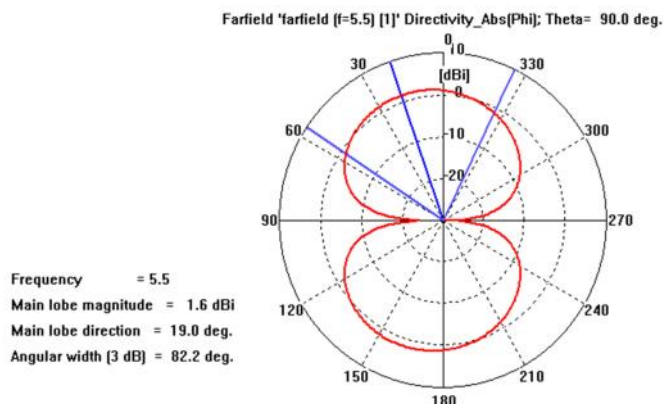
(a) 3-D plot (b) E-plane and (c) H-plane



(a)



(b)



(c)

Figure 5.10: Radiation pattern of proposed patch antenna at 5.5 GHz

(a) 3-D plot (b) E-plane and (c) H-plane

CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

5.2.4. Discussion

In this work, design procedure of a novel compact multi-frequency wide triple band MPA has been discussed. It comprises two horizontal E-shaped slots fed by a co-planar waveguide CPW. The coplanar waveguide feeding technique utilized in our design enabled straightforward and undeviating feeding of the structure without utilizing complex microstrip taper or impedance transformer. The conventional E-shaped slot at the top of rectangular patch monopole is responsible for generating the stop-band at 4 GHz. The modified E-shaped slot at the bottom of rectangular patch monopole is responsible for producing 2.45 GHz resonating frequency mode. The staircase pattern notched on the bottom of the rectangular patch plays a significant function in amending the impedance matching. The suggested antenna design could be suitable to cover 2.400-2.484 GHz/5.150-5.350 GHz/5.725-5.825 GHz for WLAN, 2.400-2.500 GHz for Wi-Fi, 3.400-3.690 GHz/5.250-5.850 GHz for WiMAX, 3.400-4.200 GHz for IMT, 5.650-5.670 GHz for up-links and 5.830-5.850 GHz for down-links of AMSAT, 5.900 GHz for WAVE and 6.1-6.85 GHz for satellite communication. Therefore, in the existing study it was ascertained that utilizing such a novel method of embedding two E-shaped slots, one conventional and the other modified, into a rectangular patch monopole together with a staircase pattern notched at the bottom of it, three different operating bands with a bandwidth of 4% from 2.40 to 2.50 GHz, a bandwidth of 21% from 3.34 to 4.13 GHz, and a bandwidth of 43% from 4.60 to 7.12 GHz, respectively, can be attained. Such an immense impedance bandwidth accomplished at all the three resonating frequency bands is considerable to the greatest extent and not described so far by utilizing such an easy, concise and closely packed design. Hence, the small size, simple structure, multiband coverage, almost monopole-like radiation properties, huge bandwidth and stable antenna gains across the operating bands make the proposed multi-frequency wide triple band antenna to be an attractive candidate for practical applications in the WLAN/WiMAX communication system. It can also be easily integrated to microwave circuits and may find successful application in the millimeter wave range.

5.3. Design III - Design of Coaxial Fed MPA for WiMAX/ IMT Applications

This antenna design presents a single co-axial feed, a single layer, wideband, concise rectangular MPA. The intended antenna is manufactured or built on a dielectric substrate with relative permittivity 2.33 and thickness 8 mm using simple coaxial feeding technique. Under the design

process, -shape slot has been trimmed beneath a Pi-shape slot in the radiating patch. To add on, four circular slots have been trimmed into the radiating terminals of patch for wideband operation covering both IMT (3900-4400MHz) and WiMAX (3400-3690MHz) communication standards. Fundamentally, the utilization of these circular slots has efficaciously agitated multi-resonant modes with appreciable impedance bandwidth at the same time. A thick substrate assists widen the bandwidth for covering the whole frequency range of IMT & WiMAX communication standards. The suggested slot loaded patch antenna resonates at 2.66 GHz and has a wideband from 3.4 GHz to 4.5 GHz with the accompanying bandwidth of 108 MHz and 1.14 GHz and reflection coefficients of -16.0 dB and -22.6 dB respectively. The antenna renders a constant and un-fluctuating radiation performance with gain above 7 dB across the whole wideband. Further, the suggested antenna yields nearly omni-directional radiation pattern, low cross polarization and comparatively increased gain. Simulated results for reflection coefficient and far-field radiation pattern of the fashioned antenna are demonstrated and talked about. The analytical study of the simulated results affirms fruitful and productive design of the present co-axial fed MPA.

5.3.1. Introduction

Slot loaded patch antennas find application in broadband communication systems on account of their mesmerizing and enthralling properties, such as low profile, broad frequency bandwidth, easy integration with monolithic microwave integrated circuits, lightweight, simple fabrication, low cost, good impedance matching and appreciable radiation pattern performance. The latest technologies render wireless communication devices to become limited in size in accordance with physical laws. Antenna size is a leading factor that limits miniaturization. The mobile communication technologies demand a very compact antenna and moreover the hot demand of multi-band antennas has increased the simultaneous transmission of video, voice and data information thus avoiding the utilization of two or more separate antennas. The requirement for multi-frequency resonant and wide-band antennas has increased recently as they could easily be integrated with the communication system. In order to fulfill these requirements, MPA is one of the best candidates. Narrow impedance bandwidth is the major drawback of a MPA [57]. WLAN and WiMAX technologies are the most speedily growing areas in modern wireless communication [248-250]. The users get the advantage of being mobile so as to move around

CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

within a wide coverage area and still be connected to the network thereby rendering increased flexibility and freedom. Portable antenna technology has fully developed along with cellular and mobile technologies because of its various advantages like improved transmission and reception, long-lasting feature, improved marketability of the communication device and reduced power consumption. Furthermore, enlarging the frequency bandwidth of antennas is the major requirement, especially to avoid channel saturation at the receptor. In the present work, slot loaded wideband MPA for WiMAX & IMT applications is designed and simulated. The suggested patch antenna resonates at 2.66 GHz with impedance bandwidth of 108 MHz and has another broadband (3.4-4.5GHz) with impedance bandwidth of 1.14 GHz. Analyzing the simulated resonant behavior of suggested patch antenna, it has been found that it is feasible candidate for WiMAX (3400MHz-3690MHz) & IMT (3900MHz-4400MHz) applications. Such a huge impedance bandwidth has been obtained by modifying the shape of radiating element which is based on the modification of surface current distribution which requires an intensive analysis.

5.3.2. Antenna Geometry

In the present antenna design, several parameters have been examined scientifically and optimized using in-built optimizer technique in transient solver window of CST-MWS V9.0 software. The geometrical configuration of slot loaded patch antenna is depicted in Figure 5.11. The detailed description of design criteria for a patch antenna is: Substrate permittivity (ϵ_r) = 2.33, Substrate thickness (h) = 8 mm, Length of patch (L_p) = 37 mm, Width of patch (W_p) = 24 mm, Feed point location = (0, 2.8), Dimensions of ground ($L_g \times W_g$) = 90 mm x 80 mm. The longer dimension of the patch is along the x-axis while the shorter dimension is along the y-axis. The pi-shape slot dimensions and T-shape slot dimensions are manipulated for optimum impedance matching and appreciable reflection coefficient. The width of each slot is 2 mm. A co-axial probe of 50-ohm is used to feed the antenna structure. The respective values for inner and outer radii of co-axial probe are 1.5 mm and 3 mm. Also, outer radius for each of the circular slots being cut into the radiating edges of patch is taken to be 3 mm with co-ordinates (x, y) as (15, 12.5) respectively.

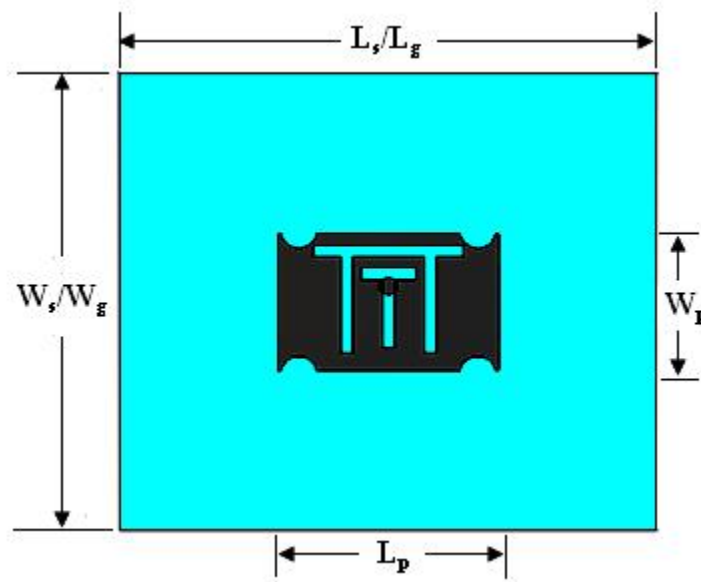


Figure 5.11: Geometry of slot loaded single layer patch antenna

5.3.3. Simulated Results

Reflection coefficient

The wideband attributes of the suggested antenna are accomplished by integrating a π -shape slot under a Pi-shape slot and four circular slots been trimmed at the radiating terminals across the width of rectangular MSA. The electrical length of these incorporated slots in the patch decides the resonating frequency bands for the present antenna design. In addition to other factors, the thick substrate having $h = 8$ mm, assists in attaining the needed broad impedance bandwidth [251]. The feed location is moved from the centre of geometry along y-axis to get the best possible impedance match to the antenna. The reflection coefficient characteristic of this presently designed slot loaded patch antenna is depicted in Figure 5.12 which demonstrates that it resonates at 2.66 GHz and has a wideband covering the frequencies from 3.4 GHz to 4.5 GHz. These resonant frequencies give the measure of impedance bandwidth characteristics of the patch antenna [63]. The impedance bandwidth for the proposed antenna is 108 MHz (2.61 GHz to 2.72 GHz) for the first band and 1.14 GHz (3.4 GHz to 4.5 GHz) for the second broadband at -10 dB reflection coefficient. Figure 5.12 presents the reflection coefficient values at the two operating bands viz. -16.0 dB and -22.6 dB respectively. These reflection coefficient values indicate that there is good matching at the frequency point below the -10 dB region. The attained values of

CHAPTER-5 SIMULATION STUDIES OF SOME NEW MPAs

reflection coefficient are small and frequencies are close as much as necessary to the specified frequency bands for WiMAX & IMT applications.

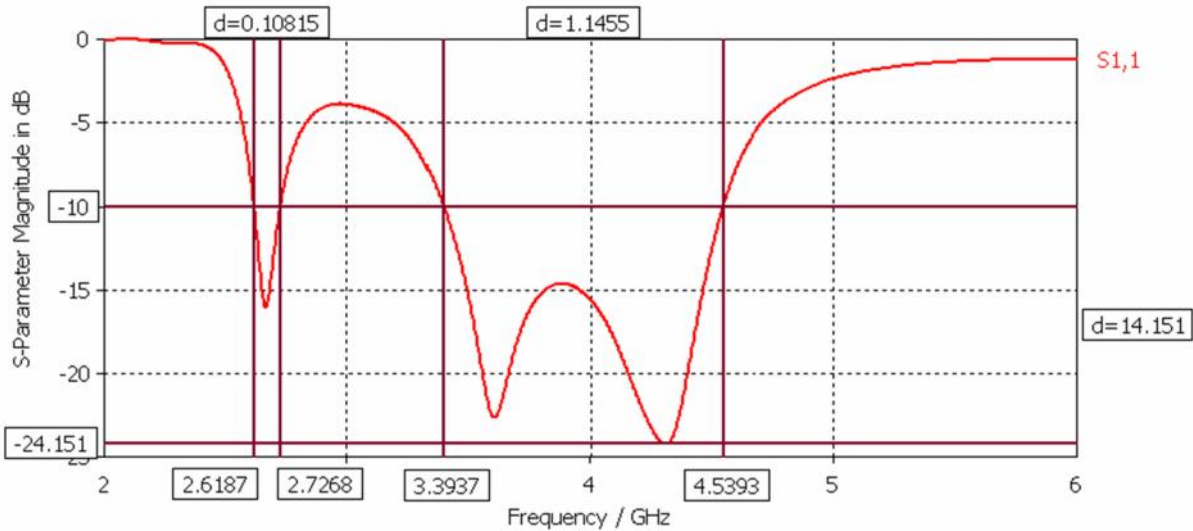


Figure 5.12: Reflection coefficient vs. frequency graph

Moreover, the value of VSWR at the resonating frequency of 2.66 GHz is 1.34 and also for the broadband from 3.4 GHz to 4.5 GHz, VSWR is below 2. The value of VSWR for both frequency bands is less than 2 which shows that there is an appropriate antenna impedance matching at these two frequencies.

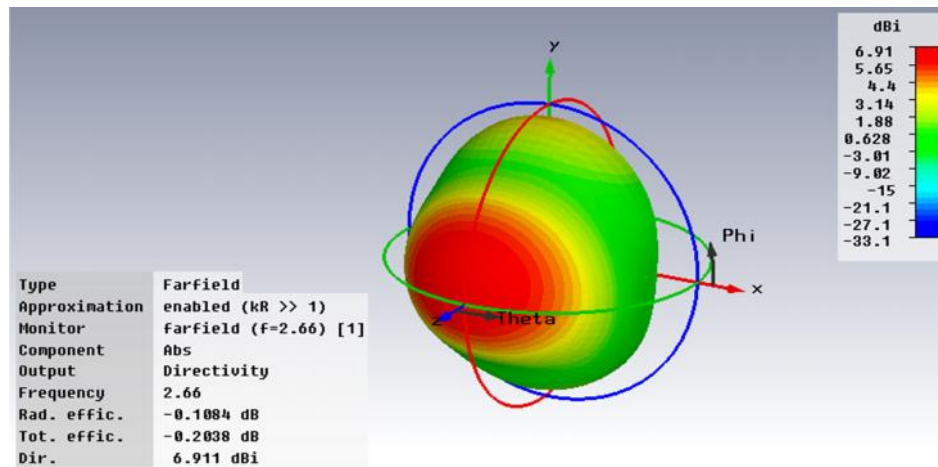
Radiation Pattern

Figures 5.13(a), (b) and (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 2.66 GHz.

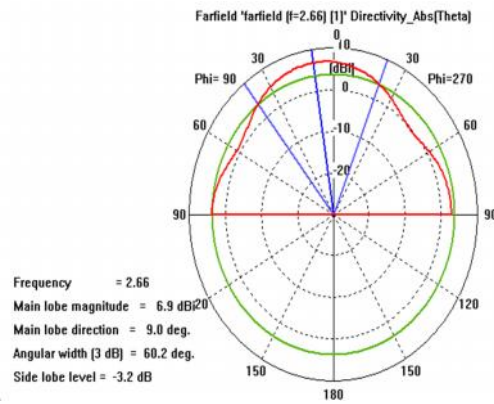
Figures 5.14(a), (b) and (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuth (H-plane) radiation patterns at the resonating frequency of 4 GHz.

These figures display that the intended antenna diverges almost in omni-directional nature. Moreover, the directivity of suggested antenna is 6.911 dBi and 7.404 dBi at the respective resonating frequencies of 2.66 GHz and 4 GHz.

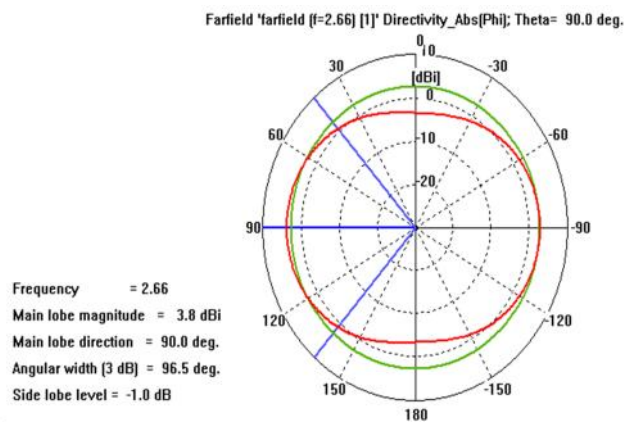
The utmost manageable gain across the whole frequency band is 6.85 dB.



(a)



(b)



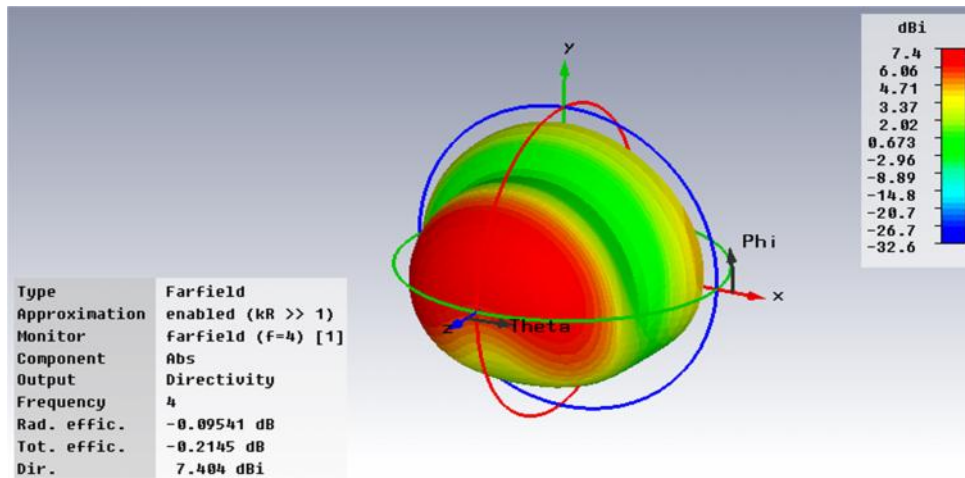
(c)

Figure 5.13: Radiation pattern of proposed patch antenna at 2.66 GHz

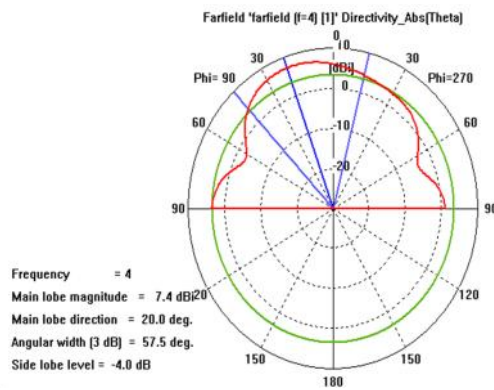
(a) 3-D plot (b) E-plane and (c) H-plane

CHAPTER-5

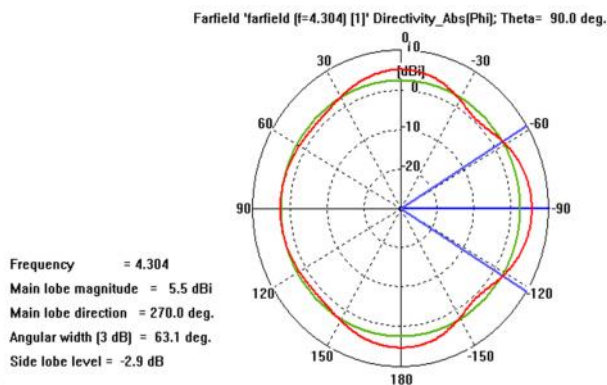
SIMULATION STUDIES OF SOME NEW MPAs



(a)



(b)



(c)

Figure 5.14: Radiation pattern of proposed patch antenna at 4 GHz

(a) 3-D plot (b) E-plane and (c) H-plane

5.3.4. Discussion

A novel wideband antenna was constructed by cutting a ϵ -shape slot under a Pi-shape slot in the patch that was fabricated on a substrate with relative permittivity 2.33 and thickness 8 mm. Furthermore, four circular slots were trimmed at the radiating edges of the patch for proper impedance matching and broadband operation. Co-axial feeding technique was used for this design as the main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. Moreover, this feed method has a low spurious radiation and is simple to fabricate. The proposed antenna design operates in two bands viz. band I (2.61 GHz to 2.72 GHz) and band II (3.4 GHz to 4.5 GHz) feasible for high speed wireless applications. The achieved impedance bandwidths of the proposed antenna with 10 dB down reflection coefficient are about 108 MHz and 1.14 GHz that correspond to 3.5 WiMAX and 3900-4400 MHz IMT frequency bands. The achievable gain is 6.54 dB and 7.17 dB with the corresponding reflection coefficients of -16.0 dB and -22.6 dB at band I (2.61 GHz to 2.72 GHz) and band II (3.4 GHz to 4.5 GHz) respectively. Stable and good radiation pattern results had been obtained across the entire operating frequency bands which seemed to be adequate for the envisaged or imagined applications. The impedance matching of the proposed antenna was achieved by conforming the feed point of the co-axial feeding structure. The wide impedance bandwidth for upper operating frequency reckons upon the size of distinct slots being cut into the patch. The proposed antenna was designed for WiMAX and IMT band applications, however, the present design idea could be protracted to other frequency bands of concern and involvement. With the simplicity of feeding, the investigated wide bandwidth antenna is a good candidate for fabrication to be used for many wireless communication applications. However, the size of MPA described here, is not very small because of the large size of ground plane. Further, the designed antenna is not so compact and thin because of the utilization of substrate material with thickness 8 mm that is quite big. A large amount of work is still in full swing to attain even improved outcomes with a good gain over a wide impedance bandwidth and a good axial ratio with better efficiency.

CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

5.4. Design IV - Design of Coaxial Fed Broadband Single Layer Rectangular MPA for WLAN/WiMAX Applications

In present work, a novel single layer co-axial fed E-shaped rectangular MPA with broadband characteristics for WLAN and WiMAX applications has been proposed. The suggested microstrip antenna has a planar geometry which consists of a ground, a substrate, a patch, and a feed. The optimization of antenna's parameters was conducted using in-built optimizer technique in transient solver window of CST-MWS V9.0. The suggested antenna has a frequency bandwidth of about 712 MHz (5.16-5.88 GHz) at -10 dB reflection coefficient that is adequate enough to make the antenna effective and usable for 5.2/5.8 GHz WLAN and 5.5 GHz WiMAX applications. The WLAN standard necessitates the antenna to cover 5.15-5.35 GHz and 5.725-5.825 GHz frequency bands and WiMAX postulates the antenna to cover 5.25-5.85 GHz frequency band. The utmost attainable gain across the whole frequency band is 5.5 dBi. A substrate of low dielectric constant is chosen to meet the demanding bandwidth specification and to incur a concise radiating structure. Moreover, reflection coefficient is below -10 dB with 50-ohm system impedance across the complete frequency band.

5.4.1. Introduction

Broadband antennas are accelerating in demand throughout modern trends for utilization in high-speed and high-frequency data communication applications. The design of an efficient, wideband, compact and high gain antenna, for diverse wireless application is a major challenge with an aim to enhance frequency bandwidth of antennas. MPAs have a wide scope of applications initiating from communication system field and stepping towards biomedical systems, because of their different irresistible and appealing features such as light weight, low-cost fabrication, small size, robustness, ease of installation and integration with feed networks, low profile, simplicity, conformability to planar and non-planar surfaces and ease of production [22]. However, despite of all these advantageous properties, two most critical restrictions of the MPAs are their limited bandwidth and degraded gain as these limit the range of frequencies across which the antenna can execute in a satisfactory manner. Poor radiation efficiency resulting from surface waves and spurious feed radiation, conductive and dielectric losses are also among their ill points. Furthermore, a compact antenna design degenerates or devolves these two parameters as there is a significant correlation among bandwidth, efficiency and size of antenna.

As antennas are made littler, either the operating bandwidth or antenna efficiency may be reduced. Moreover, small antennas typically yield lower gain than larger antennas. Hence, size reduction along with bandwidth and gain enhancement must be considered for designing microstrip antennas for wireless communication applications. In addition, a proper miniaturized antenna will ameliorate transmission and reception along with reduction of power consumption and improved marketability of the communication device. In present work, a single layer broadband E-shaped MPA for WLAN/WiMAX applications has been proposed. The suggested patch antenna has a frequency bandwidth of about 712 MHz (5.16-5.88 GHz) at -10 dB reflection coefficient with 50-ohm system impedance which is sufficient for developing antenna helpful for 5.5 GHz WiMAX and 5.2/5.8 GHz WLAN applications. Further, slots are being cut at the non-radiating edges of the upper arm and lower arm of conventional E-shaped patch which provide different resonances and better impedance matching for the entire working band of 5.16-5.88 GHz. The advantage of co-axial feeding technique used in present antenna is that it can be placed at any coveted location internal to the patch with an objective of proper matching with antenna's input impedance. This feed method is simple to manufacture and has reduced spurious radiation. Nevertheless, its primal defect is that it furnishes limited bandwidth and is troublesome to model as a hole has to be bored in the substrate and the connector projects outside the ground plane, therefore not making it entirely planar for thick substrates [1]. However, the bandwidth can be improved by various methods like adding slots into the patch, increasing the substrate height, decreasing ϵ_r of substrate [249], colligating several patch elements to build an antenna array [26], introducing a capacitive coupling among the ground plane and radiating element, altering the contour of radiating element and appending a shorting pin [228-230] [252-255]. Recently many micro strip patch antennas for different applications with coaxial-feed have been presented [231] [256-260].

5.4.2. Antenna Geometry

Figure 5.15 indicates the geometrical structure of proposed co-axial fed modified E-shaped MPA on CST-MWS V9.0 software for broadband operation covering 5.2/5.5/5.8 WLAN/WiMAX communication standards.

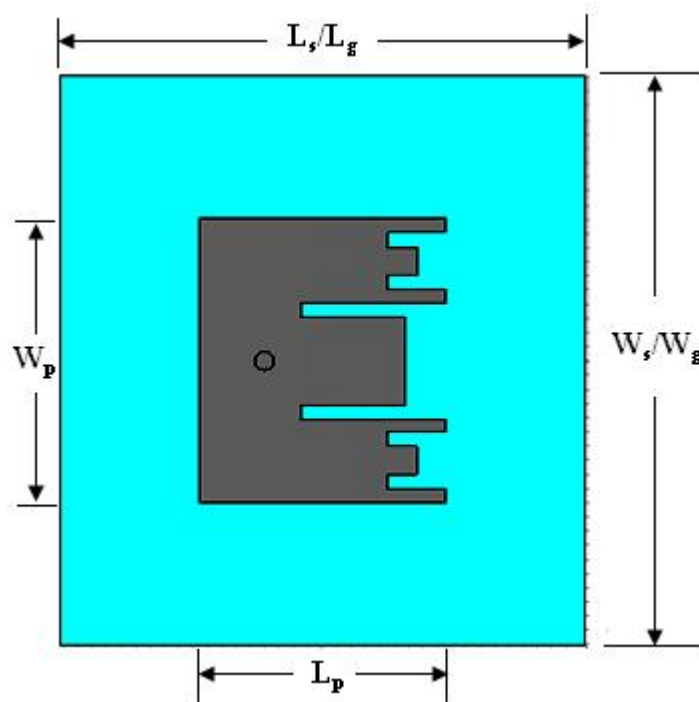


Figure 5.15: Geometry of proposed modified E-shaped patch antenna

The antenna is printed on printed circuit board where the patch length and width is 17.1 mm \times 20 mm. Radiating edges are the edges along the width and that along the length are called non-radiating edges. The substrate used has a dielectric constant of 2.2 with a loss tangent of 0.0009 and thickness of 3.2 mm. The height of the ground and the patch that are perfect electric conductors are 9.6 mm and 0.02 mm, respectively. The proposed antenna is excited by a co-axial cable, so the outer conductor (from bottom of ground to the lower level of substrate) is made of substrate's material and the inner conductor (from bottom of ground to top of patch) is made of perfect electric conductor material. The inner and outer radii of co-axial feed probe are 0.65 mm and 2.35 mm, respectively. It can be fed by employing different feeding techniques such as micro strip line feed, coaxial probe feed, aperture coupling, electromagnetic coupling, and coplanar waveguide. The feed point of the proposed antenna is (-4,0) where the best matching for a 50-ohm characteristic impedance is achieved. Proper impedance matching always yields the best desired result. The modified E-shaped patch with slots introduced in the upper and lower arm are used for ensuring frequency resonance from 5.16 to 5.88 GHz. Furthermore, perfect impedance matching, appreciable reflection coefficient and wide impedance bandwidth of 712

MHz is achieved. In-built optimization procedure has been followed for obtaining the perfect feed point location and appropriate dimensions for proposed antenna so as to get the best possible impedance match to the antenna. The optimized parameters that are used for designing the proposed antenna are: Substrate permittivity (ϵ_r) = 2.2, Thickness of substrate (h) = 3.2 mm, Length of patch (L_p) = 17.1 mm, Width of patch (W_p) = 20 mm, Length of ground (L_g) = 36.4 mm, Width of ground (W_g) = 40 mm.

5.4.3. Simulated Results

Reflection coefficient

The resonant characteristics (S_{11} parameters) for the suggested MPA have been depicted in Figure 5.16.

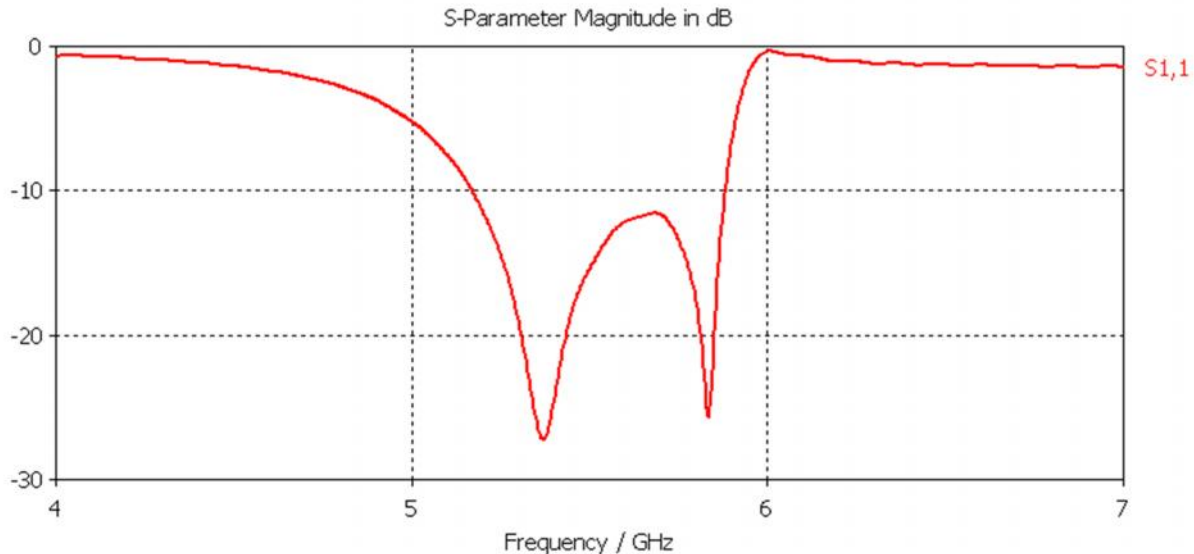


Figure 5.16: Simulated reflection coefficient of proposed antenna

S_{11} parameter basically gives the reflection coefficient at port 1, site for applying input to the micro strip patch antenna. It should be less than -10 dB for acceptable operation. The simulated impedance bandwidth of 712 MHz from 5.16 GHz to 5.88 GHz is accomplished at -10 dB reflection coefficient with VSWR less than 2, which yields a measure of wideband characteristic of MPA. The reflection coefficient that is achieved at resonant frequencies 5.37 GHz and 5.83 GHz is equal to -27.204 dB and -25.625 dB, respectively, suggesting a good impedance matching at frequency point below -10 dB region. The achieved value of reflection coefficient is small and frequency is close as much as necessary to the specified frequency band so as to

CHAPTER-5 SIMULATION STUDIES OF SOME NEW MPAs

satisfy both 5.2/5.8 GHz WLAN and 5.5 GHz WiMAX standards. The VSWR ratio is 1:1.08 which meets the required standards.

Radiation pattern

The radiation pattern of an antenna is clearly characterized as the comparative dispersion of radiated power which is associated with the spatial directional coordinates. These coordinates are expressed in terms of the azimuth angle and the elevation angle. Generally, it is a diagram of the radiated power from the antenna per unit solid angle or a pictorial representation of the relative field strength transmitted from or received by the antenna. It represents the angular/directional dependence of the strength of signal.

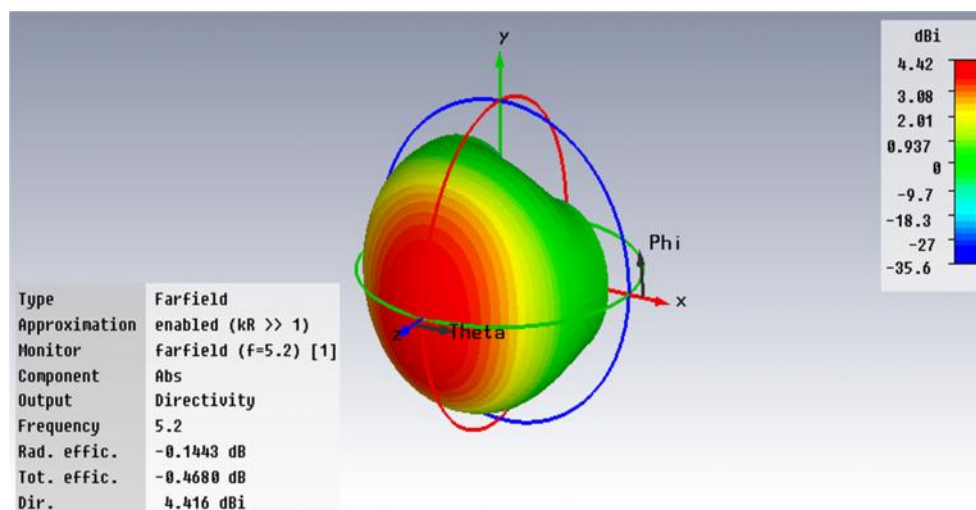
Figure 5.17(a), (b) & (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuthal (H-plane) radiation patterns at the resonating frequency of 5.2 GHz.

Figure 5.18(a), (b) & (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuthal (H-plane) radiation patterns at the resonating frequency of 5.5 GHz.

Figure 5.19(a), (b) & (c) demonstrate the simulated 3-D, elevation (E-plane) and azimuthal (H-plane) radiation patterns at the resonating frequency of 5.8 GHz.

These figures display that the intended antenna radiates nearly in omni-directional nature. Moreover, the directivity of suggested antenna is 4.416 dBi, 4.938 dBi and 5.793 dBi at the respective resonating frequencies of 5.2 GHz, 5.5 GHz and 5.8 GHz.

The utmost attainable gain across the whole frequency band is 5.541 dB which is quite appreciable for microstrip antennas.



(a)

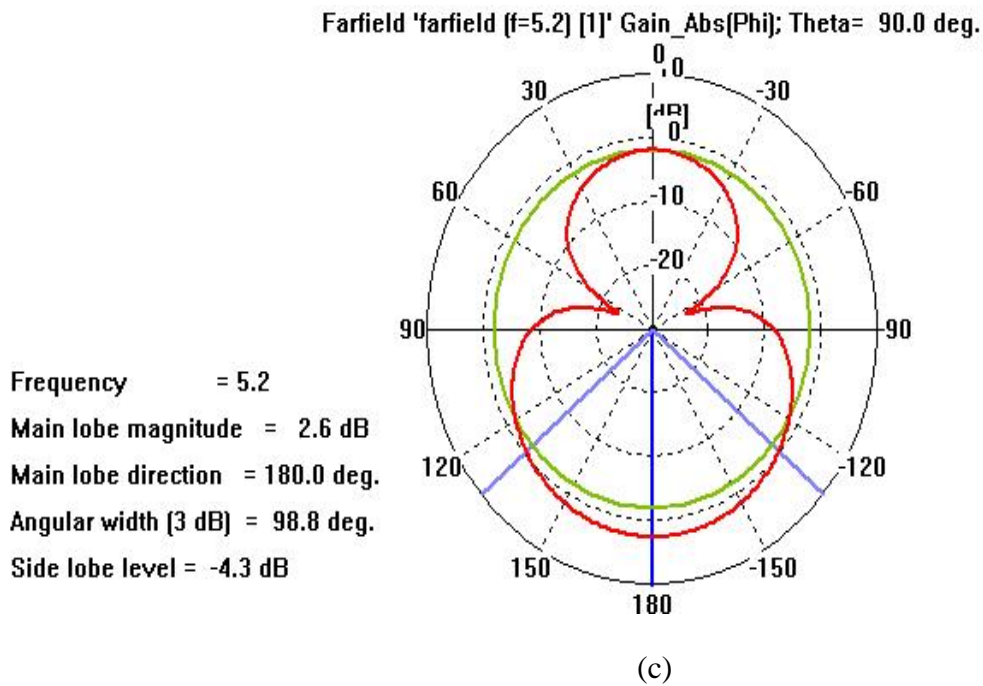
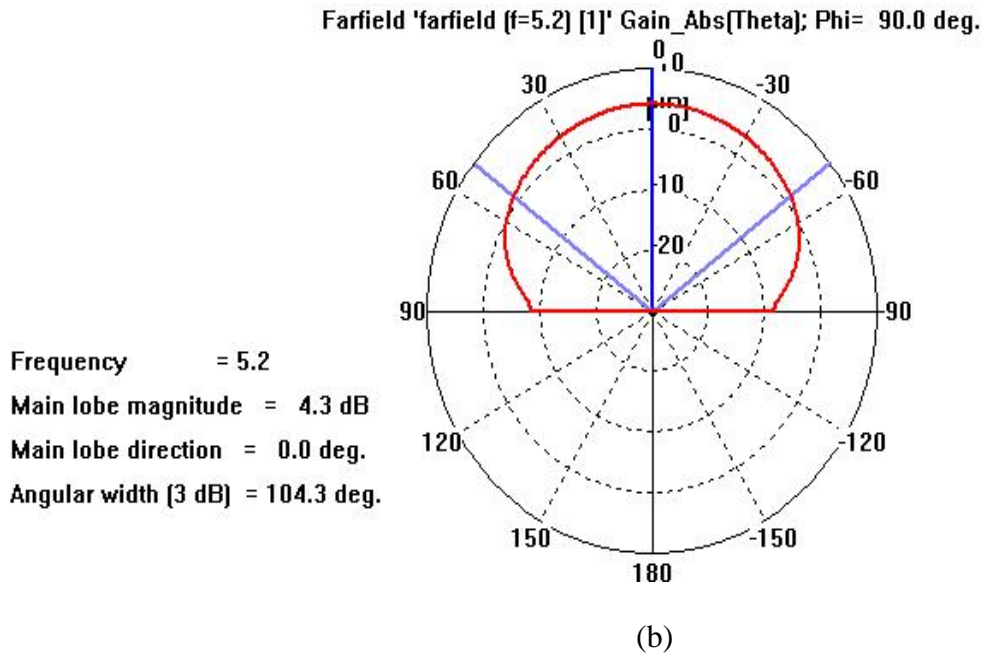
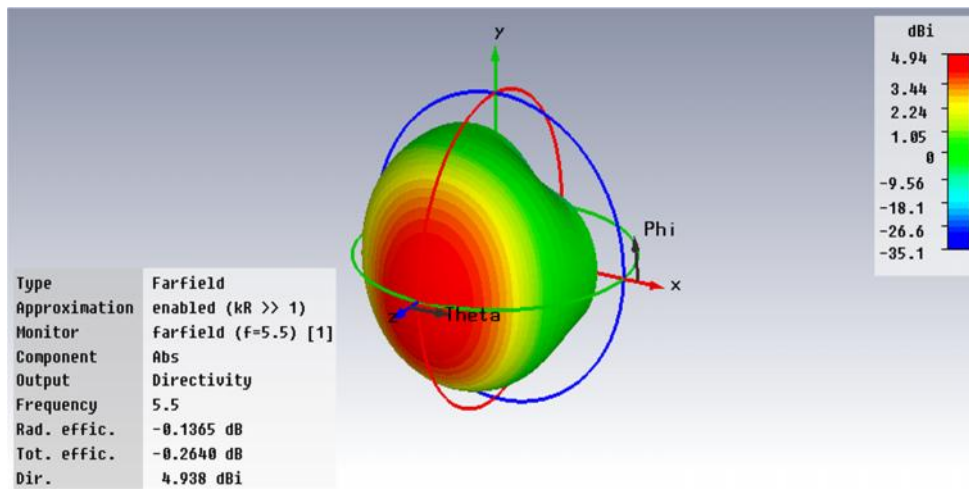


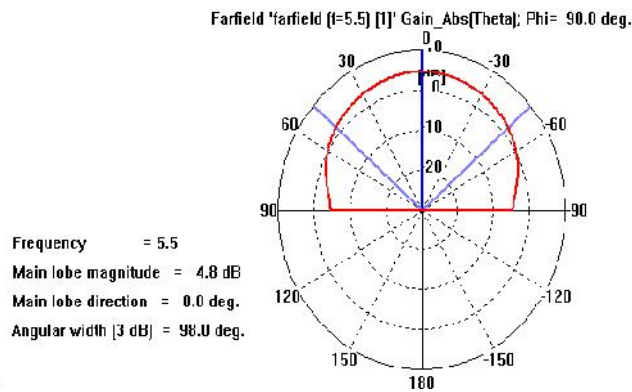
Figure 5.17: Radiation pattern of proposed patch antenna at 5.2 GHz

(a) 3-D plot (b) E-plane and (c) H-plane

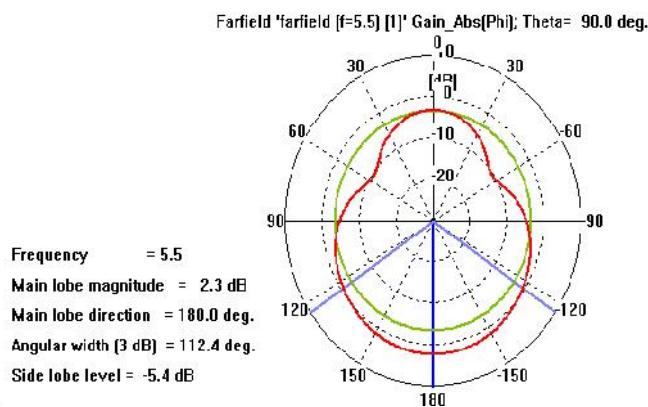
CHAPTER-5 SIMULATION STUDIES OF SOME NEW MPAs



(a)



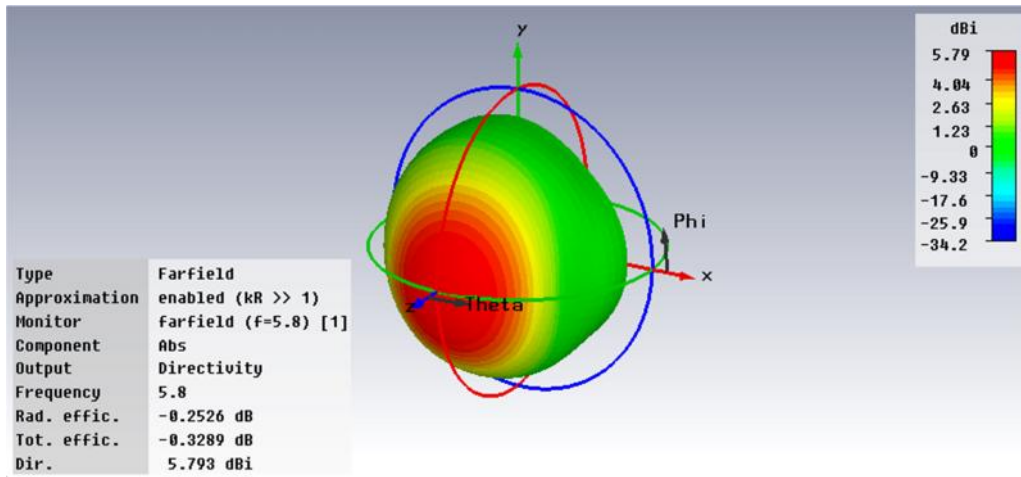
(b)



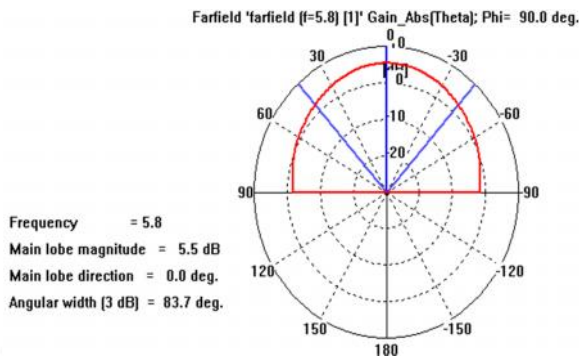
(c)

Figure 5.18: Radiation pattern of proposed patch antenna at 5.5 GHz

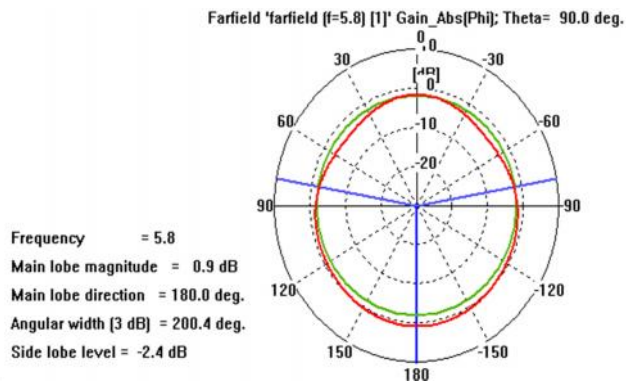
(a) 3-D plot (b) E-plane and (c) H-plane



(a)



(b)



(c)

Figure 5.19: Radiation pattern of proposed patch antenna at 5.8 GHz

(a) 3-D plot (b) E-plane and (c) H-plane

CHAPTER-5

SIMULATION STUDIES OF SOME NEW MPAs

5.4.4. Discussion

A compact single layer modified E-shaped broadband MPA suitable for WLAN/WiMAX applications is proposed. Cutting slots at the non-radiating edges of the upper arm and lower arm of conventional E-shaped patch, different resonances and better impedance matching for the entire working band of 5.16-5.88 GHz is achieved. Various parameters such as reflection coefficient, radiation pattern, gain, radiation efficiency, and their performance are also studied. The parametric study shows important and remarkable effects on the impedance bandwidth of the suggested antenna. Gain performance of antenna is satisfactory at all frequency bands. The reflection coefficient was found below -10 dB from 5.16 GHz to 5.88 GHz covering WLAN and WiMAX communication standards. The simulated impedance bandwidth of the proposed antenna design was around 712 MHz indicating wideband behavior. Performance of the intended antenna was found to be more than meeting the demanding bandwidth specification of 600 MHz for covering the 5.15-5.825 GHz frequency band. Moreover, the antenna is compact and thin with the use of low dielectric constant substrate material. These features are very helpful for worldwide portability of wireless communication equipment. This detailed parametric study provides guidance on the design and optimization of modified E-shaped MPA. The antenna gives a stable radiation performance with gain more than 5.5 dB over the entire frequency band with a good impedance matching of 52.2415 Ω . An omni-directional radiation pattern result has been obtained which is sufficient for imagined applications. Furthermore, the suggested antenna has several advantages, such as small size, easy feed mechanism, excellent radiation pattern performance, higher gain and good efficiency. These characteristics are very fascinating for some wireless communication systems. Even though this antenna has been designed for WLAN and WiMAX applications, the present design idea can be expended to other frequency bands of concern or involvement.

Chapter 6
Conclusions
& Future Scope
of Work

6.1. Conclusions

The work delineated in this thesis was actuated by the progressing and accelerating demand for low cost, small size, wideband and multi-frequency operational antennas to support the exponentially growing market of mobile communications and the general tendency of orientation is likely to proceed, primarily due to the mechanical features and ease of fabrication of microstrip antennas. Development and research in recent years have been focused on improving electrical characteristics of microstrip antennas, primarily increasing the bandwidth and developing more efficient feeding techniques. Further, the fast growth and refinements occurring in the wireless communication industry necessitate new extremely small designs that can be utilized in more than one frequency band. The simulator/software used in our thesis work for the designing of multi-frequency wideband microstrip patch antennas is CST Microwave Studio V9.0. It is based on the FIT that is a spatial discretization scheme to numerically resolve and figure out electromagnetic field problems in frequency and time domain. This method covers the entire range of electromagnetic and optic applications.

The succeeding or next job was to review the state-of-art in dual band and multiband resonant microstrip antenna design. This was not a simple job to accomplish due to the tremendous quantity of literature procurable and because novel or adapted techniques were being described sporadically during the course of this study. Furthermore, regardless of the large number of microstrip antenna design techniques described, it was realizable to group them in terms of the electrical principle which gives best description of the structure. This technique of classification turned out to be very effective in interpreting the physical operation of a given structure.

Because of the increasing demand in short span of time, the dual-band or multi-band operational antennas have incurred great interest for applications regarding multimode communication systems. These antennas are absolutely necessary for incorporating more than one communication standards in a single concise system to efficaciously boost the quality of being light enough to be carried of a modern personal communication system. Keeping in mind such an enduring field, thesis research work has been done to find novel designs so as to get multi-frequency wideband behavior of microstrip patch antennas.

So, the next step was to search some novel structures of microstrip antennas that fulfill all the design aims of antennas to be used for next generation wireless networks i.e. perfect impedance

CHAPTER-6

CONCLUSIONS AND FUTURE SCOPE OF WORK

matching, increased gain, wide bandwidth, improved reflection coefficient, increased frequency ratio, reasonable antenna size and, of course multi-frequency operation. The detailed contributions of the thesis are as follows:

Chapter 1 is an actual dosage for the motivation of the thesis. A very general introduction to antennas has been presented highlighting the need of investigations for low profile multi-frequency wideband microstrip patch antennas. The problem statement, research objectives, scope and entire methodology for conducting the necessary has been discussed. Some novel design techniques for producing multi-frequency operation of MPAs are identified as the main goal of the thesis.

Chapter 2 provides the basic introduction to structure of MPAs. The background history of MPAs is reviewed. The radiation mechanism and various analysis techniques are discussed. The design parameters of antennas in general are discussed. A point wise list of advantages and disadvantages of MPAs has been provided. Various feeding techniques are studied with relevant diagrams; however, the microstrip line feeding technique is used for most of the designs described in this thesis. A table showing the comparison of different feeding techniques in terms of their performance characteristics is also given. The applications areas of MPAs have been discussed as well. A great emphasis has been given to discuss the need for MPAs with multi-frequency behavior. Various techniques of obtaining multi-frequency behavior for MPAs have been reviewed. In the last, a brief summary of recent developments or latest research work done in MPAs with multi-frequency behavior has been presented and discussed.

Chapter 3 presents the dual band operation of a multistrip monopole antenna which could be suitable to cover IMT/WLAN/ISM/BLUETOOTH/SATELLITE/WiMAX/WLAN/ITS frequency bands. The monopole antenna fed by a cross-shaped stripline comprising one vertical and two horizontal strips was responsible for the resonance at 5.4 GHz and a notable DGS created a resonance at 2.385 GHz. The fabricated prototype upon measurement shows reasonable impedance bandwidths of around 200 MHz (2.3-2.54 GHz) and 590 MHz (5.26-5.85 GHz) in two operating bands which actually exceed the requirements of any WLAN/WiMAX application. Thus, in the present study it was observed that using such a new technique of incorporating a multistrip patch and DGS in antenna design, two distinct operating bands with an impedance bandwidth of 10% from 2.3 to 2.54 GHz and a bandwidth of 11% from 5.26 to 5.85 GHz could

be achieved. Also, appreciable gain and radiation characteristics have been observed over the entire operating range. Hence, the proposed design can be easily integrated to microwave circuits and compatible with MMIC technology for practical applications.

Chapter 4 presents a triple-band O-shaped MPA which could be used for multiple frequency bands simultaneously covering WLAN/Bluetooth/ISM/WiMAX/IMT/ITS/Satellite communication standards. A strip coupled on the right side of patch was responsible for a band rejected characteristic at the higher frequency of 5.12 GHz. An inverted L-slot and two rectangular slits of different lengths were also etched in ground plane. The longer slit was responsible for a notched band at lower frequency of 2.8 GHz and the shorter slit enlarged the impedance bandwidth of middle band from 429 MHz to 1.07 GHz during simulation. Both the strip coupled on the patch and two unequal slits etched in ground are responsible for rejection of the interfering bands in selected frequency regions. The measured impedance bandwidths of the fabricated antenna structure were found to be 510 MHz (2.35-2.86 GHz), 1.3 GHz (3.0-4.3 GHz) and 1.21 GHz (5.64-6.85 GHz) in three resonating bands, respectively that is clearly more than bandwidth required for WLAN/WiMAX standards. Therefore, in the present study it was observed that using a new technique of incorporating a strip on the right side of O-shaped MPA and an inverted L-slot with two unequal slits in ground, three different resonating bands having bandwidths of 20% from 2.35 to 2.86 GHz, 37% from 3.0 to 4.3 GHz, and 19% from 5.62 to 6.21 GHz, respectively, were obtained. Also, gain performance and radiation pattern characteristics are acceptable at all the three resonating frequency bands. Hence, the proposed triple-band antenna design can be used successfully in microwave and millimeter-wave integrated circuits for practical purposes and can be used for commercial wireless applications after being patented.

Chapter 5 presents four more antenna configurations that are designed and simulated using CST MWS V9.0 based on FIT with perfect boundary approximation. Design I presents a novel rectangular microstrip patch antenna with broadband behavior for WLAN and WiMAX applications. The suggested antenna has a frequency bandwidth of approximately 885 MHz (4.969-5.854GHz) at -10 dB reflection coefficient that is quite adequate to stimulate the antenna effectual for 5.2/5.5/5.8 GHz WLAN and 5.5 GHz WiMAX operation. The broadband multi-standard behavior so obtained is due to the pi-shape slot embedded into the ground. This

CHAPTER-6

CONCLUSIONS AND FUTURE SCOPE OF WORK

designed antenna has one more band below -10 dB ranging from 6.19-6.562 GHz which is feasible for satellite applications covering a bandwidth of 372 MHz. The greatest possible realizable gain over the whole frequency band is 4.7 dBi. Design II presents a novel compact microstrip patch antenna comprising two horizontal modified E-shape slots fed by a co-planar waveguide. In this design structure, both the slotted patch and symmetrical ground planes are embedded in the same plane. This suggested microstrip antenna design is susceptible of rendering three different operating bands with -10 dB reflection coefficient viz. 2.40-2.58 GHz, 3.4-4.26 GHz and 4.63-7.30 GHz with a satisfactory respective bandwidths of 180 MHz, 860 MHz and 2.67 GHz. Apparently, the accomplished impedance bandwidths are sufficient to cover the necessary bandwidths of several communication standards viz. WLAN/Wi-Fi/WiMAX/IMT/AMSAT/Satellite communication. Design III presents a single layer, single co-axial feed, small size and wideband rectangular microstrip patch antenna. The suggested antenna utilizes an easy co-axial feeding technique and is manufactured by integrating a T-shape slot beneath a pi-shape slot. Furthermore, in order to obtain wideband operation to cover both WiMAX (3400MHz-3690MHz) & IMT (3900MHz-4400MHz) communication standards, four circular slots have been trimmed into the radiating edges of patch for wideband operation. Fundamentally, these circular slots trimmed at corners efficaciously activate multi-resonant behavior in concert with acceptable impedance bandwidth. In order to widen the bandwidth for covering the whole frequency range of WiMAX and IMT communication standards, a thick substrate is used. The suggested slot loaded patch antenna resonates at a frequency of 2.66 GHz and has a wideband from 3.42-4.56 GHz with the accompanying bandwidth of 108 MHz and 1.14 GHz and reflection coefficients of -16.0 dB and -22.6 dB respectively. A steady radiation performance with gain greater than 7 dBi over the entire broadband has been achieved by this proposed antenna. Design IV demonstrates a novel co-axial fed, single layer E-shape rectangular microstrip patch antenna having planar geometry and wideband operational characteristics for WLAN and WiMAX applications. The suggested antenna has a frequency bandwidth of approximately 712 MHz (5.16-5.88 GHz) at -10 dB reflection coefficient that is large enough to cause the antenna helpful for 5.5 GHz WiMAX and 5.2/5.8 GHz WLAN operation. The utmost realizable gain across the whole frequency band is 5.5 dBi.

In conclusion, this thesis has met the objective of obtaining multi-frequency wideband microstrip patch antennas with increased gain, enhanced impedance bandwidth and appreciable reflection coefficient characteristics. In fact, this thesis has provided a sense of achievement as a significant amount of work has been accomplished. However, there are still important areas that require further work and some of them will be illustrated in the next section.

6.2. Future Scope

Some important areas that require attention may be suitably inquired into for the future scope of this work to get more deep feeling of understanding into the multi-frequency microstrip antennas covering various applications. They include greatly reduced scale of the antenna element without the loss of efficiency, since nowadays, the entire apparatus is getting more and more reduced to the smallest possible size in order to incorporate antennas within least possible space, thus needs further research work. Making the electromagnetic energy absorption by the user's head insignificant can be another remarkable field of study, as there may be health hazards, if the user's head is confined by a strong electromagnetic energy on all sides for a long time. The antennas designed and discussed in chapters three, four and five can be further optimized. This can possibly be done by using different thicknesses/dielectric constants for the substrate, or patches with different dimensions. Also, an external network can be integrated into the circuit, achieving even more bands. The utilization of defected ground structures shows extraordinary and fantastic inherent capability for designing antennas for various applications. Still, a large number of DGS geometries exist whose secret and concealed capacity is yet to be ascertained. The analysis of DGS for finding the resonant behavior from its dimensions from the analytical or soft-computing techniques can be carried out for the ease in integration of DGS with the antennas. It is found that more than 60% size reduction of the antenna with the DGS can be achieved by doing modifications in the slot that is located in the ground plane. As antenna size is a matter of concern, investigations for the various DGS slots and their proper frequency behavior is an interesting future problem. The use of specific DGS in the specific antenna geometry with various feeding techniques is also an area of future work. The DGS has been examined scientifically for dual band/multiband/multi-frequency operations in the antennas. In addition, a numerical and unquestionable model can also be formulated for a specific DGS structure for particular application of antennas. Perhaps, an orderly arrangement of DGSs in the ground plane

CHAPTER-6

CONCLUSIONS AND FUTURE SCOPE OF WORK

of antenna can be a fascinating and stimulating subject for the research scholars. The conduct of DGS may also be useful for the ultra wideband antennas for notch applications. In our thesis work, antennas have been optimized by using in-built optimizers available in transient solver window of CST Microwave Studio V9.0. Still, there is a scope to explore the full potential of various soft-computing techniques like Particle Swarm Optimization, Bacterial Foraging, Genetic Algorithms and Artificial Neural Network etc. Further, incurring broader bandwidth using a thick substrate and tunable bandwidth for each frequency band can be inquired into as a future work. The inclusion of Split Ring Resonators (SRR) in the patch and DGS in the ground plane may be a new topic for researchers because use of SRR will increase the gain and reduce the size and DGS will increase the bandwidth. Photonic Band gap (PBG) Structures generally known as Electromagnetic Band Gap (EBG) structures can also be compared with Defected Ground Structure (DGS) in a particular antenna geometry in terms of improved performance issues. Mathematical modeling of all the designed antennas in chapters three, four and five can be a future topic of investigation. Modifications can be incorporated to realize various multi-frequency microstrip antennas with increased gain, compact size and improved radiation characteristics. Also, microstrip antennas can be further extended for satisfying biomedical applications as well.

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*Author's
Publications*

Papers in SCI Journals

- Jaswinder Kaur, Rajesh Khanna and M.V. Kartikeyan, "Novel Dual Band Microstrip Monopole Antenna with Defected Ground Structure for WLAN/IMT/Bluetooth/WiMAX Applications", International Journal of Microwave and Wireless Technologies, vol. 6, iss. 1, pp. 93-100, February 2014.
- Jaswinder Kaur, Rajesh Khanna and M.V. Kartikeyan, "Optimization and Development of O-Shape Triple band Microstrip Patch Antenna for Wireless Communication Applications", IETE Journal of Research, vol. 60, no. 2, pp. 95-105, April 2014.

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Presentations at National Conferences

- Presented paper at International Conference on Science and Engineering of Materials held at Sharda University, Greater Noida on Jan 6-8, 2014 titled "FR-4 Based Novel Optimized Design of a Dual Band Microstrip Patch Antenna for WLAN/WiMAX/AMSAT/WAVE Applications" authored by Jaswinder Kaur, Rajesh Khanna and M.V. Kartikeyan.
- Presented paper at National Conference on Microwave 2012 held at Jaipur on July 30-August 1, 2012 titled "Design of a Multi-Frequency Wideband Microstrip Patch Antenna for 5.2/5.5/5.8 GHz Wireless Applications" authored by Jaswinder Kaur, M.V. Kartikeyan and Rajesh Khanna.

AUTHOR'S PUBLICATIONS

Research Papers under writing process

- Jaswinder Kaur, Rajesh Khanna and M.V. Kartikeyan, “CPW fed novel compact L-S shape Multiband Microstrip Antenna for wireless applications” in writing process since February 2014, fabrication has been done for this proposed antenna.
- Jaswinder Kaur, Rajesh Khanna and M.V. Kartikeyan, “Novel CPW fed E-G shaped Multiband Microstrip Antenna” in writing process since February 2014, fabrication has been done for this proposed antenna.
- Jaswinder Kaur, Rajesh Khanna and M.V. Kartikeyan, “Design of a U-shape microstrip monopole antenna modified with a staircase pattern with Defected Ground Structure (DGS)”, in writing process, experimental work to be done yet.
- Jaswinder Kaur and Rajesh Khanna, “Design of a Broadband Microstrip Monopole Antenna with reduced ground structure for wireless communication”, in writing process, experimental work to be done yet.

Vita

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RESEARCH PAPER

Novel dual-band multistrip monopole antenna with defected ground structure for WLAN/IMT/BLUETOOTH/WIMAX applications

JASWINDER KAUR¹, RAJESH KHANNA¹ AND MACHAVARAM KARTIKEYAN²

In the present work, a novel multistrip monopole antenna fed by a cross-shaped stripline comprising one vertical and two horizontal strips has been proposed for wireless local area network (WLAN)/Industrial, Scientific, and Medical band (ISM)/International Mobile Telecommunication (IMT)/BLUETOOTH/Worldwide Interoperability for Microwave Access (WiMAX) applications. The designed antenna has a small overall size of $20 \times 30 \text{ mm}^2$. The goal of this paper is to use defected ground structure (DGS) in the proposed antenna design to achieve dual-band operation with appreciable impedance bandwidth at the two operating modes satisfying several communication standards simultaneously. The antenna was simulated using Computer Simulation Technology Microwave Studio (CST MWS) V9 based on the finite integration technique (FIT) with perfect boundary approximation. Finally, the proposed antenna was fabricated and some performance parameters were measured to validate against simulation results. The design procedure, parametric analysis, simulation results along with measurements for this multistrip monopole antenna using DGS operating simultaneously at WLAN (2.4/5.8 GHz), IMT (2.35 GHz), BLUETOOTH (2.45 GHz), and WiMAX (5.5 GHz) are presented.

Keywords: Multistrip, Monopole antenna, Dual band, Defected ground structure (DGS), WLAN/IMT/BLUETOOTH/WiMAX, CST MWS V9

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1. INTRODUCTION

The rapid developments in the wireless communications industry demand novel micro designs that can be used in more than one frequency band. The most widely used antenna on existing mobile telecommunication applications is probably the standard monopole antenna [1]. In recent years, the dual-band or multi-band antennas have received much attention for applications to multimode communication systems as these antennas are vital for integrating more than one communication standards in a single compact system to effectively promote the portability of a modern personal communication system [2, 3]. The currently popular antenna designs suitable for the applications of wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) have been reported [4–9]. The traditional monopole antenna is inherently a narrow-band structure. To enhance the impedance bandwidth, the

monopole with different shapes is used. As reported in [10], a simple microstrip stub served as the impedance matching element and provided around 13% bandwidth enhancement when compared with the traditional design. To realize much wider bandwidth, additional stub could be added but the feedline becomes lengthy. In order to achieve multi-band operation, the traditional approach is to use multi-resonator elements [11], which generally leads to a large volume [12–14], or requires a large ground-plane [15]. In [4], Kuo *et al.* proposed a dual-band double T-monopole antenna, which achieves a certain miniaturization factor but with a narrow bandwidth at the upper WLAN band.

In the present work, we proposed a new technique for enhancing the impedance bandwidth of a multi-frequency dual-band microstrip patch antenna. The proposed antenna employs a multistrip-based geometry fed by a cross-shaped stripline comprising one vertical and two horizontal strips and a notable ground structure named defected ground structure (DGS). Defected ground structures or slotted ground planes have been used to provide multi-band performance in handset antennas [16–20]. The usage of DGS with double microstrip stub feedline for size reduction, bandwidth enhancement, and resonance mode increment has not been addressed for antenna's application yet. Parametric analysis and optimization of the design parameters of proposed

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Optimization and Development of O-shaped Triple-band Microstrip Patch Antenna for Wireless Communication Applications

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Optimization and Development of O-shaped Triple-band Microstrip Patch Antenna for Wireless Communication Applications

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ABSTRACT

In this work, a triple-band patch antenna for wireless communication applications has been proposed. For designing an antenna with suitable resonance characteristics to cover many frequency bands simultaneously, a strip is coupled on the right side of an O-shaped patch element and ground plane has been modified with an inverted L-slot and two unequal slits. The proposed design resonates in three different bands, viz. 2.35–2.86, 3.0–4.3, and 5.64–6.85 GHz with respective bandwidths of 510 MHz, 1.3 GHz, and 1.21 GHz. Obviously, the achieved bands are suitable to cover wireless local area network/industrial, scientific and medical band, Bluetooth, Globalstar satellite phone uplink, worldwide interoperability for microwave access, International Mobile Telecommunication, intelligent transport systems, and satellite communication. The overall size of the proposed antenna is $35 \times 30 \text{ mm}^2$. The fabrication and measurement of parameters of proposed structure was carried out to verify the simulated results. Finally, complete geometrical method for the design of O-shaped microstrip patch antenna with modified ground plane is presented.

Keywords:

Microstrip patch antenna, Triple-band, O-shaped patch, CST MWS V9.0, Wireless communication.

1. INTRODUCTION

In electromagnetic history, the microstrip patch antenna (MPA) design is gaining interest due to its advantages such as low fabrication and production cost, conformal nature, compact size and low weight, ease of integration with other devices, and remarkably good radiation characteristics. The geometry and substrate characteristics of the MPA control its operation and performance [1,2]. The integration of various communication standards into one antenna is gaining hot demand for portable wireless communication device. Therefore, a multiband antenna operating at different frequency bands is an attractive and a useful feature, as it avoids the use of multiple antennas. Many promising dual and multiband planar antenna designs have been studied and investigated suitable for wireless local area network/worldwide interoperability for microwave access (WLAN/WiMAX) operation. Printed double-T monopole [3], G-shape monopole [4], multistrip monopole [5], and complementary Sierpinski gasket fractal antenna [6] were used to generate two resonances for dual-band applications. Some tri-band and quad-band multifrequency antennas like meander monopole [7], monopole using defected ground structure [8], compact size triple-band antenna [9], Coplanar Waveguide (CPW)-fed miniature slotted multifrequency wideband

MPA [10], Y-shape monopole [11], triangle-shape monopole [12], composite meta-material resonators [13], a flower-like monopole [14], a fractal monopole [15], a parasitic C-shape strip [16], multifrequency wideband [17], and co-axial-fed MPA with Pi slot under T-slot [18] have been reported in the literature. All these reported antennas are having good multiband characteristics but large size or complicated structure restricts their applicability. A wide open U-slot antenna with a pair of symmetrical L-strips [19], triple-band open L-slot antenna with a slit and a strip [20], non-symmetric ground $\lambda/4$ open slot antenna [21], broadband single-layer rectangular MPA [22], and band-rejected design of the printed open slot antenna [23] have been reported for wideband applications. To cover the ultrawide band frequency range, a bandwidth enhancement scheme was applied to improve the limited operation band greatly but unfortunately, this novel broadband antenna had higher cost as it used a filter to reject the undesired bands [24].

In the present work, we propose a compact triple-band microstrip-fed O-shaped patch antenna for wireless applications. The patch antenna is simply constructed by coupling a strip on the right side of the resonator and by etching an inverted L-slot and two slits of different lengths in the ground plane. The design approach is

Co-axial Fed Rectangular Microstrip Patch Antenna for 5.2 GHz WLAN Application

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Abstract In this paper, the design of a co-axial fed single layer microstrip patch antenna (MSA) for 5.2 GHz WLAN application is presented. The impedance matching and the radiation characteristics of this proposed structure are studied and analyzed using Computer Simulation Technology (CST) Microwave Studio, which is a commercially available electromagnetic simulator based on the method of finite difference time domain technique to achieve the desired specification. The proposed antenna based on co-axial feed configuration has the maximum achievable bandwidth obtained about 219.2 MHz (5.14-5.36 GHz) at -10 dB reflection coefficient which corresponds to WLAN 5.2 GHz frequency band and the maximum achievable gain is 5.208 dB. Stable radiation characteristics are obtained across the frequency band.

Keywords WLAN, Impedance Bandwidth, Co-Axial Fed, Microstrip Patch Antenna (MSA), CST Microwave Studio

1. Introduction

The growth of wireless systems and booming demand for a variety of new wireless applications such as WLAN (Wireless Local Area Network), it is important to design broadband and high gain antennas to cover a wide frequency range. The design of an efficient wide band small size antenna, for recent wireless applications, is a major challenge. In applications like high performance aircraft, satellite, missile, mobile radio and wireless communications small size, low-cost fabrication, low profile, conformability and ease of installation and integration with feed networks are the main constraints. Also, with advancement of the technology, the requirement of an antenna to resonate at more than one frequency i.e. multi-banding is also increasing day by day. Here microstrip patch antenna is the best choice to fulfill all the above requirements. Along with that a microstrip patch antenna offers many advantages above other conventional antennas like low fabrication cost,

supports both, linear as well as circular polarization etc. Microstrip patch antenna have some disadvantages also like surface wave excitation, narrow bandwidth etc. But bandwidth of a microstrip patch antenna can be improved by various methods like cutting U-slot [1], increasing the substrate height, decreasing ϵ_r of substrate etc. Antenna array can also be used to improve the bandwidth [2].

Here, to start with, a simple microstrip patch antenna with coaxial feed is designed [3-4]. In this feeding technique, the inner conductor of the coaxial connector extends from ground through the substrate and is soldered to the radiating patch, while the outer conductor extends from ground up to substrate. The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to properly match with its input impedance. This feed method is easy to fabricate and has low spurious radiation. However, its major drawback is that it provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate and the connector protrudes outside the ground plane, thus not making it completely planar for thick substrates. But the bandwidth can be improved by various methods written above. Recently many microstrip patch antenna for different applications with coaxial-feed have been presented [5-8]. Figure 1 shows the co-axial feeding technique. Further, the details of the proposed design performance are presented and discussed.



Figure 1. Co-axial feeding technique

2. Antenna Design

Figure 2 shows the geometry of proposed coaxial fed microstrip patch antenna with single band operation for WLAN application. The antenna is excited by coaxial feed

Design of Co-Axial Fed Broadband Single Layer Rectangular Microstrip Patch Antenna for Wireless Applications

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ABSTRACT

In present work, a novel co-axial fed single layer E-shaped rectangular micro strip patch antenna with broadband behavior for wireless local area network (WLAN) and world-wide interoperability for microwave access (Wi-MAX) applications is proposed. The micro strip antenna has a planar geometry that consists of a ground, a substrate, a patch, and a feed. The basic theory about the proposed structural design, impedance matching, and the radiation characteristics are studied and analyzed using method of finite difference time domain technique. Simulation was conducted using computer simulation technology microwave studio software for optimization of antenna's properties. The proposed antenna has a frequency bandwidth of about 712 MHz (5.16-5.88 GHz) at -10 dB return loss which is sufficient to make the antenna useful for 5.2/5.8 GHz WLAN and 5.5 GHz Wi-MAX application. The WLAN standard requires the antenna to cover 5.15-5.35 GHz and 5.725-5.825 GHz frequency bands and Wi-MAX requires the antenna to cover 5.25-5.85 GHz frequency band. Maximum achievable gain over the entire frequency band is 5.5 dBi. To meet the demanding bandwidth specification, a substrate of low dielectric constant is selected to obtain a compact radiating structure. Furthermore, reflection coefficient is below -10 dB over the entire frequency band at the input of the optimized E-shaped micro strip patch antenna with $50\text{-}\Omega$ system impedance.

Key words: Broadband, co-axial fed antenna, E-shaped patch, micro strip antenna, wireless local area network, worldwide interoperability for microwave access

I. INTRODUCTION

During recent trends, broadband antennas are increasing in demand for use in high-frequency and high-speed data communication applications. The design of an efficient, wideband, compact and high gain antenna, for diverse wireless application is a major challenge with an aim to enhance frequency bandwidth of antennas. Micro strip patch antennas are used in a broad range of applications from communication systems to biomedical devices, because of some attractive properties such as small size, low-cost fabrication, low-profile, robustness, simplicity, light weight, ease of production, conformability, ease of installation, and integration with feed networks. However, despite these advantageous properties, some limitations of micro strip antennas such as low-gain and narrow bandwidth are to be addressed for satisfactory performance of antennas. Moreover, poor radiation efficiency resulting from surface waves and spurious feed radiation, conductive, and dielectric losses should also be checked. The compact antenna configuration further, deteriorates these two parameters as there is a fundamental relationship between size, bandwidth, and efficiency of an antenna. As antennas are made smaller, either the operating bandwidth or antenna efficiency may be decreased. Moreover, small antennas typically provide lower gain than larger antennas. Therefore, size reduction along with gain and bandwidth enhancement must be considered for designing micro strip antennas

for wireless communication applications. Furthermore, proper miniaturized antenna will improve transmission and reception alongside reduction of power consumption, and improved marketability of the communication device. The present work was aimed at designing and simulating single layer broadband micro strip patch antenna (E-shaped) using computer simulation technology (CST) microwave studio for wireless local area network (WLAN)/worldwide interoperability for microwave access (Wi-MAX) applications. The proposed patch antenna has a frequency bandwidth of about 712 MHz (5.16-5.88 GHz) at -10 dB return loss with $50\text{-}\Omega$ system impedance which is sufficient for developing antenna useful for 5.2/5.8 GHz WLAN and 5.5 GHz Wi-MAX applications. Further, slots are being cut at the non-radiating edges of the upper arm and lower arm of conventional E-shaped patch which provide different resonances and better impedance matching for the entire working band of 5.16-5.88 GHz. In this feeding technique, the inner conductor of the co-axial connector extends from ground through the substrate and is soldered to the radiating patch, while the outer conductor extends from ground up to substrate. The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to properly match with its input impedance. This feed method is easy to fabricate and has low spurious radiation. However, its major shortcoming is that it provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate and the connector protrudes outside the ground plane, thus not making it completely

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RESEARCH ARTICLE

Design of Coaxial Fed Microstrip Patch Antenna for Wi-MAX/ IMT Applications

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ABSTRACT:

In this paper, a single layer, single co-axial feed, broadband, compact rectangular microstrip patch antenna is proposed. This proposed antenna is constructed by cutting a T-shape slot under a Pi-shape slot in the patch fabricated on a substrate with relative permittivity 2.33 and thickness 8mm using simple coaxial feeding technique. In addition, four circular slots have been cut into the radiating edges of patch for broadband operation to cover both Wi-MAX (3400MHz-3690MHz) & IMT (3900MHz-4400MHz) communication standards. Basically, the use of these circular slots has effectively excited multi-resonant modes together with good impedance bandwidth. A thick substrate helps broaden the bandwidth for covering the entire frequency range of Wi-MAX & IMT communication standards. The proposed slot loaded patch antenna resonates at 2.66 GHz and has a broadband from 3.4 GHz to 4.5 GHz with the corresponding bandwidth of 108 MHz and 1.14 GHz and return losses of -16.0 dB and -22.6 dB respectively. The antenna gives a stable radiation performance with gain greater than 7dB over the entire broadband. The simulation has been performed by using CST Microwave Studio, which is a commercially available full wave electromagnetic simulator based on the method of finite difference time domain technique. Meanwhile, the proposed antenna exhibit almost omni-directional radiation pattern, relatively high gain and low cross polarization. Results for reflection coefficient and far-field radiation pattern of the designed antenna are presented and discussed. The analysis of the simulated results confirms successful design of co-axial fed microstrip patch antenna (MPA).

KEY WORDS: Wi-MAX, IMT, broadband, impedance bandwidth, microstrip patch antenna (MSA), CST Microwave Studio

INTRODUCTION:

Slot loaded patch antennas are currently under consideration for use in broadband communication systems due to their attractive features, such as wide frequency bandwidth, low profile, lightweight, easy integration with monolithic microwave integrated circuits (MMIC), low cost, good impedance matching, appreciable radiation patterns and ease of fabrication. Recent technologies enable wireless communication devices to become physically smaller in size. Obviously, antenna size is a major factor that limits miniaturization..

With the rapid growth of the wireless mobile communication technology, the future technologies need a very small size antenna and also the need of multi-band antennas is increased to avoid using two antennas and to allow video, voice and data information to be transmitted simultaneously

Recently, there is an increased demand for multi-frequency resonant and wide-band antennas that can be easily integrated with the communication system. In order to meet the above mentioned requirements, microstrip patch antenna (MPA) is one of the best candidates. The major drawback of microstrip antenna is their narrow impedance bandwidth [1]. Wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (Wi-MAX) technology is the most rapidly growing area in the modern wireless communication [2-4]. This gives users the mobility to move around within a broad coverage area and still be connected to the network. This provides greatly

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Comparison of Un-slotted and Slotted Rectangular MSA for Wireless Applications

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Abstract: Microstrip patch antennas are strong candidates for use in many wireless communication applications. This paper proposes the use of un-slotted and slotted patch antenna configurations to obtain single band and broadband operation respectively. A single layer, single co-axial feed, broadband, compact rectangular microstrip patch antenna is developed. Antenna size has been reduced by 32% by cutting three equal rectangular slots at the edges of the patch with a wideband ranging from 5.4209 GHz - 5.816 GHz. Return losses of about -29.62 dB and -16.93 dB are obtained for un-slotted and slotted RMSA configurations with the corresponding impedance bandwidth of 206.74 MHz and 395.64 MHz respectively. Experimental investigations and detailed simulations are conducted so that the proposed design can be used for 5.5 GHz Wi-MAX and 5.8 GHz WLAN communication standards. Details of the antenna design and experimental results are presented and discussed. The simulation has been performed by using CST Microwave Studio, which is a commercially available electromagnetic simulator based on the method of finite difference time domain technique.

Keywords: Wi-MAX/WLAN, broadband, microstrip antenna (MSA), impedance bandwidth, CST Microwave Studio.

I. INTRODUCTION

Recently, the rapid growth of wireless communication technology requires a compact terminal, which leads to the requirement of a single antenna to cover different applications. Wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (Wi-MAX) is the most popular area of research in the modern wireless communication due to ease of installation and location freedom [1-6]. Microstrip antennas have some good features like low profile, lightweight, low manufacturing cost, low process simplicity and easy integration into circuit boards. Due to these attractive features microstrip antennas (MSA) are well suited for WLAN/Wi-MAX application systems. The size of the antenna can be reduced by cutting slots on patch antennas. Microstrip antennas (MSAs) with rectangular slots have been investigated in this paper since it can operate as a broadband antenna.

Wireless local area network requires three bands of frequencies: 2.4GHz (2400-2484MHz), 5.2GHz (5150-

5350MHz) and 5.8GHz (5725-5825MHz). Also, to support the worldwide interoperability for microwave access (Wi-MAX) applications, the antenna design should achieve a dual band or a broadband response with sufficiently large bandwidth to cover the 2.5GHz (2500-2690MHz), 3.5GHz (3400-3690MHz) and 5.5GHz (5250-5850MHz) frequency bands. The design needs to consider many dimension parameters and the resulting bandwidth is still not sufficient to cover Wi-MAX frequency bands. This paper also provides detailed antenna dimensions and various simulated results.

The work presented is a comparison of un-slotted and slotted rectangular microstrip antenna with co-axial feeding arrangements.

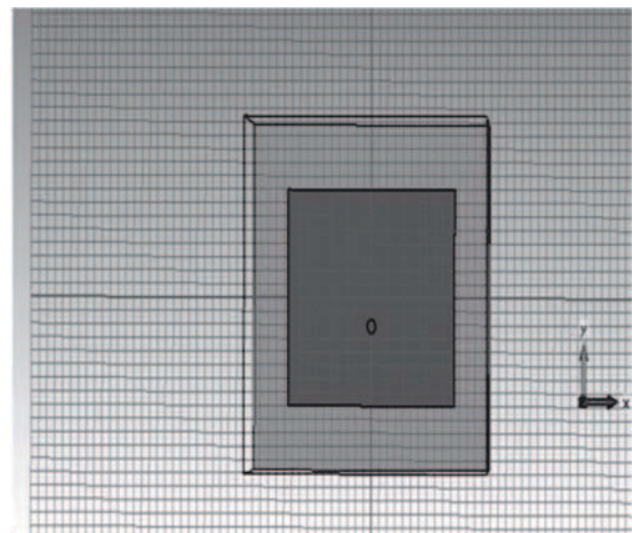


Figure 1: Geometry of un-slotted rectangular MSA

The un-slotted antenna shown in Figure1 can be used for 5.5 GHz Wi-MAX communication standard only, whereas the slotted antenna shown in Figure 5 can be used for 5.5 GHz Wi-MAX and 5.8 GHz WLAN operation. The initial parameters of this design can be calculated using transmission line model (TEM) approximation in which microstrip radiating element is viewed as a transmission line resonator

FR-4 MATERIAL BASED CPW FED SLOTTED MULTIFREQUENCY WIDEBAND MICROSTRIP PATCH ANTENNA FOR WIRELESS APPLICATIONS

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Keywords: Microstrip Patch Antenna, CPW, Multifrequency, E-shaped slots, CST MWS V9, WLAN/Wi-Fi/WiMAX/AMSAT/WAVE, Wireless applications.

In the present work, a novel compact microstrip patch antenna comprising two horizontal E-shaped slots fed by a co-planar waveguide (CPW) has been proposed. In this design structure, both the slotted patch and symmetrical ground planes are embedded in the same plane. Both the radiating patch and ground plane are perfect electric conductors (PEC) which are printed on a readily available and inexpensive Epoxy Glass (FR-4) substrate material with thickness 1.6 mm, relative permittivity 4.4 and loss tangent 0.0024. The proposed microstrip patch antenna (MPA) design is capable of generating three distinct operating bands with -10 dB reflection coefficient viz. 2.40-2.58 GHz, 3.38-3.77 GHz and 4.02-6.09 GHz with an adequate bandwidth of 180 MHz, 390 MHz and 2.07 GHz respectively. Obviously, the achieved impedance bandwidths are wide enough to cover the required bandwidths of many communication standards simultaneously i.e. 2.400-2.484 GHz/5.150-5.350 GHz/5.725-5.825 GHz for Wireless Local Area Network (WLAN), 2.400-2.500 GHz for Wireless Fidelity (Wi-Fi), 3.400-3.690 GHz/5.250-5.850 GHz for World-Wide Interoperability for Microwave Access (WiMAX), 5.650-5.670 GHz for up-links and 5.830-5.850 GHz for down-links of Amateur Satellite (AMSAT) and 5.900 GHz Wireless Access in the Vehicular Environment (WAVE). Proposed antenna was simulated using Computer Simulation Technology Microwave Studio V9 (CST MWS V9) based on the finite integration technique (FIT) with perfect boundary approximation (PBA). Finally, the proposed antenna was fabricated with optimized parameters and some performance measurements were taken to validate against simulation results. The design procedure to achieve the required performance is presented and discussed thereafter.

Design of a Multi-Frequency Wideband Microstrip Patch Antenna for 5.2/5.5/5.8 GHz Wireless Applications

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Abstract - In present work, a novel single layer rectangular microstrip patch antenna with broadband behavior for WLAN and Wi-MAX applications is proposed. The proposed antenna has a frequency bandwidth of about 885 MHz (4.969-5.854GHz) at -10 dB return loss which is sufficient to make the antenna useful for 5.2/5.5/5.8 GHz WLAN and 5.5 GHz Wi-MAX operation. The broadband behavior so obtained is due to the pi-shaped slot embedded into the ground. This designed antenna has one more band below -10dB ranging from 6.19 GHz - 6.562 GHz which is feasible for satellite applications covering a bandwidth of 372 MHz. The maximum achievable gain over the entire frequency band is 4.7 dBi. In this paper various simulated results are presented and directions for further study are discussed.

Design Studies of Edge Coupled Microstrip Patch Antenna with Defected Ground Structure

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Abstract- In this work, an extensive design study of a edge coupled microstrip patch antenna with dumbbell shaped DGS has been presented. The antenna consists of patch radiator and a quarter wave length section for feeding with a 50 Ohm impedance line. The EM Full wave simulator, CST Microwave Studio has been used to optimize the antenna parameters and as well as the dumbbell shaped DGS parameters. DGS is realized by etching off a simple shape defected from the ground plane, depending on the shape and dimensions of the defect, the shielded current distribution in the ground plane is disturbed, resulting a controlled excitation and propagation of the electromagnetic waves through the substrate layer. The shape of the defect may be changed from the simple shape to the complicated shape for the better performance. The single patch has an inherent narrow BW, several techniques to improve the BW of the antenna have been reported by the researchers e.g., capacitive compensation, thicker substrates, reactive matching networks, Stacked patches. In general, the impedance bandwidth of a patch antenna is proportional to the antenna volume, measured in wavelengths. A study on edge coupled patch antenna using a quarter-wavelength section with and without dumbbell shaped defected ground structure will be presented in the proposed work. The simulated results indicate that using the dumbbell shaped DGS under the feed connecting edge, the bandwidth can be improved.