

**“DUAL FREQUENCY WIDEBAND RECTANGULAR
MICROSTRIP PATCH ANTENNA FOR WIRELESS
COMMUNICATION SYSTEMS”**

(Thesis submitted towards the partial fulfilment of requirement for the award of
degree of)

MASTER OF ENGINEERING

IN

ELECTRONICS AND COMMUNICATION ENGINEERING



Submitted by

RAKESH KUMAR TRIPATHI

Roll No:-800961013(ECED)

Under the guidance of

Dr. Rajesh Khanna

Professor (ECED)

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

PATIALA-147004(PUNJAB)

CERTIFICATE

I, Rakesh Kumar Tripathi hereby certify that the work which is being presented in this thesis entitled **“Dual Frequency Wideband Rectangular Microstrip Patch Antenna for Wireless Communication Systems”** by me in partial fulfilment of the requirements for the award of degree of Masters of Engineering in Electronics and Communication Engineering from Thapar University, Patiala is an authentic record of my own work carried under the supervision of **Dr. Rajesh Khanna** and referred other researcher's work which are duly listed in the reference section.


The matter presented in this report has not been submitted in any University/Institute for the award of Masters of Engineering.


Rakesh Kumar Tripathi

Roll No: 800961013


Date: 24-06-11


This is certified that the above statement made by the candidate is correct to best of my knowledge.


Dr. Rajesh Khanna
Professor, ECED

Date: 24/6/11

Countersigned By


Head of Department
ECED, Thapar University, Patiala
Date: 24/6/11


(Dr. S.K. Mohapatra)
Dean of Academic Affairs
Thapar University, Patiala
Date:

ACKNOELEDGEMENT

I would like to extend my gratitude and my sincere thanks to my honourable, esteemed supervisor **Dr. Rajesh Khanna**. He is not only a great professor with deep vision but also and most importantly a kind person. I sincerely thank for his exemplary guidance and encouragement. His trust and support inspired me in the most important moments of making right decisions and I am glad to work with him.

My special thank goes to **Dr. A. K. Chatterjee** head of the Department of Electronics and Communication Engineering, Thapar University, Patiala, for his encouragement, support and providing the facilities for the completion of this thesis.

I am also thankful to entire faculty and staff members of Electronic and Communication Engineering Department for their unyielding encouragement.

I am greatly indebted to all my friends, who have graciously applied themselves to the task of helping me with ample morale support and valuable suggestions. Finally, I would like to extend my gratitude to all those persons who directly or indirectly helped me in the process and contributed towards this work.

Last but not least I would like to thank my parents, who taught me the value of hard work by their own example. They rendered me enormous support during the whole tenure of my stay in Thapar University, Patiala.

Rakesh Kumar Tripathi

Roll No- 800961013

Date:

ABSTRACT

Wireless communications have been developed widely and rapidly in the modern world especially during the last two decades. The future development of the personal communication devices will aim to provide image, speech and data communications at any time, and anywhere around the world. This indicates that the future communication terminal antennas must meet the requirements of multi-band or wideband to sufficiently cover the possible operating bands. However, the difficulty of antenna design increases when the number of operating frequency bands increases. In addition, for miniaturizing the wireless communication system, the antenna must also be small enough to be placed inside the system. However, in order to transmit and receive more information large bandwidths are required, and bandwidth enhancement is currently a popular research area.

The aim of this thesis is to design a broad band dual frequency rectangular Microstrip patch antenna for wireless communication systems and study the effect of various antenna parameters like patch length (L), width (W), substrate parameters relative dielectric constant, substrate thickness etc. Here, coaxial feed method is used to excite the patch antenna.

In this thesis, five designs have been proposed for broad banding of patch antenna. The proposed antennas have been modelled, designed and simulated using Computer Simulation Technology (CST) Microwave Studio version 5. These designs include chip resistor, slotted patch, reduced ground plane and stacking of patch. The maximum impedance bandwidth is achieved for reduced ground plane patch antenna.

Four designs are also presented for dual banding of antenna depending on polarization. It has been found that by embedding a cross slit in the patch, the performance of patch antenna improves as compared to rectangular patch antenna without cross slit. Two antennas E shaped and slot loaded patch antenna are designed and simulated. The simulated results show that the slot loaded patch antenna achieves impedance bandwidth of 4.1% and 14.8% for $VSWR < 2$, covering a frequency range from 2.39 GHz to 2.49 GHz and 3.33 GHz to 3.849 GHz respectively. The E shaped patch antenna is resonating on two frequencies: 5.14GHz and 5.81GHz with return loss of -35dB and -27dB respectively. This patch antenna is operating in two bands viz band 1 (4.97GHz to

5.37GHz) and band 2 (5.72GHz–5.86GHz). These bands are suitable for WLAN applications.

CONTENTS

	Page No.
Abstract	
List of Figure and Tables	
Chapter 1. Introduction	
1.1 Overview	1
1.2 GSM	2
1.3 IMT	3
1.4 IEEE Standard for WLAN	4
1.5 IEEE Standard for WiMax	4
1.6 Thesis Motivation	5
1.7 Thesis Objective	6
1.8 Thesis Outline	6
1.9 Conclusion	7
Chapter 2. Literature Survey	8
Chapter 3. Single Band Microstrip Patch Antenna Design	
3.1 Rectangular Microstrip Patch Antenna	13
3.2 Design Procedure of Single Band Rectangular Microstrip Patch Antenna	13
3.3 Designing of Single Band Rectangular Microstrip	15
3.4 Simulation Setup And Result	16
3.5 Conclusion	22
Chapter 4. Broadband Microstrip Patch Antenna Design	
4.1 Introduction	23
4.2 <u>Impedance Bandwidth</u>	24
4.3 Broadband Techniques	24
4.4 Conclusion	46
Chapter 5. Dual Band Microstrip Patch Antenna Design	
5.1 Introduction	47
5.2 Dual Band Antenna Concept	48
5.3 Dual Frequency Operation with a Simple Rectangular	49
5.4 Dual Frequency Microstrip Patch Antenna with Cross	52
5.5 Slot Loaded Patch Antenna for Dual Band Applications	54
5.6 E-Shaped Microstrip Patch Antenna	59
Chapter 6. Conclusion and Future Scope	
6.1 Conclusion	64

6.2 Future Scope	65
Publications	67
References	68

LIST OF FIGURES

		Page No.
figure 3.1	Rectangular Microstrip Patch Antenna	13
figure 3.2(a)	Geometry of Proposed Antenna	16
figure 3.2(b)	Designed Structure on CST Microwave Studio	16
figure 3.3	Return Loss (S11 in dB)	17
figure 3.4	Smith Chart	18
figure 3.5	VSWR versus Frequency Plot	19
figure 3.6	Z Parameter	20
figure 3.7(a)	Simulated Far Field Radiation Pattern for $\varphi = 90$ degrees	20
figure 3.7(b)	Simulated Far Field Radiation Pattern for $\varphi = 0$ degrees	21
figure 3.8	Gain versus Frequency Plot	21
figure 3.9	Effect of feed point location	22
figure 4.1(a)	Geometry of Chip Resistor Loaded Patch Antenna	26
figure 4.1(b)	Structural View of Chip- Resistor Loaded Patch Antenna.	27
figure 4.2	Effect of Resistance Location	27
figure 4.3(a)	Return loss Vs Frequency Plot for chip-resistor-loaded patch	28
figure 4.3(b)	Return Loss Vs Frequency Plot for Conventional Patch	29
figure 4.4(a)	Smith Chart For Chip-Resistor-Loaded Patch Antenna	29
figure 4.4(b)	Smith Chart for Conventional Patch Antenna	30
figure 4.5	Stacked Coupling Schemes	31
figure 4.6	Return Loss Plot for Stacked Patch Antenna and Single Patch Antenna	32
figure 4.7	Smith Chart Plot	33
figure 4.8(a)	Radiation Pattern of Stacked Patch Antenna at $\varphi=0^0$	33
figure 4.8(b)	Radiation Pattern of Single Patch Antenna at $\varphi=0^0$	33
figure 4.9	Structure of U-Slot Patch Antenna	35
figure 4.10	Effect of Variation in a (Horizontal Slot Length)	36
figure 4.11	Effect of Variation in Vertical Slot Length (b)	36
figure 4.12	Effect of Variation in Slot Width	37
figure 4.13	Effect of Feed Point Location in U Slot Patch Antenna	37
figure 4.14	Return Loss versus Frequency Plot	38
figure 4.15	Smith Chart for Proposed Antenna	38
figure 4.16	Simulated VSWR versus Frequency Plot	39
figure 4.17	Simulated Z Parameter	39
figure 4.18	Simulated Gain versus Frequency Plot	40

figure 4.19	Geometry of Patch Antenna	41
figure 4.20	Effects of Variation of p	42
figure 4.21	Simulated Return Loss versus Frequency Plot	42
figure 4.22	Smith Chart	42
figure 4.23	Gain Vs Frequency Plot	43
figure 4.24	Geometry of E-Shaped Patch Antenna	44
figure 4.25	Simulated Return Loss for E Shaped Patch Antenna	44
figure 4.26	VSWR Plot for E Shaped Patch Antenna	45
figure 4.27	Z Parameter Plot	45
figure 4.28	Smith Chart	46
figure 5.1	Geometry of Rectangular Patch Antenna for Dual Frequency	50
figure 5.2	Simulated Return Loss for Feed Position at Point A, B	51
figure 5.3	Simulated Return Loss at Feed Point C	51
figure 5.4	Simulated VSWR Plot	52
figure 5.5	Geometry of Dual Frequency Rectangular Microstrip Patch	53
figure 5.6	Return Loss Vs Frequency Plot	53
figure 5.7	VSWR Plot	54
figure 5.8	Gain Vs Frequency Plot	54
figure 5.9	Geometry of Slotted Patch Antenna	55
figure 5.10	Effects of Vertical Slot Length (a) on Antenna Performances	56
figure 5.11	Effects of Variation in b on Antenna Performances	57
figure 5.12	Effects of Variation in c on Antenna Performance	57
figure 5.13(a)	Return Loss Plot for Proposed Antenna	58
figure 5.13(b)	Simulated VSWR Plot	58
figure 5.13(c)	Gain Vs Frequency Plot	58
figure 5.14(a)	Geometry of E-Shaped Micrpstrip Patch Antenna	60
figure 5.14(b)	Front View of Designed Antenna on CST Microwave Studio	60
figure 5.15	Simulated Return Loss for Various Ls	61
figure 5.16	Simulated Return Loss for Various Ws	61
figure 5.17	Simulation Return Loss for Various L _t	62
figure 5.18	Simulated Return Loss for Various W _t	62
figure 5.19(a)	Simulated Return Loss	63
figure 5.19(b)	Smith Chart	63

List of Tables

	Page No.	
Table 1.1	various type of wireless applications and its frequency band	5
Table 3.1	Single Patch Antenna Design Specifications	15
Table 4.1	Broadband Techniques for Microstrip patch antenna	25
Table 4.2	Dimension and Material Properties of Chip-Resistor Loaded Patch Antenna	26
Table 4.3	Effect of resistance location	28
Table 4.4	Comparing Chip-Resistor- Loaded Patch Antenna with Conventional Antenna	28
Table 4.5	Design Parameters of Stacked Patch Antenna	32
Table 4.6	Comparison between Single and Double Patch Antenna	34
Table 4.7	Design Specifications of U Slot Patch Antenna	34
Table 4.8	Increasing the Parameter a	35
Table 4.9	Design Parameter of Patch Antenna	41
Table 4.10	Dimensions of E-Shaped Patch Antenna	44
Table 5.1	Dimensions of Dual Band Patch Antenna with Cross-Slot	53
Table 5.2	Design Specifications of Slotted Patch Antenna	55
Table 5.3	Effects of slot length 'a' on antenna performances	56
Table 5.4	Design Specifications of E-shaped Patch Antenna	60
Table 6.1	Simulation Results of Broadband Patch Antennas	65

INTRODUCTION

1.1 Overview

In high-performance aircraft, spacecraft, satellite and missile applications, where size, weight, cost, performance, ease of installation, and aerodynamic profiles are constraints, low profile antennas may be required. Presently there are many other government and commercial applications, such as mobile radio and wireless communications that have similar specifications. To meet these requirements, Microstrip antennas can be used. These antennas are low profile, conformable to planer and non planer surface, simple and inexpensive to manufacture using modern printed circuit technology, mechanically robust when mounted on rigid surfaces, compatible with MMIC designs. When the particular patch shape and mode are selected; they are very versatile in terms of resonant frequency, polarization, pattern and impedance. In addition by adding the load between patch and ground plane such as pins, adaptive elements with variable resonant frequency, impedance, polarization and pattern can be designed.

The concept of Microstrip radiators was first proposed by Deschamps in 1953. A patent was issued in France in 1955 in the names of Gutton and Baissinor. However 20 years passed before practical antennas were fabricated. Development during the 1970's was accelerated by the availability of good substrates with low loss tangent and attractive thermal and mechanical properties, improved photolithographic techniques, and the better theoretical models. The first practical antenna was developed by Howell [49] and Munson [50].

Wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (Wi-MAX) technology is most rapidly growing area in the modern wireless communication. This gives users the mobility to move around within a broad coverage area and still be connected to the network. This provides greatly increased freedom and flexibility. For the home user, wireless has become popular due to ease of installation, and location freedom. Naturally, these applications require antennas. This being the case, portable antenna technology has grown along with mobile and cellular technologies. It is important to have the proper antenna for a device. The proper antenna will improve

transmission and reception, reduce power consumption, last longer and improve marketability of the communication device.

Microstrip antennas (MSA) have some good features, like low cost, low profile. Due to this Microstrip antennas (MSA) are well suited for WLAN/Wi-MAX application systems. Microstrip antennas (MSA) have some disadvantages, like narrow bandwidth, low gain etc. Broad banding is the main problem, for solving this problem we propose new structures for devices that require more than one frequency band of operation [1]. Dual-band wireless phones have become popular recently because they allow using the one phone in two networks that have different frequencies. Tri-band phones have also gained popularity. Still, there exist more than three frequency bands used for wireless applications. Table 1-1 lists a few useful wireless applications and their operating frequencies. The systems having multi-band operation require antennas that resonate at the specified frequencies. This only adds complexity to the antenna design problem.

Recently, coplanar waveguide (CPW)-fed antenna has been more popular because of their many attractive features such as wider bandwidth, better impedance matching, and simplest structure of a single metallic layer, no soldering point, and easy integration with active devices or monolithic microwave integrated circuits.

Microstrip patch, with inserted slits at one of the radiating edges, is one of the techniques of widening the bandwidth of the antenna [1]. As for the CPW-fed structure, there are many attractive features such as wide bandwidth, simplest structure of a single metallic layer, easy integration with MMICs, etc. [2]

1.2 GSM

GSM networks operate in a number of different carrier frequency ranges (separated into GSM frequency ranges for 2G and UMTS frequency bands for 3G), with most 2G GSM networks operating in the 900 MHz or 1800 MHz bands. Where these bands were already allocated, the 850 MHz and 1900 MHz bands were used instead (for example in Canada and the United States). In rare cases the 400 and 450 MHz frequency bands are assigned in some countries because they were previously used for first-generation systems. Most 3G networks in Europe operate in the 2100 MHz frequency band.

Regardless of the frequency selected by an operator, it is divided into timeslots for individual phones to use. This allows eight full-rate or sixteen half-rate speech channels per radio frequency. These eight radio timeslots (or eight burst periods) are grouped into

a TDMA frame. Half rate channels use alternate frames in the same timeslot. The channel data rate for all 8 channels is 270.833 kbit/s, and the frame duration is 4.615 ms.

The transmission power in the handset is limited to a maximum of 2 watts in GSM850/900 and 1 watt in GSM1800/1900.

1.3 IMT (International Mobile Telecommunications)

In the mid 1980's the ITU started work to define the next "generation" of mobile radio standards to move existing mobile networks from specific National and Regional standards onto a global basis. This necessitated finding a new globally available frequency band as well as attempting to maximize convergence within the many existing second generation mobile wireless technologies.

At the 1992 ITU World Radio Conference 230 MHz of new radio spectrum was identified for the terrestrial component of 'Future Public Land Mobile Telecommunication Systems' (FPLMTS), later to be known as International Mobile Telecommunications-2000 (IMT-2000). This provided the necessary impetus to complete ITU standards for the third generation of mobile radio technologies in time for initial commercial implementation of IMT-2000 (3G) in the year 2000.

Early work on 3G in the ITU was directed towards obtaining a global spectrum allocation since multi-band radios were at that time economically unattractive. Similarly a single global standard for 3G seemed at the time the only realistic solution. However it became rapidly clear that even the 230 MHz of new spectrum identified in 1992 would be insufficient for future mobile needs. At the ITU World Radio Conference in 2000 all the major existing cellular bands were also added, increasing the potential IMT-2000 spectrum availability by approximately three times. Fortunately it also became practical to produce economical multi-band radios.

Due to the rapid growth of 2G mobile during the 1990's it became necessary for the ITU to offer a number of possible routes from the various existing 2G systems to a 3G capability. Fortunately it also became economically realistic to offer multi-mode/multiband mobile equipment to smooth the transition from 2G to 3G operations. Mobile radio technologies are proving to be the only economical approach to making telecom services available to underserved regions in developing countries and globally mobile users far outstrip fixed telecom users. In developed countries mobile use is near saturation and so the driving force in these areas is new "broadband" multimedia

services. These new services will be provided through enhancements to IMT-2000 (3G) and through IMT-Advanced (4G) in the future. IMT is the generic ITU name for 3G/4G. Radio spectrum below 1 GHz is optimum for the needs of developing countries, due to the ability to serve larger rural areas from a single cell site compared to spectrum above 2 GHz. However, it is very challenging to find wide bandwidths below 1 GHz so “broadband” needs must be met primarily through spectrum above 2 GHz. The 2007 World Radio Conference made valuable strides in identifying additional spectrum for IMT, both below 1GHz and above 2 GHz.

1.4 IEEE standard for WLAN

The IEEE 802.11 standard was proposed in 1997 for WLANs application. After few year new standard was proposed, operating on the 2.4 GHz ISM band (2.4 - 2.484 GHz), is called 802.11b or 802.11 HR (High Rate), which provides a data rate up to 11 Mbps. The IEEE 802.11a standard was approved in 1999, operating on the 5 GHz ISM bands (5.15 - 5.35GHz and 5.725 -5.825GHz). The change of band shows that 802.11a and 802.11b products are not compatible. Therefore, the IEEE proposed 802.11g standard which is compatible with both 802.11b and 802.11a technology. The 802.11g standard was accepted in 2003.

Since 802.11b and 802.11g are using 2.4 GHz frequency band while 802.11a uses 5 GHz frequency band so a dual band antenna is requirement for WLAN applications. The popularity of WLAN is increased due to high-speed transfer rate. This increased the development of broadband antennas [3].

1.5 IEEE standard for WiMAX

WiMAX technology is based on the IEEE 802.16 standard also called Broadband Wireless Access. The name WiMAX was created by the WiMAX forum which was formed in June 2001 to promote conformity and interoperability of the standard. The forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL". There is no uniform global licensed spectrum for WiMAX, although the WiMAX Forum has published three licensed spectrum profiles: 2.5 GHz (2.5-2.69 GHz), 3.5 GHz (3.4-3.69 GHz) and 5.5 GHz (5.25-5.85 GHz). WiMAX provide the data rate upto70 Mbps over 50 Km. IEEE 802.16-2004 is often called IEEE 802.16d, since that was the working party that

developed the standard. It is also frequently referred to as "fixed WiMAX" since it has no support for mobility. It replaced IEEE Standards 802.16-2001, 802.16c-2002, and 802.16a-2003. 802.16e-2005 is an amendment to 802.16-2004 and is often referred to in shortened form as 802.16e. It introduced support for mobility, amongst other things and is therefore also known as "mobile WiMAX" [3].

Table 1.1 Various wireless standards and their frequency band

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

1.6 Thesis Motivation

Conventional Microstrip antennas in general have a conducting patch printed on a grounded microwave substrate, and have the attractive features of low profile, light weight, easy fabrication, and conformability to mounting hosts [4]. However, Microstrip

antennas inherently have a narrow bandwidth, and bandwidth enhancement is usually demanded for practical applications.

In recent years, the demand for broadband antennas have increased for use in high-frequency and high-speed data communication systems. Printed antennas are economical and easily hidden inside packages, making them well suited for consumer applications. Unfortunately, a “classical” Microstrip patch antenna has a very narrow frequency bandwidth that precludes its use in typical communication systems. However, if the frequency bandwidth could be widened, a broad-band Microstrip antenna would prove very useful in commercial applications such as 2.5 G and 3 G wireless systems, wireless local area networks (WLAN), and Bluetooth personal networks. For these reasons, studies to achieve compact and broadband operations of Microstrip antennas have greatly increased.

Dual-frequency operation of antennas has become a necessity for many applications in recent wireless communication systems, such as GPS, GSM services operating at two different frequency bands.

1.7 Thesis Objective

The aim of this thesis is to design broadband dual frequency Microstrip patch antenna for wireless communication systems. To design a Microstrip patch antennas for a specific resonating frequency, accurate dimensions of patch is required. Therefore, it becomes necessary to use simulation programs to test the performance of the patch before fabrication. For the modelling and simulation of patch antennas, here we are using Computer Simulation Technology (CST) Microwave Studio version 5.

1.8 Thesis Outline

The outline of this thesis is as follows.

Chapter 1: It presents the background information about the typical Microstrip patch antenna. It also introduces about various wireless frequency bands.

Chapter 2: A brief literature review of patch antenna used for broad-banding and multi-banding is presented in this chapter.

Chapter 3: This chapter describes the design procedure of Single Band Rectangular Microstrip patch antenna. The modelling and simulation of this single band rectangular Microstrip patch antenna is done and simulation results are presented.

Chapter 4: This chapter describes some techniques to improve the patch antenna impedance bandwidth. Basically three techniques are described in this chapter. They are:

- By lowering the Q factor.
- By introducing multiple resonances.
- By using impedance matching

Some design example is also given. These designs are simulated using CST Microwave studio.

Chapter 5: In this chapter the Dual Frequency Operation of Microstrip patch antenna and the concept of dual frequency operation using the slots are described. The simulated results are also discussed.

Chapter 6: This chapter gives the conclusion to this thesis and suggests the future scope of work.

1.8 Conclusion

The table 1.1 indicates that for different wireless application, there is different band of frequencies. So, an antenna should be designed which covers multiple bands of frequencies and should be wideband also. These antennas should be low profile, conformable to planer and non planer surface, simple and inexpensive and can be manufactured using modern printed circuit technology. To meet these requirements, Microstrip antennas is one of the best candidates.

A brief literature review of patch antenna used for multi banding and broad banding is presented in the next chapter.

LITERATURE SURVEY

2.1 Introduction

Prior to stating of my thesis, it is important to have a deep understanding on the existing pages of Microstrip antenna. The main sources of information for the dissertation are books, journal, theses and dissertations and the internet. There are three major areas of reading in the literature review, which are antenna design, methods for improving performance of Microstrip patch antenna and related simulation software. These chapters include the research paper literature review.

2.2 Research Paper Literature Review

In order to start the thesis, the first step is to study the research papers that have been performed previous by other researchers. Papers related to this work are chosen and studied. With the help of literature review, it becomes clearer to perform this project.

The concept of Microstrip radiator was first proposed by Deschamps in 1953. A patent was issued in France in 1955 in the name of Gutton and Baissinot. Development during the 1970s was accelerated by the availability of good substrates. The first practical antennas were developed by Howell and Munson. Since then extensive research and development on Microstrip antennas aimed at exploiting their advantages.

2.2.1 CALCULATION OF THE BANDWIDTH OF MICROSTRIP RESONATOR ANTENNAS [5]

In this paper the bandwidth of Microstrip resonator antenna is analyzed. Starting from the general expression for the quality factor of the resonator, it will be proved that the bandwidth of Microstrip resonator antenna is directly proportional to the thickness of the substrate, to the square of resonant frequency and inversely proportional to the square root of relative permittivity of the substrate material.

2.2.2 ACCURATE TRANSMISSION LINE MODEL FOR THE RECTANGULAR MICROSTRIP ANTENNA: [6]

An accurate and numerically efficient model for the rectangular Microstrip antenna is presented. It concerns a transmission line model which features the following three major improvements with respect to earlier such models

- The mutual radiative coupling (both real and imaginary parts) between the equivalent slots is fully taken into account.
- The influence on the side slots on the radiation conductance is taken into account implicitly.
- Simple analytic expressions are introduced for all relevant model parameters

This new model is applied to antennas with a single Microstrip feed line. Due to its numerical efficiency, this model is extremely well suited for design purposes. The model has a very broad range of validity in terms of patch aspect ratio (W/L), substrate dielectric constant (ϵ_r) and substrate electrical thickness (h/λ_0). However, some physical effects are still neglected by the model, such as the excitation of substrate waves, the mutual coupling with neighbouring elements, and the diffraction at the substrate and ground plane edges. Further, because it is a transmission-line model, the model does not take into account the effects of the higher-order modes.

2.2.3 DESIGN OF COAXIAL FED MICROSTRIP ANTENNA FOR LEO SATELLITES [7]

This paper presents a step by step procedure for designing Microstrip antenna for LEO satellites. The design uses transmission line method as it offers good physical insight. The modelling and designing of Microstrip patch antenna is done by using HFSS TM V9.2 which employs finite element method to achieve the desired specification. The paper presents simulated results for total gain and far field radiation patterns. The analysis of the simulated results confirms successful design of coaxial fed Microstrip antenna.

2.2.4 DESIGN AND SIMULATION OF BROADBAND RECTANGULAR MICROSTRIP ANTENNA: [8]

In this paper some techniques are suggested to increase the bandwidth of Microstrip antennas. The methods for increasing the BW of (MSA)'s are continuously getting upgraded. The search for an ideal broadband (MSA) is still continuing. The main techniques used to increase the bandwidth of Microstrip antennas are

- Low quality factors
- Modified shape patches
- Multilayer configurations

Also it is shown that by adjusting the substrate height with respect to dielectric constant of substrate material, surface wave excitation in MSA can be reduced.

2.2.5 MICROSTRIP PATCH ANTENNA WITH POLYPYRROLE GROUND PLANE [9]

In this paper, a Microstrip Patch Antenna (MPA) using a conducting polymer Polypyrrole (PPy), as a ground plane is modelled and simulated using CST Microwave Studio. The antenna is designed to operate in the 11 GHz region. After the successful simulation of proposed antenna, it is fabricated and results are measured. The measured and simulated results at the resonant frequency such as return loss, gain, radiation pattern and bandwidth are presented in comparison with a similar copper ground plane antenna. The results show that a Microstrip antenna with PPy as the ground plane provides a gain of 4.1 dB at 10.5 GHz as against 5.35 dB for copper ground plane at 11 GHz. The maximum return loss observed for PPy ground plane is about 15.76 dB at 10.5 GHz, while for copper ground plane MPA it is 13.86 dB at 11.5 GHz. The Q-factor for PPy as ground plane is 7.65, while in the case of copper as ground plane it is 13.74. The variation of conductivity of the ground plane has a significant effect on the -10 dB return loss bandwidth of the antenna.

2.2.6 DESIGN OF C-SLOT MICROSTRIP PATCH ANTENNA FOR WiMAX APPLICATIONS [10]

In this paper, a small compact Microstrip patch antenna with C-shaped slot is presented and simulated using Advanced Design Systems. It is developed to operate in the WiMAX frequency range of 2.5-2.69 GHz. The antenna presents a size reduction of about 37% when compared to a conventional patch antenna. The return loss is -19.1 dB and the antenna presents a broad radiation pattern.

2.2.7 SMALL DUAL-FREQUENCY MICROSTRIP ANTENNA WITH CROSS SLOT [11]

In this article, a new design of single-feed, reduced-size dual-frequency rectangular patch antenna with a cross slot of equal length is presented. The frequency ratio of the two operating frequencies is mainly determined by the aspect ratio of the rectangular patch, and the reduction in the two operating frequencies is achieved by cutting a cross slot of equal length in the Microstrip patch. The length of cross slot affects the frequency ratio of the two operating frequencies.

2.2.8 DUAL-FREQUENCY PATCH ANTENNAS [12]

In this paper, an overview of dual-frequency patch antennas is carried out. Attention has been focused on the geometry of the radiators; avoiding the important problem of the dual-frequency feed network. The use of a single feed network for both frequencies may be practical only when the two frequencies are very close to each other. For large separations between the frequencies (a frequency ratio of 2.5 to 3), two different Microstrip networks have to be designed. This must be done taking into account the coupling between them; they are forced to coexist in a restricted space, especially when dual polarization is required.

2.2.9 A DOUBLE U-SLOT PATCH ANTENNA WITH DUAL WIDEBAND CHARACTERISTICS [13]

This paper proposes the use of a patch antenna with two U-shaped slots to achieve dual band operation. The proposed antenna is designed and simulated using IE3D simulation software. A prototype antenna is fabricated and experimentally verified for the required performance. The primary advantage of this approach is the ease of fabrication as the

design does not require alignment between multiple layers of dielectrics and metals. Two U-slots are included to provide the above operating frequency bands. By adjusting the width and aspect ratio of slots and the offset of feed location from the centre on this thick substrate, the desired bandwidths can be obtained for the antenna.

2.2.10 E SHAPED PATCH ANTENNAS FOR HIGH SPEED WIRELESS NETWORKS [14]

In this paper, a thin, broadband, E shaped patch antenna, operating in 5-6 GHz range, is presented. This proposed antenna is broadband enough to cover the two bands of the IEEE 802.11a high-speed WLAN standard. The bandwidth achievable from a 3.5-mm ESPA is wider than what is required for this standard, and it appears possible to extend these antennas to cover other proposed international WLAN standards to achieve global usage.

2.2.11 EFFECTS OF GROUND PLANE SIZE ON A SQUARE MICROSTRIP PATCH ANTENNA DESIGNED ON A LOW-PERMITTIVITY SUBSTRATE WITH AN AIR GAP [48]

In this article, the effects of ground plane size on the characteristics of a square Microstrip patch antenna designed on a low-permittivity substrate with an air gap were investigated. It is observed that the gain is a periodic function of ground plane size with a maximum at around 1.3λ . The HPBW and radiation patterns of the antenna changed in accordance with the variation of gain. The height of the antenna affects the critical size of the ground plane for impedance matching, and changed the radiation pattern appreciably.

2.3 Conclusion

Based upon the above literatures, the design of an efficient wide band dual frequency small size patch antenna for recent wireless applications is a major challenge. So, in the next chapters, methods to increase the antenna impedance bandwidth and how to design the dual frequency patch antennas are discussed.

SINGLE BAND MICROSTRIP PATCH ANTENNA DESIGN

In this chapter, the procedure for designing a rectangular Microstrip patch antenna is explained. The design is simulated using Computer Simulation Technology (CST) Microwave Studio. Finally, the results obtained from the simulations are demonstrated.

3.1 Rectangular Microstrip Patch Antenna

The rectangular patch antenna is approximately a one-half wavelength long section of rectangular Microstrip transmission line. When air is the antenna substrate, the length of the rectangular Microstrip antenna is approximately one-half of a free-space wavelength. The length of the antenna decreases as the relative dielectric constant of the substrate increases. The resonant length of the antenna is slightly shorter because of the extended electric "fringing fields" which increases the electrical length of the antenna slightly. [15]

3.2 Design Procedure of Single Band Rectangular Microstrip Patch antenna

A single element of rectangular patch antenna, as shown in figure 3.1, can be designed for 2.45 GHz resonant frequency using transmission line model equations [15].

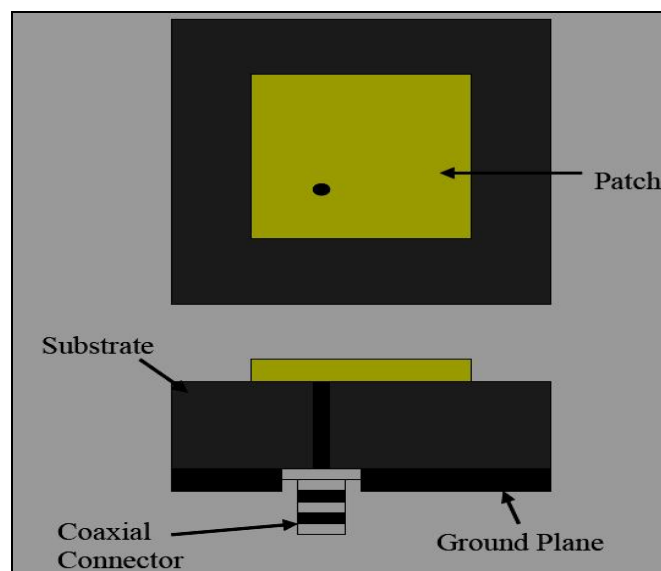


Fig 3.1 Rectangular Microstrip patch antenna

In the typical design procedure of rectangular Microstrip patch antenna, three essential parameters are :

- **Frequency of operation (f_r):** The resonant frequency of the antenna must be selected appropriately. The Mobile Communication Systems uses the frequency range from 2100-5600 MHz. Hence the antenna designed for the mobile communication system must be able to operate in this frequency range. The resonant frequency selected for my design is 2.45 GHz.
- **Dielectric constant of the substrate (ϵ_r):** The dielectric constant of substrate material plays an important role in the patch antenna design. A substrate with a high dielectric constant reduces the dimensions of the antenna but it also affects the antenna performance. So, there is a trade-off between size and performance of patch antenna.
- **Height of dielectric substrate (h):** For the Microstrip patch antenna to be used in communication systems, it is essential that the antenna is not bulky. Hence, the height of the dielectric substrate should be less.

After the proper selection of above three parameters, the next step is to calculate the radiating patch width and length.

Step 1: Calculation of Width (W)

For an efficient radiator, practical width that leads to good radiation efficiencies is [16]

$$W = \frac{1}{2f_r\sqrt{\mu_o\epsilon_o}} \sqrt{\frac{2}{\epsilon_r + 1}} \quad 3.1$$

Where v_o is the free space velocity of light.

Step 2: Calculation of Effective Dielectric Coefficient (ϵ_{reff})

The effective dielectric constant is

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad 3.2$$

Step 3: Calculation of Effective Length (L_{eff})

The effective length is

$$L_{eff} = \frac{c}{2f_o\sqrt{\epsilon_{reff}}} \quad 3.3$$

Step 4: Calculation of Length Extension (ΔL)

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{\text{reff}} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{\text{reff}} - 0.258) \left(\frac{W}{h} + 0.8 \right)} \quad 3.4$$

Step 5: Calculation of actual Length of Patch (L)

The actual length of radiating patch is obtained by

$$L = L_{\text{eff}} - 2\Delta L \quad 3.5$$

Step 6: Calculation of Ground Dimensions (L_g, W_g)

The transmission line model is applicable to infinite ground planes only. However, for practical considerations, it is essential to have a finite ground plane. It has been shown by [15] that similar results for finite and infinite ground plane can be obtained if the size of the ground plane is greater than the patch dimensions by approximately six times the substrate thickness all around the periphery. Hence, for this design, the ground plane dimensions would be given as:

$$\begin{aligned} L_g &= 6h + L \\ W_g &= 6h + W \end{aligned} \quad 3.6$$

3.3 Designing of Single Band Rectangular Microstrip Antenna:

This section describes the design of rectangular Microstrip patch antenna satisfying the given specifications-

Table 3.1 Single Patch Antenna Design Specifications

Frequency (f_r)	2.45 GHz
Dielectric Constant (ϵ_r)	2.3
Substrate Height (h)	3.048 mm

As for the substrate selection, the major consideration will be the dielectric constant ϵ_r . A high dielectric constant will result in a smaller patch size but this will generally reduce bandwidth efficiency and might have difficulty in fabricating a very small patch size antenna.

PATCH DIMENSION:

Length (L) = 37 mm

Width (W) = 47.70 mm

GROUND DIMENSION:

Length (L_g) = 57 mm

Width (W_g) = 66mm

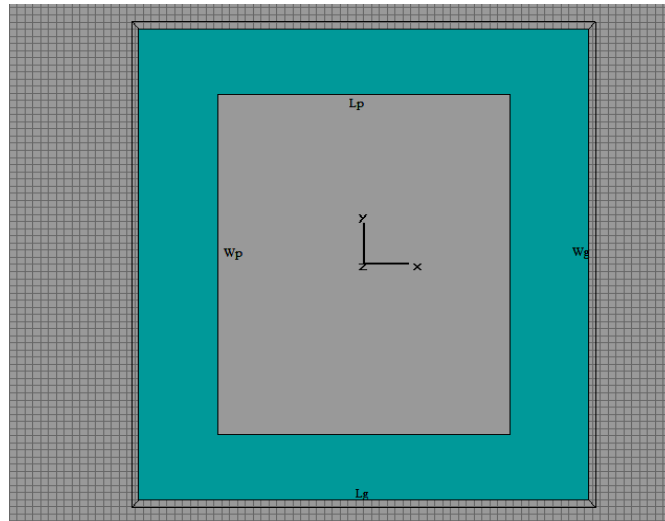


Figure 3.2 (a)

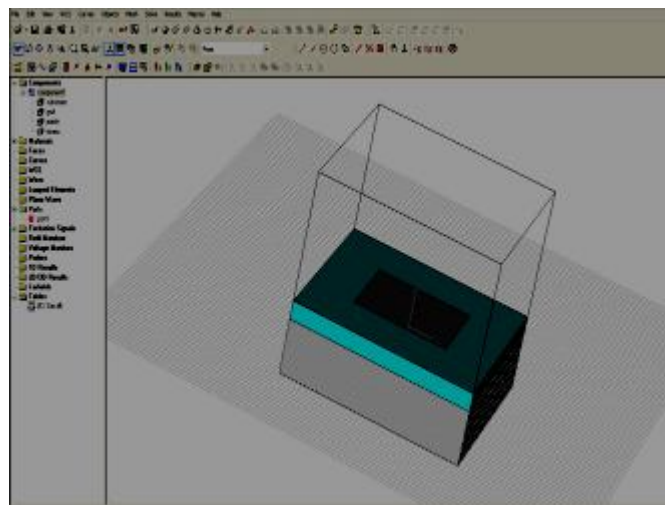


Figure 3.2 (b)

Figure 3.2 (a): Geometry of Proposed Antenna

(b): Designed structure on CST microwave studio

3.4 Simulation Setup and Result:

The software used to model and simulate the Microstrip patch antenna is CST Microwave Studio version 5. It analyzes 3D and multilayer structures of general shapes. It has been widely used in the design of MICs, RFICs, patch antenna, wire antenna and

other RF/wireless antennas. It can be used to calculate return loss plot, VSWR plot, current distributions, radiation patterns, smith chart etc.

The simulated results of the proposed antenna are presented in the below figures.

3.4.1 Return Loss and Antenna Bandwidth

Return loss is the difference between forward and reflected power, in dB, generally measured at the input to the coaxial cable connected to the antenna.

If the power transmitted by the source is P_T and the power reflected back is P_R , then the return loss is given by P_R divided by P_T .

For maximum power transfer the return loss should be as small as possible. This means that the ratio P_R/P_T should be as small as possible, or expressed in dB, the return loss should be as large a negative number as possible. For example a return loss of -40dB is better than one of -20dB.

This Return Loss is determined in dB as follows: [28]

$$R_L = -20 \log |\Gamma| \text{ (dB)} \quad 3.7$$

$$\text{here } |\Gamma| \text{ is } \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$|\Gamma|$ = is the reflection coefficient

V_0^- = is the reflected voltage

V_0^+ = is the incident voltage

Z_L and Z_0 are the load and characteristic impedance.

Figure 3.3 shows the S_{11} parameters (return loss) for the proposed antenna. The designed antenna resonates at 2.43 GHz.

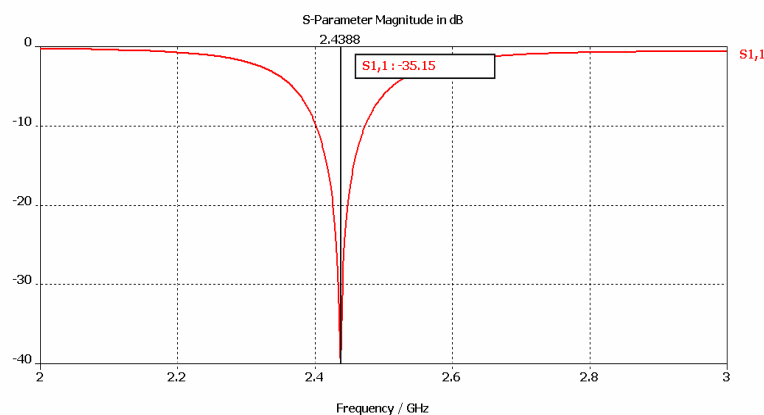


Figure 3.3 Return Loss(S_{11} in dB)

The bandwidth of the antenna can be said to be those range of frequencies over which the return loss is greater than -10 dB (corresponds to a VSWR of 2). Thus, the bandwidth of antenna can be calculated from return loss versus frequency plot. The bandwidth of the proposed patch antenna is 70 MHz and resonant frequency is 2.43 GHz which is very close to WLAN standard.

3.4.2 Smith Chart

The **Smith Chart**, invented by Phillip H. Smith (1905-1987), is a graphical aid or nomogram specializing in radio frequency (RF) engineering to assist in solving problems with transmission lines and matching circuits. The Smith Chart is plotted on the complex reflection coefficient plane in two dimensions and is scaled in normalized impedance (the most common), normalized admittance or both, using different colours to distinguish between them. These are often known as the Z, Y and YZ Smith Charts respectively. Normalized scaling allows the Smith Chart to be used for problems involving any characteristic impedance or system impedance, although by far the most commonly used is 50 ohms.

The Smith Chart plot (figure3.4) represents that how the antenna impedance varies with frequency.

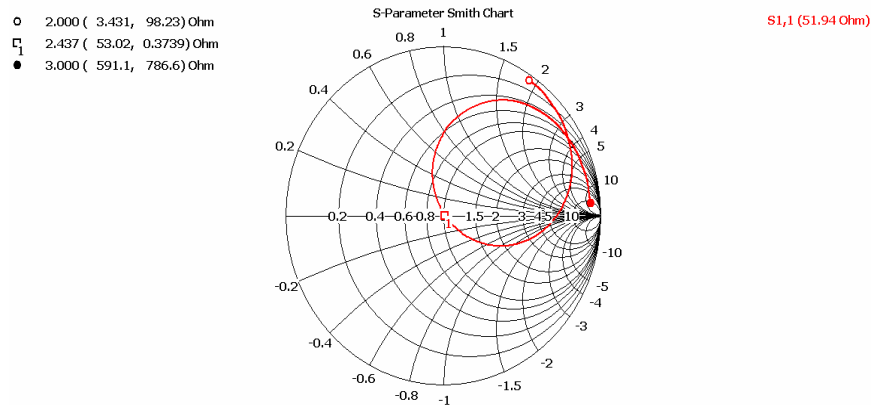


Figure 3.4 Smith Chart

3.4.3 Voltage Standing Wave Ratio (VSWR)

The most common case for measuring and examining VSWR is when installing and tuning transmitting antennas. When a transmitter is connected to an antenna by a feed line, the impedance of the antenna and feed line must match exactly for maximum energy

transfer from the feed line to the antenna to be possible. When an antenna and feed line do not have matching impedances, some of the electrical energy cannot be transferred from the feed line to the antenna. Energy not transferred to the antenna is reflected back towards the transmitter. It is the interaction of these reflected waves with forward waves which causes standing wave patterns.

Matching the impedance of the antenna to the impedance of the feed line is typically done using an antenna tuner. The tuner can be installed between the transmitter and the feed line, or between the feed line and the antenna. Both installation methods will allow the transmitter to operate at a low VSWR. Ideally, VSWR must lie in the range of 1-2 which is achieved in figure 3.5 for the frequency 2.438 GHz, near the operating frequency value.

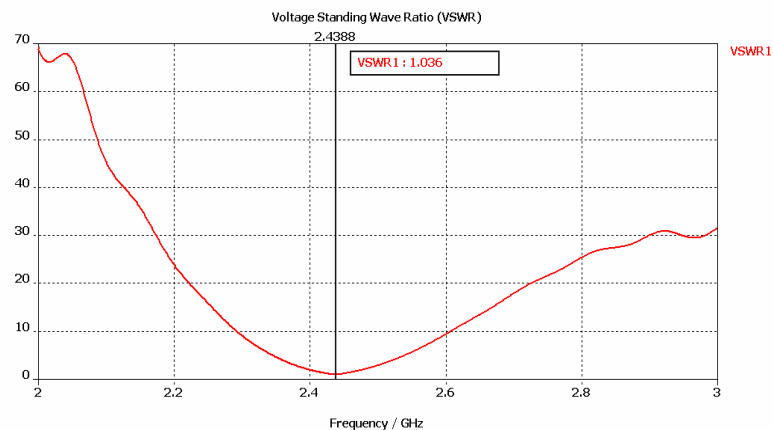


Figure 3.5 VSWR Versus Frequency Plot

3.4.4 Input Impedance

We expect pure real impedance at frequencies where the patch resonates, that is, where the patch is designed to radiate. As a result, the input impedance plot in Fig 3.6 shows that around the desired radiating frequency, sufficient reactance cancellation can only occur inside a narrow bandwidth. In addition, one needs to match the resonant resistance with the characteristic impedance of the feed line. A small antenna can be tuned to resonate with an appropriate addition of reactance, or it can be made to self-resonate so that the reactance cancellation at resonance happens naturally in the antenna structure. Since adding external reactance for this purpose increases the power loss and it also requires extra space, it is advisable to follow the second alternative.

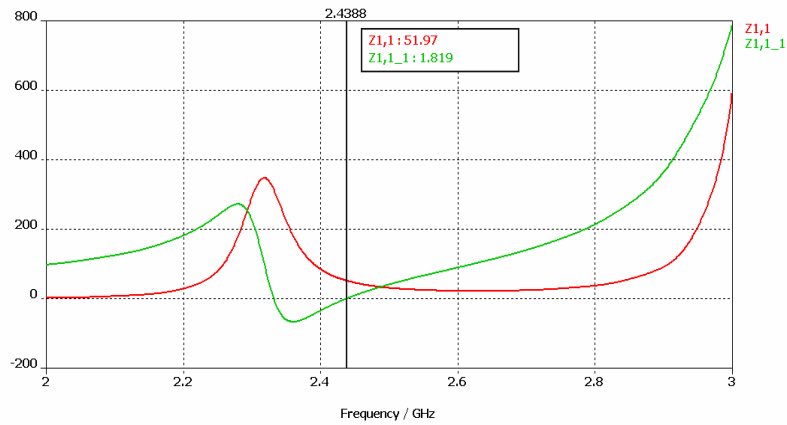


Figure 3.6 Z Parameter

3.4.5 Radiation Pattern Plots

The radiation pattern is a graphical depiction of the relative field strength transmitted from or received by the antenna. Antenna radiation patterns are taken at one frequency, one polarization, and one plane cut. The patterns are usually presented in polar or rectilinear form with a dB strength scale.

Since a Microstrip patch antenna radiates normal to its patch surface, the elevation pattern for $\phi = 0$ and $\phi = 90$ degrees would be important. Figure 3.7 below shows the gain of the antenna at 2.438 GHz for $\phi = 0$ and $\phi = 90$ degrees.

The maximum gain is obtained in the broadside direction and this is measured to be 6.8dBi for both, $\phi = 0$ and $\phi = 90$ degrees.

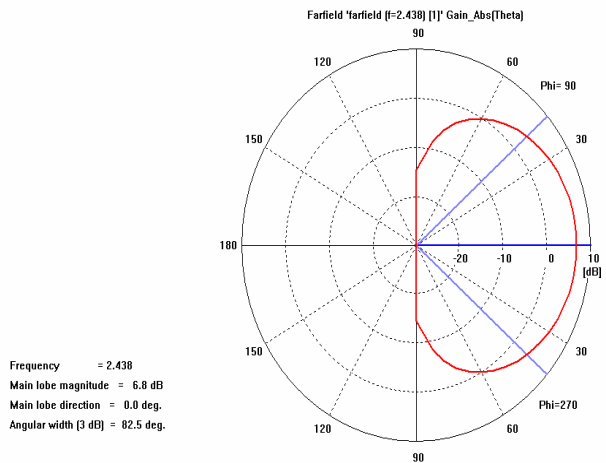


Figure 3.7 (a)

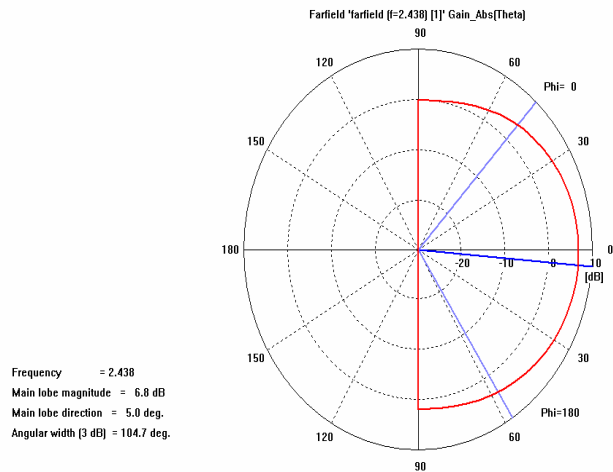


Figure 3.7 (b)

Figure 3.7 Simulated Far-field Radiation Pattern at 2.43 GHz

(a) For $\phi = 90$ degrees

(b) For $\phi = 0$ degrees.

3.4.6 Gain Versus Frequency Plot

The figure 3.8 shows the gain Versus frequency plot. This plot indicates that the gain is 6.79 dBi at the resonating frequency 2.438 GHz.

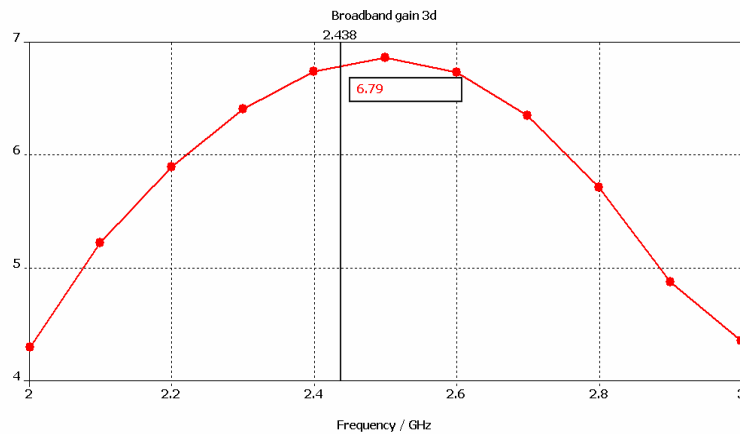


Figure 3.8 Gain Versus Frequency Plot

3.4.7 EFFECT OF FEED POINT LOCATION:

Feed point should be chosen in such a way so that there is a good impedance match between the generator impedance and the input impedance of the patch element. Figure 3.9 shows that how the return loss varies as the feed point changes.

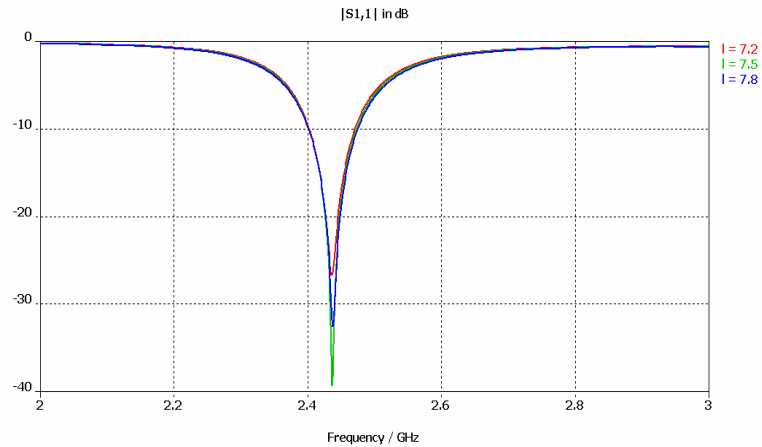


Figure 3.9 Effect of feed point location

3.5 Conclusion

With the ever-increasing need for wireless communication, it is important to design broadband 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. Microstrip patch antennas have found extensive application in wireless communication system owing to their advantages such as low-profile, conformability, low-cost fabrication and ease of integration with feed networks. However, conventional Microstrip patch antenna suffers from very narrow bandwidth, typically about 5% bandwidth with respect to the centre frequency. This poses a design challenge for the Microstrip antenna designer to meet the broadband techniques.

Some methods to increase the bandwidth of patch antennas, including increase of the substrate thickness, the use of a low dielectric substrate, the use of various impedance matching and feeding techniques, and the use of slot antenna geometry etc. are discussed in the next chapter.

BROADBAND MICROSTRIP PATCH ANTENNAS DESIGN

4.1 Introduction

The rapid development of wireless communication systems is bringing about a wave of new wireless devices and systems to meet the demands of multimedia applications. Multi-frequency and multi-mode devices such as cellular phones, wireless local area networks (WLANs) and wireless personal area networks (WPANs) place several demands on the antennas. Primarily, the antennas need to have high gain, small physical size, broad bandwidth, versatility, embedded installation, etc. In particular, as we shall see, the bandwidths for impedance, polarization or axial ratio, radiation patterns and gain are becoming the most important factors that affect the application of antennas in contemporary and future wireless communication systems.

The bandwidths vary from 7% to 13% for commercial mobile communication systems, and reach up to 109% for ultra-wideband communications. The antennas used must have the required performance over the relevant operating frequency range. Antennas for fixed applications such as cellular base-stations and wireless access points should have high gain and stable radiation coverage over the operating range. Antennas for portable devices such as hand phones, personal digital assistants (PDAs) and laptop computers should be embedded, efficient in radiation and Omni-directional in coverage. Most importantly, the antennas should be well impedance-matched over the operating frequency range. For example, an array designed for a cellular base-station operating in the GSM1900 band should have an impedance bandwidth of 7.3% for a return loss of less than -15 dB. Antennas for mobile terminals must be small in physical size so that they can be embedded in devices or conform to device platforms. More often than not, the antennas are electrically small in size, which significantly narrows the impedance bandwidth and greatly reduces radiation efficiency or gain [17].

Consequently, the bandwidth requirement for small or compact antennas has become a very critical design issue. Researchers in academia and industry have devoted much effort to the development of a variety of techniques for such small or compact broadband antenna designs. Antennas with broad bandwidths have additional advantages, such as to mitigate design and fabrication tolerances, to reduce impairment due to the installation

environment, and most importantly, to cover several operating bands for multi-frequency or multi-mode operations.

This chapter reviews the techniques for improving the bandwidth of a Microstrip patch antenna. Before discussing the various broad-banding techniques of patch antenna, we discuss about the antenna impedance bandwidth.

4.2 Impedance Bandwidth

In general, an antenna is a resonant device. Its input impedance varies greatly with frequency even though the inherent impedance of its feed remains unchanged. If the antenna is well matched to its feed across a certain frequency range, then that frequency range is defined as its impedance bandwidth. The impedance bandwidth can be specified in terms of return loss (S parameter) or a voltage standing-wave ratio (VSWR) over a frequency range.

The well-matched impedance bandwidth must totally cover the required operating frequency range for some specified level, such as $VSWR = 2$ or 1.5 or a return loss S_{11} of less than -10 dB or -15 dB. Furthermore, the impedance bandwidth is inversely proportional to the quality factor (Q) [17, 18] of an antenna as given by

$$BW = \frac{VSWR - 1}{Q\sqrt{VSWR}} \quad 4.1$$

4.3 Broadband Techniques

A variety of broadband techniques have been developed using the three approaches categorized in Table 4.1. It is known that the factors affecting the bandwidth of a Microstrip patch antenna are primarily the shape of the radiator, the feeding scheme, the substrate and the arrangements of radiating and parasitic elements. Essentially, the broad bandwidth of a Microstrip patch antenna can be attributed to its low Q value and simultaneously well excited multiple resonances. If the antenna is considered as a high-Q filter, lowering the Q by reducing the energy around the radiator or increasing losses broadens the bandwidth at its resonance. Alternatively, by inserting a broadband impedance network between the antenna and the feeder, good matching over a broad frequency range can be attained. If two or more adjacent modes are well excited simultaneously, the bandwidth can be twice or more than that for the single resonance.

Table 4.1 Broadband Techniques for Microstrip patch antenna

Approach	Techniques
Lowering the Quality Factor	By increasing the substrate height
	Decreasing the relative permittivity
	Increasing the losses
Introducing Multiple Resonances	By using Parasitic elements (Stack or co-planer)
	By using slotted patches
	By using proximity or aperture coupling
Use Impedance Matching	Use slotting and notching patches
	Insert a matching network

4.3.1 Lowering the Q Factor

A Microstrip patch antenna suffers from a narrow bandwidth as the whole volume of the antenna is not utilized effectively. Therefore, a Microstrip patch antenna can be considered as a high-Q circuit, so one way to alleviate the narrow bandwidth problem is to reduce the Q [20].

Investigations have shown that the height and dielectric constant of the substrate material affects the antenna impedance bandwidth. However, the improvement in the bandwidth is quite limited [15, 20].

It is clear that the bandwidth is affected by the geometry of the antenna due to the lower Q from the larger size. The impedance bandwidth for $S_{11} < -10$ dB is still around 1%. The shape of a radiator, which affects the operating modes, is critical for its radiation performance. Therefore, this technique is hardly employed in practical designs [21]. As an alternative, a thick substrate with low dielectric constant is good for improving the impedance bandwidth of patch antennas [22, 23]. This monotonically reduces the Q and broadens the bandwidth.

Another important consideration to increase the antenna impedance is to increase the losses in substrate material. These losses may arise due to undesired surface waves, which lowers the radiation efficiency, excites spurious radiations, and degrades the radiation patterns.

It has been pointed out by the Pozar [20, 19], that the impedance bandwidth of patch antenna can be increased by introducing losses in the antenna. The losses can be in the form of lossy substrate materials, layer of lossy film, or a discrete chip resistor.

Compact Broadband Microstrip Patch Antenna with Chip-Resistor Loading

This section describes the design of chip-resistor-loaded rectangular Microstrip patch antenna with probe-feed is presented. These antenna designs have the advantages of small antenna size and wide impedance bandwidth, compared to a conventional rectangular patch antenna.

The geometry of a probe-fed rectangular Microstrip antenna with chip-resistor loading given in Figure 4.1(a) is studied first. The rectangular patch had dimensions $L \times W$, and the substrate had a relative permittivity ϵ_r and a thickness h . A 1.0Ω resistance was selected and placed at about the edge of the patch ($d_c=1\text{mm}$) for maximum resonant frequency reduction. The patch antenna is fed by the co-axial probe of 50Ω . We first analyze the behaviour of chip-resistor-loaded rectangular patch antenna and then compare its behaviour with conventional rectangular patch antenna. The substrate has dimensions $L_g \times W_g$. The geometric and material parameters for the proposed antenna are given in Table 4.2. The dimensions of the patch antenna are given in mm.

Table 4.2 Dimension and Material Properties of Chip-Resistor Loaded Patch Antenna

L(mm)	W(mm)	h(mm)	ϵ_r	d_c (mm)	d_p (mm)	L_g (mm)	W_g (mm)
28	22	1.6	4.4	1	7.33	41	36

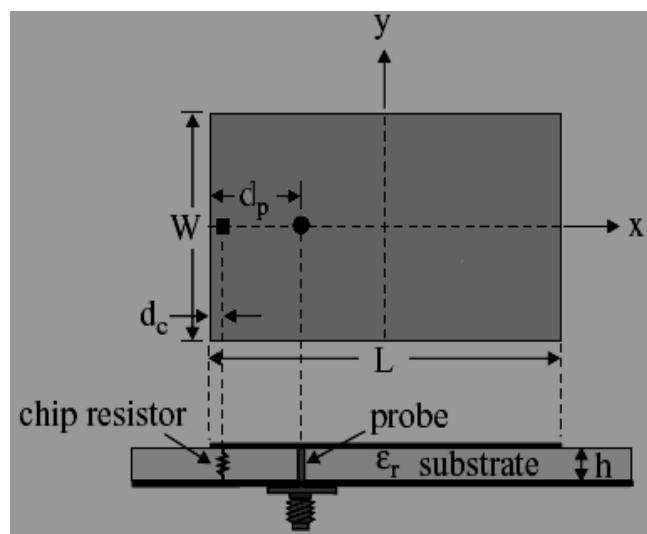


Figure 4.1(a)

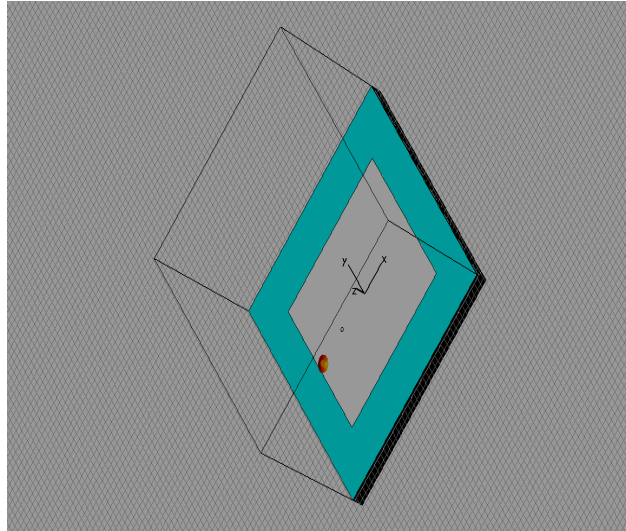


Figure 4.1(b)

Figure 1 (a): Geometry of Chip Resistor Loaded Patch Antenna
 (b): Structural View of Chip-Resistor-Loaded Patch Antenna

We conducted a parametric study on the above structure by changing the parameter d_c (location of chip resistor). The figure 4.2 shows that how return Loss and resonant frequency varies with the location of resistance (d_c) along the x axis.

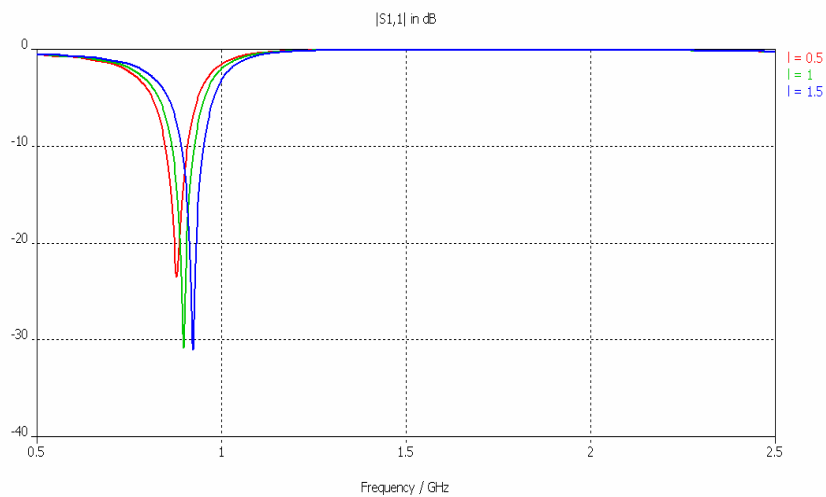


Figure 4.2 Effect of Resistance Location.

Table4.3 Effect of resistance location

d_c	Resonant frequency (f_r)	S_{11}
0.5mm	876.45 MHz	-21.5 dB
1.0mm	897.48 MHz	-30.5 dB
1.5mm	918.51 MHz	-30.5 dB

A chip resistor of 1Ω is selected in this study and is placed at the edge of the patch (d_c) for maximum resonant frequency reduction. The resistance position designated by d_c is varied from 0.5 to 1.5 mm. From the Table 4.3 we can conclude that the optimum value of d_c for better response of proposed antenna is 1 mm.

The result of the simulated return loss against frequency for chip-resistor-loaded patch with impedance matching is shown in figure 4.3 (a). It can be observed that the resonant frequency is about 897.48 MHz and the bandwidth that determined from the -10 dB return loss is 7.6%. For the purpose of comparison, an antenna using the same size and substrate but without chip resistor is also analysed and its return loss versus frequency plot is shown in figure 4.3(b). It is observed that conventional patch antenna is resonating at about 2.4448 GHz and -10dB bandwidth is about 1.4% around the centre frequency.

Table 4.4 compares the resonant frequency (f_r) and the return loss (S_{11}) of the proposed antenna with a conventional patch antenna (without chip resistance).

Table 4.4 Comparing Chip-Resistor- Loaded Patch Antenna with Conventional Antenna

Antenna	f_r (GHz)	S_{11} (dB)	Impedance Bandwidth
Conventional	2.4448	27.7	1.4%
Resistance loaded	0.8974	30.5	7.6%

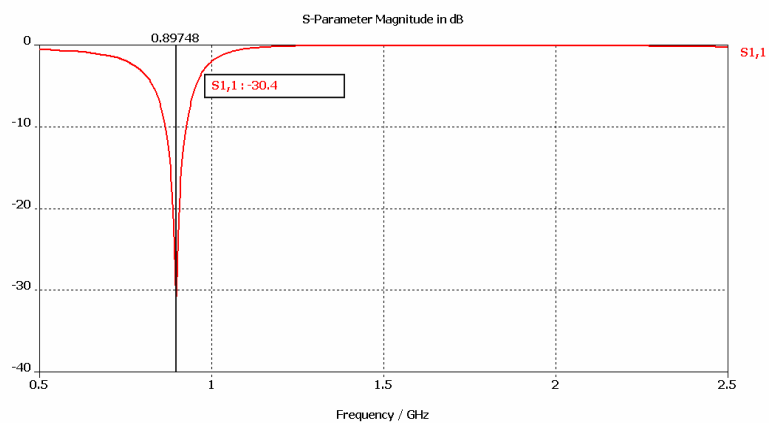


Figure 4.3(a)

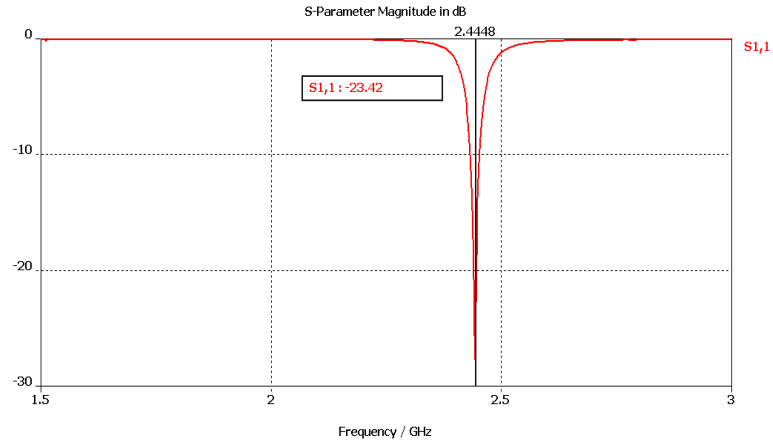


Figure 4.3(b)

Figure 4.3(a): Return loss Vs Frequency Plot for chip-resistor-loaded patch antenna.
 (b): Return Loss Vs Frequency Plot for Conventional Patch Antenna.

The simulated input impedance of this antenna is shown in figure 4.4. This plot shows that how the antenna impedance varies with frequency. This chart indicates that there is a good impedance matching between feed line and patch antenna at the resonating frequency.

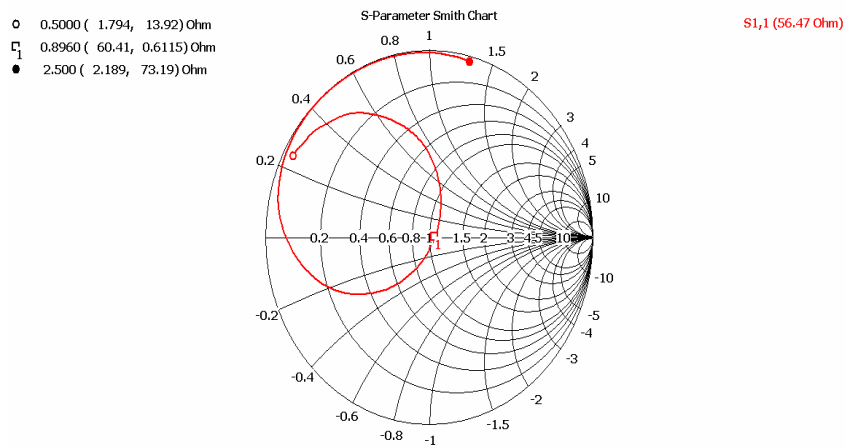


Figure 4.4(a)

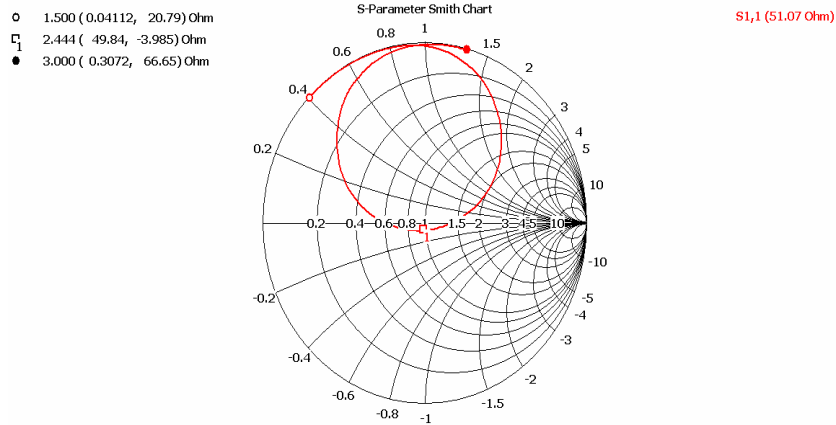


Figure 4.4(b)

Figure 4.4(a): Smith Chart For Chip-Resistor-Loaded Patch Antenna.
 (b): Smith Chart for Conventional Patch Antenna.

4.3.2 Introducing Multiple Resonances

Microstrip patch antennas are basically structures operating at the resonant frequencies with a very limited bandwidth. Operation at adjacent multiple resonances has been shown to be a practical way of enhancing the bandwidth. Using this approach, two or more adjacent resonances are well excited within the operating frequency range simultaneously. This technique has been commonly used in RF circuits such as stage-tuned filters and other antenna applications, such as log-periodic toothed planar antennas and log-periodic dipole arrays. The most direct way is to introduce additional radiating patches located close to the main radiator. These parasitic patches are excited by means of the electromagnetic coupling between them and the main patch. The parasitic patches can be in the same plane as, or stacked above, the main patch.

Stacked Arrangement

Figure 4.5 shows arrangements whereby parasitic elements are placed above the main patch. By dint of the coupling between stacked elements and the driven element, the impedance bandwidth can be increased greatly. Usually, for VSWR=1.5 the bandwidth can reach 10–20%, particularly as the medium between the upper and bottom patches is air or a material with low permittivity.

Arrangements (a)–(c) are basic stacked Microstrip patch antennas [24–26]. The bottom patch is fed directly by either probe or strip line and is usually smaller than the top parasitic element. Typically the bandwidth can be in the order of 10–20%. In order to

increase the gain of the antenna, more than two top elements are stacked right above the bottom one (or with a slight offset) as illustrated in arrangement (d) [27].

Other possible arrangements include combining the co-planar and stacked structures for a low-profile design with a broad bandwidth and high gain. Examples are shown in Figure 4.5 (e) and (f). One drawback is the increased lateral size, making design difficult for array applications. However, stacked Microstrip antennas and their variations have been applied widely in practical systems, particularly in arrays, due to their broad impedance, good radiation performance and high gain.

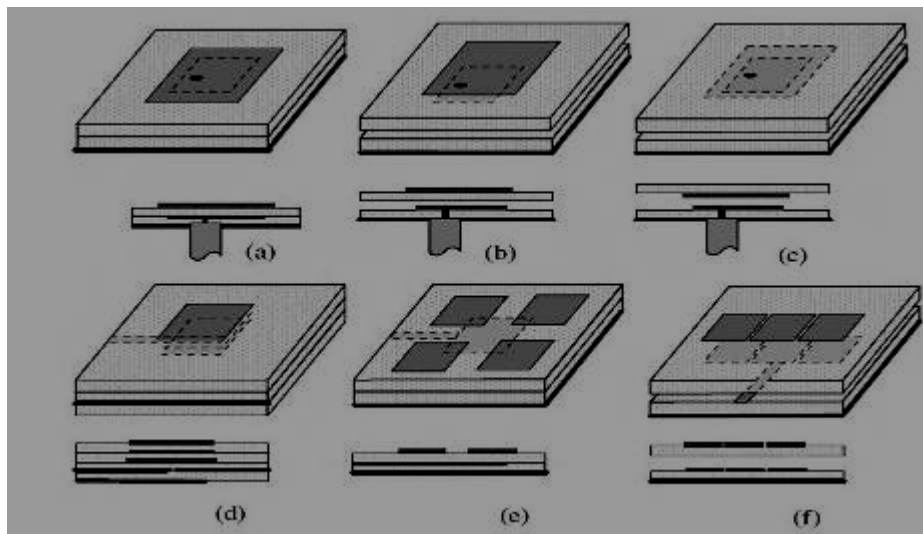


Figure 4.5 Stacked Coupling Schemes.

Designing of Patch Antenna with Stacked Elements

In this design example, we shall consider an antenna for use in an indoor 2.45-GHz WLAN base station. The frequency range of the system is from 2.4 GHz to 2.484 GHz.

To broaden the impedance bandwidth, two rectangular patches were stacked up on two substrates with the same thickness of $h_1=h_2= 1.524$ mm and $\epsilon_{r1}=\epsilon_{r2}= 4.4$. As in the single patch antenna, the double patch Microstrip antenna is fed by coaxial probe feed at one of the edges in the middle of the width of the bottom patch. The location of the feed point is manipulated for optimum impedance matching. With this configuration the -10 dB bandwidth is increased up to 113.57 MHz from 71 MHz (obtained from single patch configuration).

The design parameters of stacked patch antenna are given in Table 4.5. The patch antenna is fed by the co-axial probe of 50Ω. Here, a comparison is made between the stacked patch configuration and conventional patch antenna.

Table 4.5 Design Parameters of Stacked Patch Antenna.

L	W	$\epsilon_{r1} = \epsilon_{r2}$	$h_1 = h_2$	L_g	W_g
37	47.70	2.3	1.524	57	66

The S_{11} parameter for the designed antenna is simulated and shown in figure 4.6. It is resonating at 2.43 GHz with a return loss of -40.6 dB and 41.46 dB for single patch and double patch (stacked) configuration respectively. The achieved values of return loss are small enough and frequencies are closed enough to specified frequencies bands for WLAN applications. These return loss values suggest that there is good matching at the frequency point below the - 10 dB region. The impedance bandwidth for the single patch antenna is 70 MHz (approximately from 2.4 GHz to 2.470 GHz) while the bandwidth for double patch antenna is 87.7 MHz (form 2.396 GHz to 2.484 GHz). Figure 4.8 shows the simulated radiation pattern of proposed antenna with directivity 6.8dBi and 4.88dBi for single patch and double patch configuration respectively at the resonating frequency of 2.43 GHz.

The smith chart is also shown in figure 4.7 for both the patch antennas. This plot indicates that both the antennas are perfectly matched at the resonating frequency of 2.43GHz.

A comparison between single patch antenna and stacked patch antenna is shown in Table 4.6.

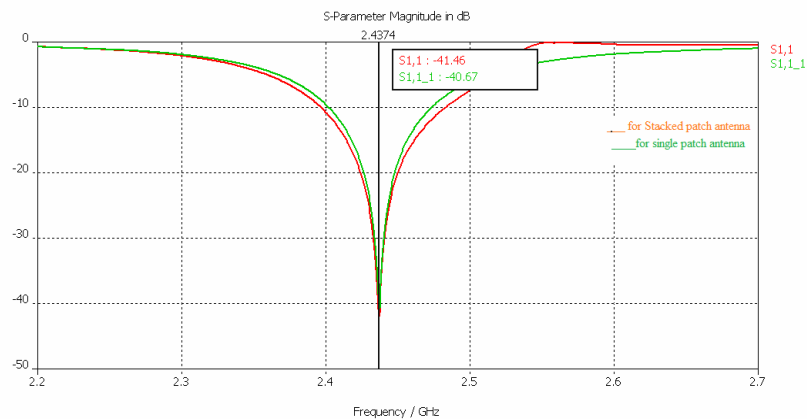


Figure 4.6 Return Loss Plot for Stacked Patch Antenna and Single Patch Antenna

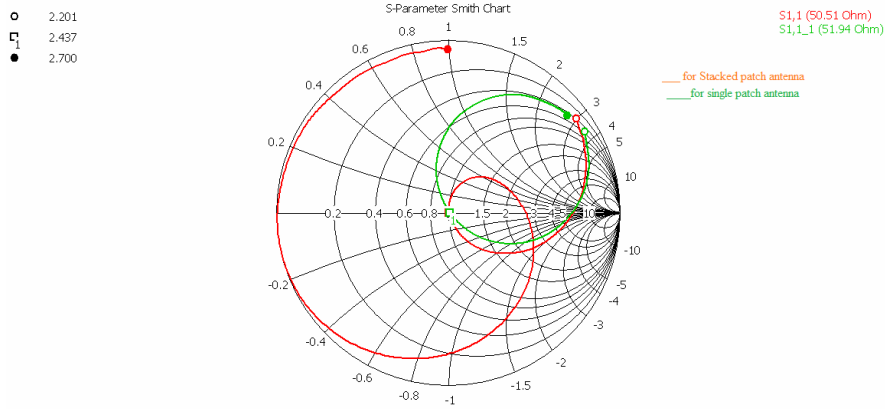


Figure 4.7 Smith Chart Plot

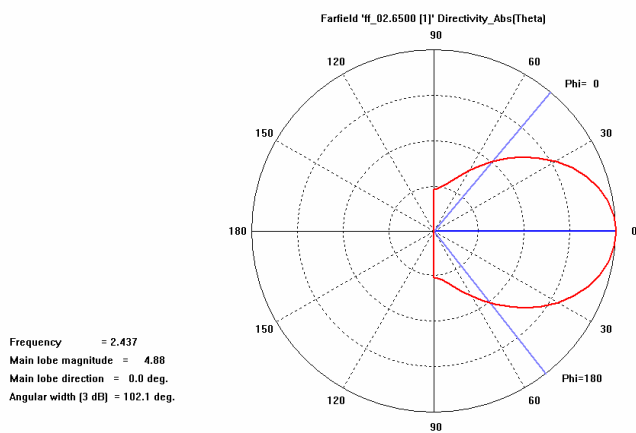


Figure 4.8 (a)

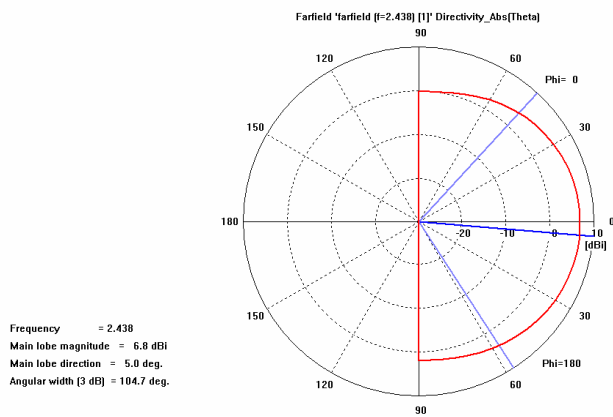


Figure 4.8 (b)

Figure 4.8 (a): Radiation Pattern of Stacked Patch Antenna at $\phi=0^\circ$
(b): Radiation Pattern of Single Patch Antenna at $\phi=0^\circ$

Table 4.6 Comparison between Single and Double Patch Antenna

Parameter	Single Patch Antenna	Double Patch antenna
Return Loss	-40.6dB	-41.46dB
Impedance Bandwidth	70 MHz	87.7 MHz
Directivity	6.8dBi	4.88dBi

U Slot Loaded Patch Antenna

Researchers have devised several methods to increase the bandwidth of Microstrip antennas in addition to the common techniques of increasing patch height and decreasing substrate permittivity. These include using a multilayer structure consisting of several parasitic radiating elements with slightly different sizes above the driven element (a stacked patch antenna) [29] or a planar patch antenna surrounded by closely spaced parasitic patches (a coplanar parasitic sub array) [30]. The stacked patch antenna increases the thickness of the antenna while the coplanar geometry increases the lateral size of the antenna. Incorporation of a dissipative load in a single-layer single-patch antenna through addition of high loss material or resistors also increases bandwidth but compromises the antenna's efficiency and gain [31, 32]. The bandwidths of single patch antennas can also be increased by implementing internal structures such as shorting pins [33, 34] or slots [35].

In this section, we present a simple design for the rectangular U-slot Microstrip patch antenna on a substrate. The geometry of patch antenna is shown in figure 4.9 and the design specifications are given in table 4.7. The width of each slot is 2mm. The antenna structure is fed with a 50Ω co-axial probe. The inner and outer radius of coaxial probe is 0.3mm and 2 mm respectively.

Table 4.7 Design Specifications of U Slot Patch Antenna

Lp(mm)	Wp(mm)	Lg(mm)	Wg(mm)	h(mm)	a(mm)	b(mm)	ϵ_r
36	26	90	80	8	14	18	2.33

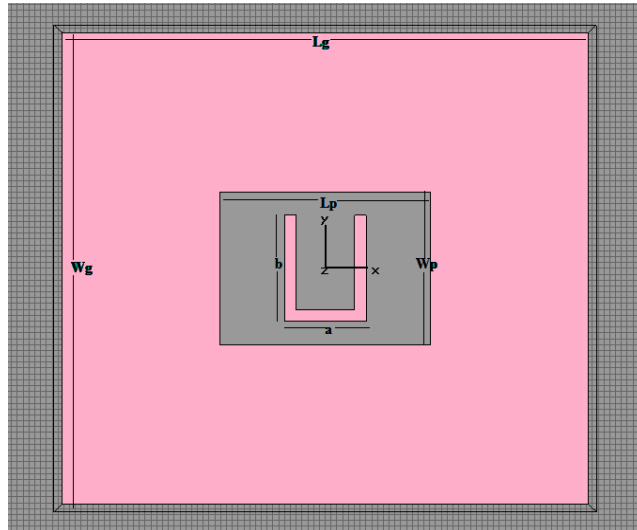


Figure 4.9 Structure of U-Slot Patch Antenna.

Effect of Geometrical Parameter

In order to study the effect of the various geometrical parameters on the antenna performances, the parameters were varied one at a time keeping the others fixed.

Effect of Variation in Horizontal Slot Length (a)

Form the table 4.8 and figure4.10, it is cleared that increasing a, the matching between the feed line and patch antenna increases (return loss improves). But after the certain values of a, it starts decreasing. The change in a does not affects the resonant frequency significantly.

Table 4.8 Increasing the Parameter a

Horizontal Slot Length	Return Loss(S_{11} in dB)
10	-5.4
12	-10.8
14	-45.85
16	-13.9

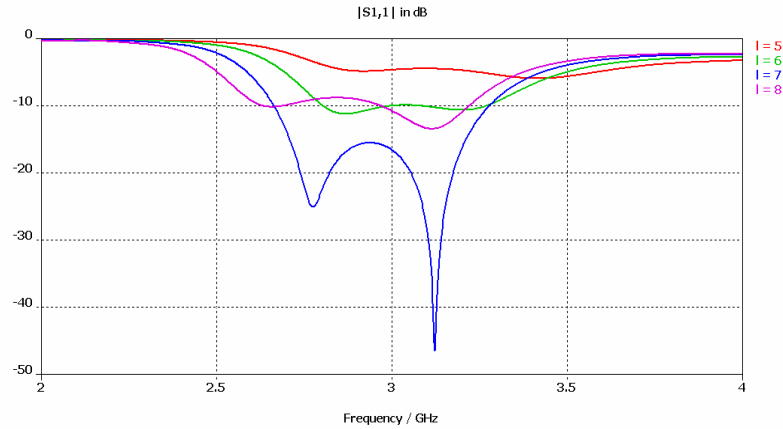


Figure 4.10 Effect of Variation in a (Horizontal Slot Length)

Effect of Variation in Vertical Slot Length (b)

Figure 4.8 shows that as we increase the parameter b (vertical length of slot U), the higher resonating frequency decreases significantly, but the magnitude of S_{11} in dB decreases at a very fast rate and after a certain value of b , S_{11} Starts increasing. From the plot 4.8, we can conclude that the optimum value of vertical slot length (b) is 18mm.

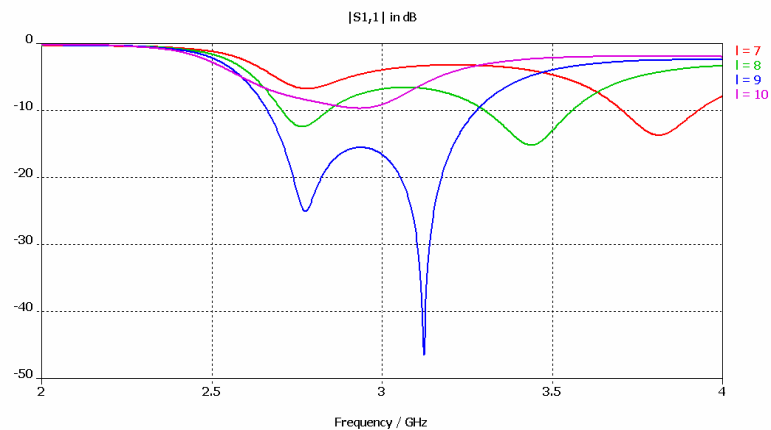


Figure 4.11 Effect of Variation in Vertical Slot Length (b)

Effect of variation in slot width (w)

As the slot width increases, the matching impedance between the coaxial feed and patch antenna improves. Figure 4.9 depicts that the optimum value of slot width is 2mm for better antenna performance.

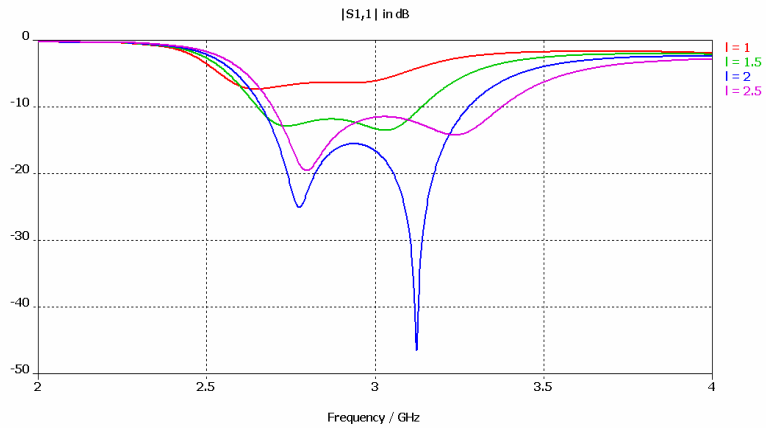


Figure 4.12 Effect of Variation in Slot Width

Effect of variation in Feed point Location

As we know that feed point location greatly affects the antenna performances. Figure 4.13 shows that proper impedance matching between feed and patch occurs at $y=1$ along the centre line of y axis.

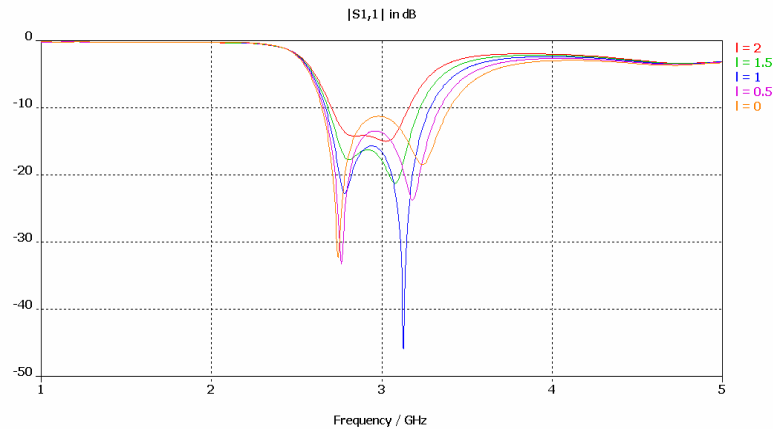


Figure 4.13 Effect of Feed Point Location in U Slot Patch Antenna

The simulated results of U slot patch antenna are given below.

Return Loss Parameter

The simulated return loss result of the proposed U slot patch antenna is shown in figure 4.14. It depicts that the antenna resonates at 3.1245 GHz frequency and the bandwidth that is determined from -10dB return loss is about 19.6%.

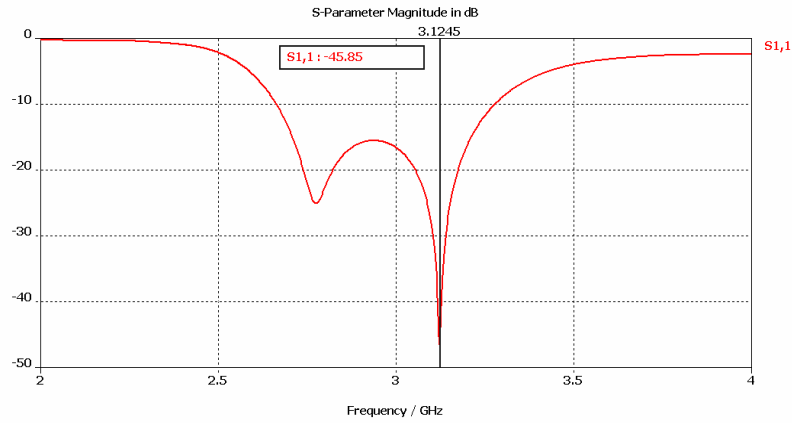


Figure 4.14 Return Loss Versus Frequency Plot

Smith Chart

Figure 4.15 depicts that how the antenna impedance varies with frequency. The antenna impedance is properly matched at the resonating frequency.

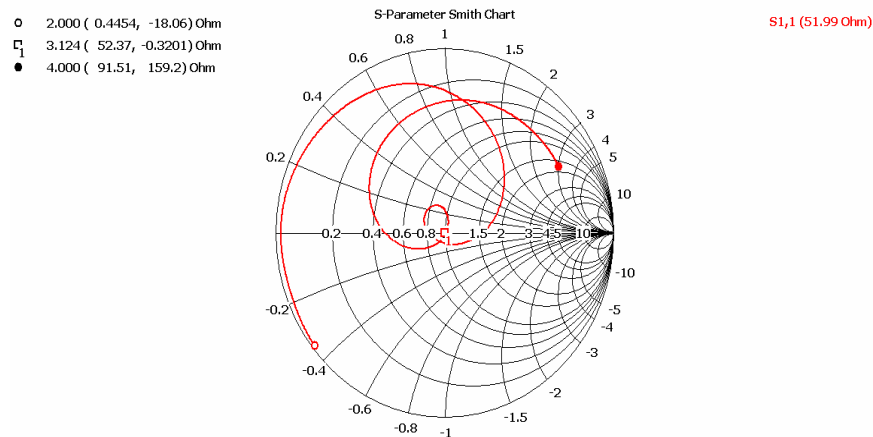


Figure 4.15 Smith Chart for Proposed Antenna

VSWR

Voltage Standing Wave Ratio (VSWR) of the patch antenna is shown in figure 4.16. This plot shows that the value of VSWR is 1.01 (less than 2) at the resonating frequency 3.1245 GHz. The impedance bandwidth of this proposed antenna is 19.6% for VSWR<2.

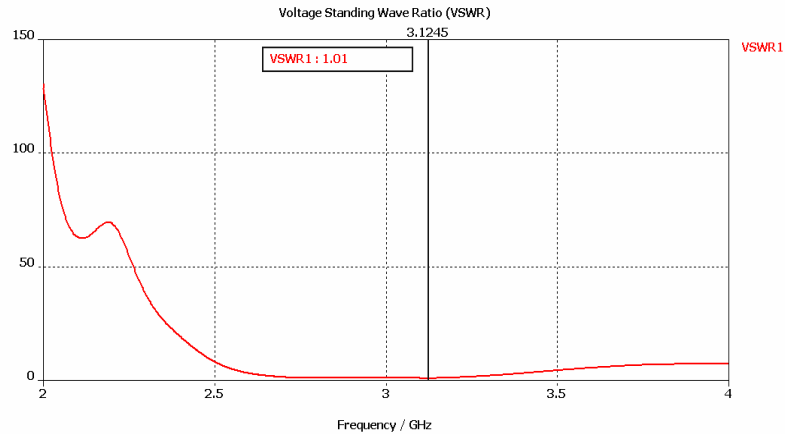


Figure 4.16 Simulated VSWR Versus Frequency Plot

Input Impedance

Ideally, the antenna impedance should be purely real at the resonating frequency. The input impedance (Z parameter) of patch antenna is plotted against frequency in figure 4.17. It shows that the antenna impedance is almost real at the resonating frequency.

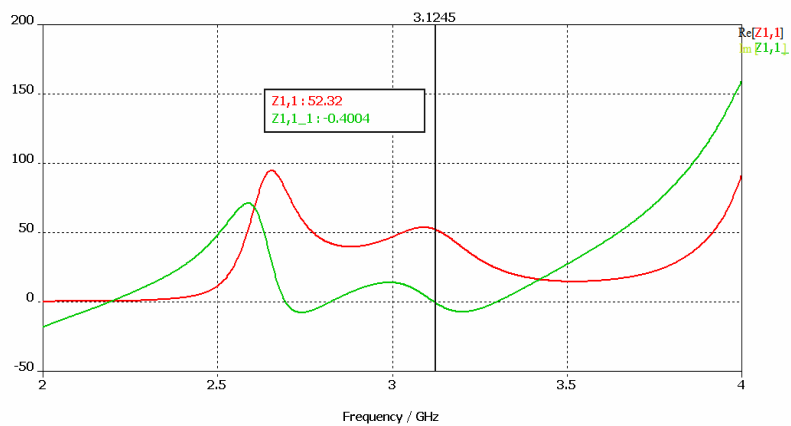


Figure 4.17 Simulated Z Parameter

Gain Versus Frequency Plot

The gain of patch antenna is plotted against frequencies in figure 4.18. The gain of antenna is 8.022 dBi at the resonating frequency.

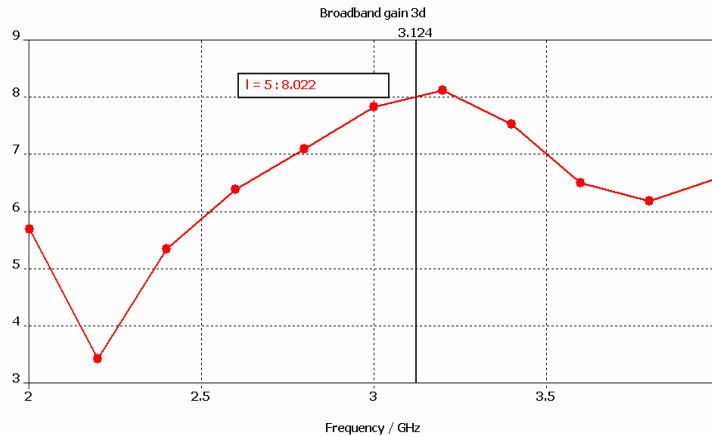


Figure 4.18 Simulated Gain Versus Frequency Plot

4.3.3 Using an Impedance Matching Network

An impedance matching network can be introduced to realize good matching between a radiator having frequency-dependent impedance and a feed structure with a constant characteristic impedance. This naturally leads to a broader bandwidth. There are two common methods employed in Microstrip patch antennas. One is to insert a separate matching network without altering the radiator. Another is to introduce an on-patch matching network either by slotting or notching the radiator. With both methods, the insertion of a lossy or lossless impedance matching network between the antenna and feeding structure can directly improve the impedance bandwidth. This method has been commonly used in a variety of antenna applications [36-38].

Bandwidth Enhancement by Reducing Ground Size

Several bandwidth enhancement techniques have been considered, such as associating several elements (patch) to form an array antenna [4], using log periodic arrays in which the different elements are deduced from an homothetic ratio in order to reach the desired bandwidth, introducing a capacitive coupling between the radiating element and the ground plane (Rmili and Floc'h, 2008), adding slots on the side of the radiating element (Shackelford et al., 2003; Chiou et al., 2003), using a tapered feed line (Kshetrimayum and Pillalamarri, 2008), notching the ground plane and/or the patch (Tourette et al., 2006; Zhang et al., 2009), modifying the shape of the radiating element (Tran et al., 2007) and adding a shorting pin (Shackelford et al., 2003). All these techniques are based on the modification of the surface current distribution to ameliorate the antenna's impedance bandwidth.

In this section, the modification of ground plane dimensions and feed line position were chosen for the design of wideband antennas for wireless applications. This technique leads to the design of patch antennas with a reduced ground plane.

The geometry of patch antenna is shown in figure 4.19. The antenna is fabricated on standard substrate material FR4 (thickness=1.6 mm and relative permittivity=4.4). The antenna is fed by 50Ω micro-strip line. A reduced ground plane is printed the bottom of substrate. The designing parameters of patch antenna are summarized in Table 4.9.

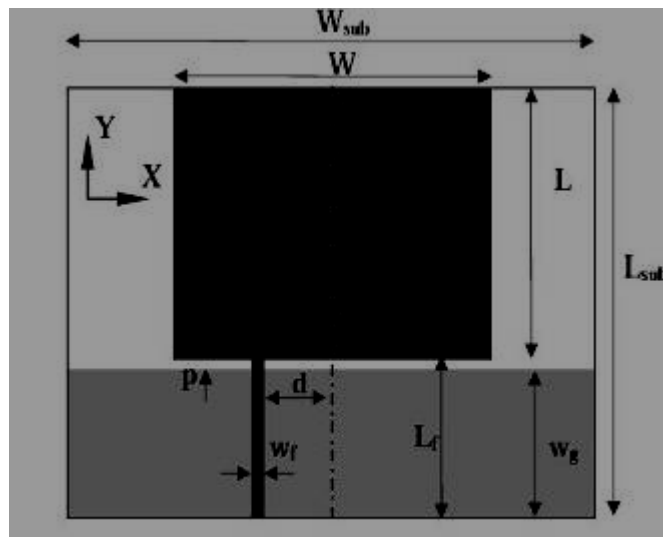


Figure 4.19 Geometry of Patch Antenna

Table 4.9 Design Parameter of Patch Antenna

W_{sub}	L_{sub}	W	L	W_f	D	P	L_f	W_g
100mm	90mm	60mm	60mm	3.5mm	12.75mm	2.5mm	30mm	27.5mm

In order to achieve a better impedance matching, a parametric study was performed on the gap distance p , which is mainly responsible for return loss parameter at the resonating frequency, as plotted in Figure 4.20. The figure depicts that the optimum value of p is 2.5 for the better antenna performances.

The figure 4.21 indicates that the square patch antenna with reduced ground size resonates at 2.84GHz frequency with a return loss of -38.36 dB. It covers a frequency band ranging from 1.58 GHz to 4.06 GHz with an impedance matching around 87.3%.

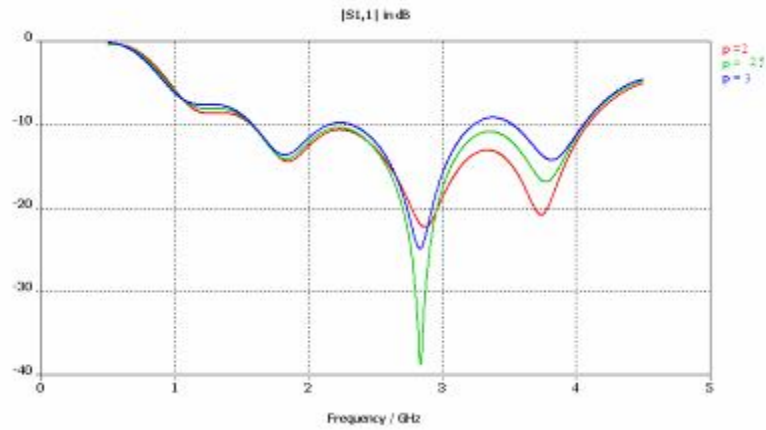


Figure 4.20 Effects of Variation of p.

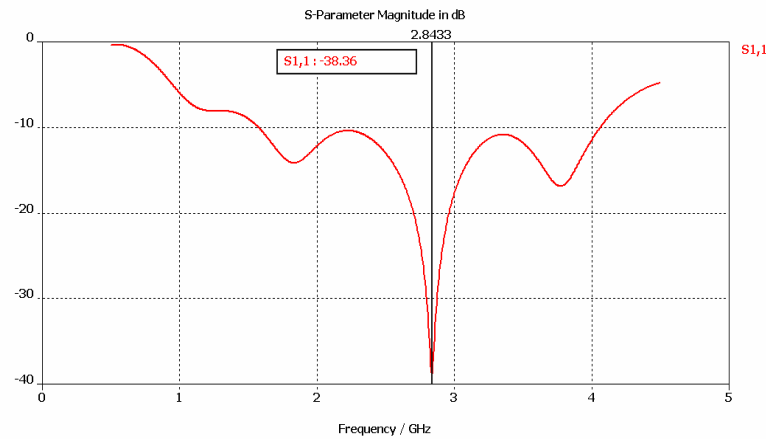


Figure 4.21 Simulated Return Loss Versus Frequency Plot.

The smith chart shown in figure 4.22 shows that there is good impedance match between the feed line and antenna. The antenna impedance is almost real at the resonating frequency 2.84 GHz.

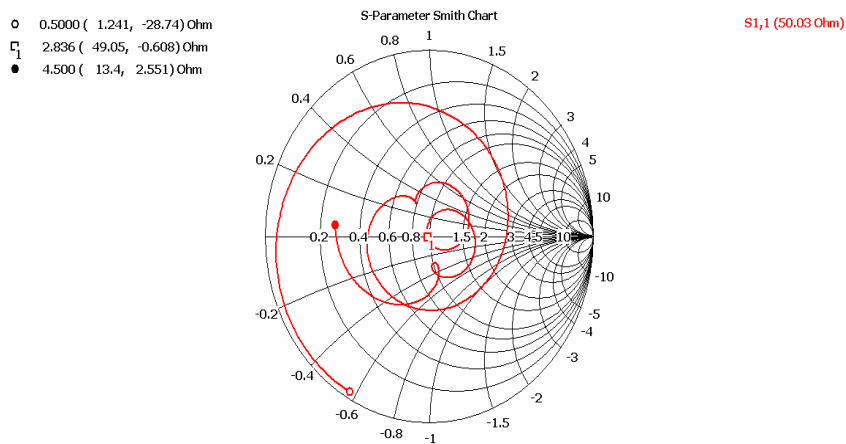


Figure 4.22 Smith Chart

The simulation plot of gain is plotted against frequency in figure 4.23. This shows that the average gain of patch antenna is approximately 5.5dBi in the pass-band.

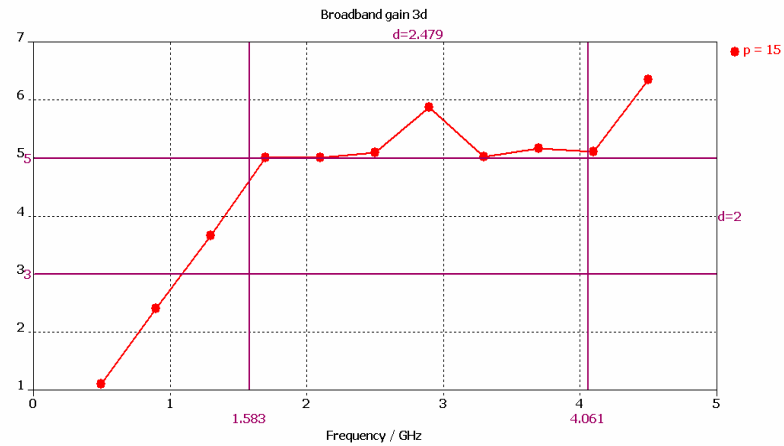


Figure 4.23 Gain Vs Frequency Plot.

E-shaped Broad-band Patch Antenna

Microstrip patch antennas have been used for many applications, such as Direct Broadcasting Satellite (DBS) systems, mobile communications, Global Positioning System (GPS) and various radar systems [1]. Their advantages include low profile, light weight, low cost, ease of fabrication and integration with RF devices, etc. They can also be made conformal to mounting structures [2]. However, when they are applied in the frequency range below 2GHz, the sizes of conventional rectangular Microstrip patches seem to be too large, which makes it difficult for them to be installed on televisions, notebook computers or other hand-held terminals, etc. Several techniques have thus been proposed to reduce the sizes of conventional half-wavelength Microstrip patch antennas. Material of high dielectric constant has been used. However, this will lead to high cost and high loss. Also, poor efficiency due to surface wave excitation is another drawback of this method.

In this section, we propose a compact rectangular E-shaped patch antenna. The objective of the proposed design is to improve the impedance bandwidth. The proposed configuration of the antenna is shown in figure 4.24. The proposed design consists of a single layer of thickness 6mm. An E-shaped patch with two circles is deposited on it. To excite the patch, a single probe feed is applied to the patch at the centre of upper circle. The radius of each circle is 1mm. Polystyrene-ceramic is used as a substrate. The

dielectric constant of this substrate is 6. The dimensions of this E-shaped patch antenna are given in table 4.10.

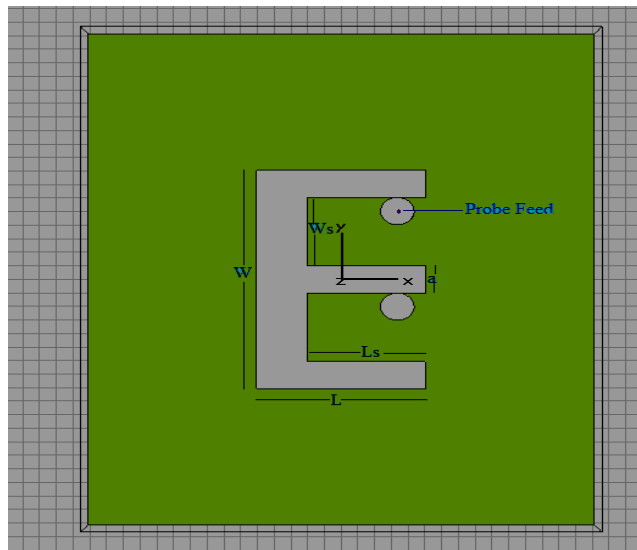


Figure 4.24 Geometry of E-Shaped Patch Antenna

Table 4.10 Dimensions of E-Shaped Patch Antenna

L(in mm)	W(in mm)	Ls(in mm)	Ws(in mm)	a(in mm)	h(in mm)	ϵ_r
10	16	7	5	2	6	6

The return loss of slot loaded patch antenna is shown in figure 4.25. It resonates at 5.40 GHz frequency. The resonant frequency gives the measures of impedance bandwidth characteristics of the patch antenna. The impedance bandwidth for the proposed antenna is 3.06GHz (from 3.68GHz to 6.74GHz). From the figure 2 the return loss value at the resonant frequency $f_r = 5.40$ GHz is -46.92 dB. The achieved value of return loss is small enough.

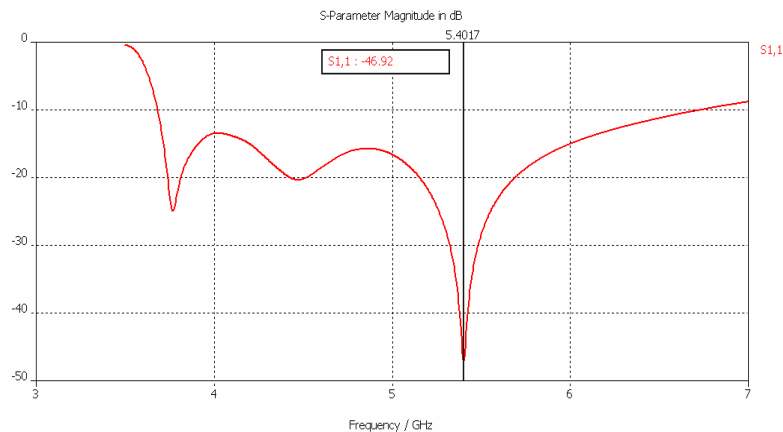


Figure 4.25 Simulated Return Loss for E Shaped Patch Antenna

Figure 4.26 shows the variation of VSWR with frequency. The value of VSWR at the resonating frequency (5.40 GHz) is 1.009 i.e. there is a good impedance matching between the antenna and feed line. The simulated result shows that the proposed patch antenna achieves impedance bandwidth of approximately 56.7% for VSWR <2, covering a frequency range from 3.68GHz to 6.74GHz. The bandwidth obtained is remarkable as far as the simplicity of the geometry is concerned.

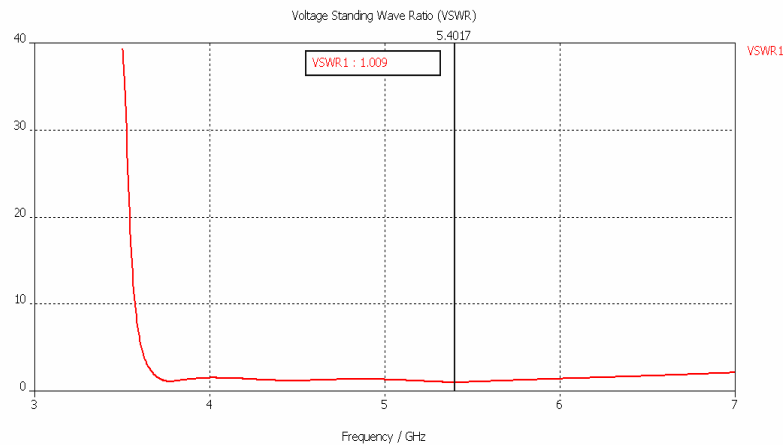


Figure 4.26 VSWR Plot for E Shaped Patch Antenna

Figure 4.27 shows the input impedance plot of patch antenna. This plot indicates that the antenna impedance is almost real at the resonating frequency.

Figure 4.28 shows the impedance loci of the proposed patch antenna.

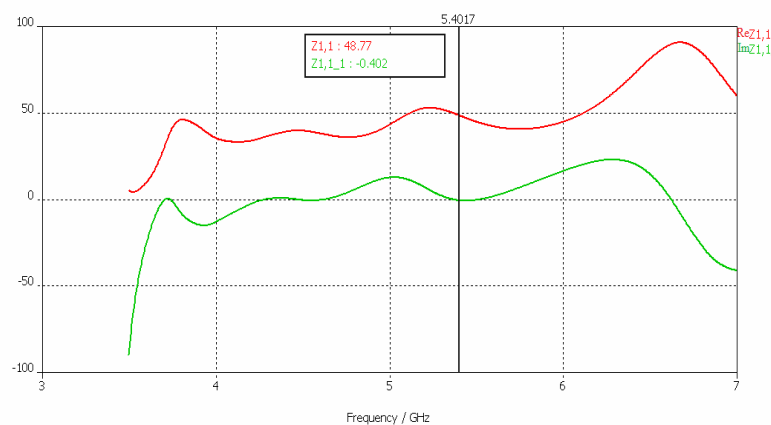


Figure 4.27 Z Parameter Plot

- 3.500 (5.457, -89.74) Ohm
- 7.000 (60.19, -40.91) Ohm

S_{1,1} (48.61 Ohm)

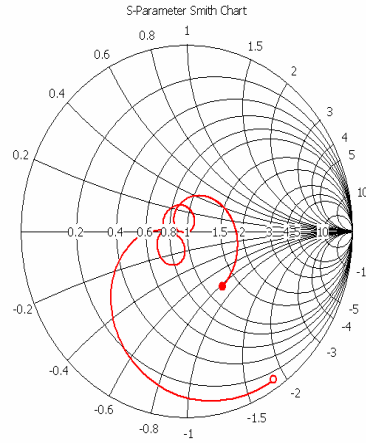


Figure 4.28 Smith Chart

4.4 Conclusion

Microstrip patch antennas are being used in communication systems due to their low profile. However in some systems, such as two way wireless communications, in order to have simply one antenna to transmit and receive the information, the antenna must be capable of operating in two distinct frequency ranges rather than just one. In addition, due to the miniaturization of portable communication devices, a small antenna is desirable. So, the modelling and designing of new small dual-band rectangular patch antenna is presented in the next chapter.

DUALBAND MICROSTRIP PATCH ANTENNAS DESIGN

5.1 Introduction

Patch antennas are popular for their well-known attractive features, such as a low profile, light weight, and compatibility with monolithic microwave integrated circuits (MMICs). Their main disadvantage is an intrinsic limitation in bandwidth, which is due to the resonant nature of the patch structure. On the other hand, modem communication systems, such as those for satellite links (GPS, vehicular, etc.), as well as emerging applications, such as wireless local networks (WLAN), often require antennas with compactness and low-cost, thus rendering planar technology useful, and sometimes unavoidable. Furthermore, thanks to their lightness, patch antennas are well suitable for systems to be mounted on airborne platforms, like synthetic-aperture radar (*SAR*) and scatter meters. From these applications, a new motivation is given for research on innovative solutions that overcome the bandwidth limitations of patch antennas. In applications in which the increased bandwidth is needed for operating at two separate sub-bands, a valid alternative to the broadening of total bandwidth is represented by dual-frequency patch antennas. Indeed, the optimal antenna for a specific application is one that ensures the matching of the bandwidth of the transmitted and/or the received signal. Dual-frequency antennas exhibit a dual-resonant behaviour in a single radiating structure. Despite the convenience that they may provide in terms of space and cost, little attention has been given to dual-frequency patch antennas. This is probably due to the relative complexity of the feeding network which is required, in particular for array applications. The need to operate at dual-frequency can arise in vehicular satellite communication systems where low-cost antennas with an almost isotropic pattern over the upper hemisphere are required; this matches well the characteristics of patch antennas.

When the system requires operation at two frequencies too far apart, dual-frequency patch antennas may avoid the use of two different antennas; a typical case is that of *SAR*. As is well-known, the present *SAR* antennas employ different arrays for each band. The trend of *SAR* antennas of the future generation is to cover at least two of the three bands with a dual-frequency antenna. This would reduce weight and surface, thus improving the possibilities of accommodation under the launcher fairing. A dual-frequency patch

antenna for SAR is very complicated to conceive, and represents an example in which all the possible critical issues involved in dual-frequency antennas coexist.

Thus, dual-frequency operation is an important subject in Microstrip antenna design [1], and many such designs are known. These dual-frequency Microstrip antennas include the use of multilayer stacked patches [2, 3], a rectangular patch with a pair of narrow slots placed close to the patch's radiating edges [4], a square patch with a rectangular notch [5], a rectangular patch loaded with shorting pins and slots [6], a rectangular patch fed by an inclined coupling slot [7], among others. Recently, many single-feed, single-layers, dual-frequency Microstrip antenna designs have been demonstrated [8–15], and a new design for a dual-frequency feed network for feeding a Microstrip array with dual-frequency radiating elements has been achieved [16]. These designs, however, are mainly applicable for regular-size Microstrip antennas. To achieve dual-frequency operation in reduced-size or compact Microstrip antennas, many promising designs have been reported [17–36]. Details of these compact dual frequency designs and some recent advances in regular-size dual-frequency designs are presented in this chapter. Finally, recent advances in compact dual-polarized designs [40] are reviewed, and design examples of some promising compact dual-polarized Microstrip antennas are given. Compact Microstrip antennas capable of dual-polarized radiation are very suitable for applications in wireless communication systems that demand frequency reuse or polarization diversity.

5.2 Dual Band Antenna Concept

In principle, multi-band planar antennas should operate with similar features, both in terms of radiation and impedance matching, at two or more separate frequencies. It is known, a simple rectangular Microstrip patch can be regarded as a cavity with magnetic walls on the radiating edges. The first three modes with the same polarization can be indicated by TM_{10} , TM_{20} and TM_{30} . TM_{10} is the mode typically used in practical applications; TM_{20} and TM_{30} are associated with a frequency approximately twice and triple of that of the mode. This provides the possibility to operate at multiple frequencies. In practice, the TM_{20} and TM_{30} modes cannot be used owing to the facts that the pattern has a broadside null and the pattern has grating lobes.

The simplest way to operate at dual frequencies is to use the first resonance of the two orthogonal dimensions of the rectangular patch, i.e., the TM_{10} and the TM_{01} modes. In

this case, the frequency ratio is approximately equal to the ratio between the two orthogonal sides of the patch. The obvious limitation of this approach is that the two different frequencies excite two orthogonal polarizations. Anyway, this simple method is very useful in low-cost short-range applications, where polarization requirements are not pressing.

The most popular technique for obtaining a dual-frequency behaviour is to introduce a reactive loading to a single patch, including stubs[40], notches [42], pins [41, 43], capacitors [42], and slots [44-45]. In [15-10], by these reactive-loading approaches, one can modify the resonant mode of the patch, so that the radiation pattern of the higher order mode could be similar to that of the fundamental mode. This indicates that the use of a single feed for both frequencies on a single radiating element can be realized. In 1995, a rectangular patch with two narrow slots etched close to and parallel to the radiating edge was used to obtain the dual-frequency operation proposed by S. Maci [44]. In this dual-frequency design, the two operating frequencies are associated with the TM_{10} and TM_{30} modes of the un-slotted rectangular patch. In addition, this two operating frequencies have the same polarization planes and broadside radiation patterns, with a frequency ratio within the range of 1.6-2.0 for the inset feed case.

The above approach characterizes a first category of dual-frequency patch antennas, which will be identified as 1) orthogonal mode dual-frequency patch antenna [44]. This category can be extended to any kind of patch shape that offers two cross-polarized resonant modes. Most of the other dual-frequency patch antennas found in the literature can be subdivided into 2) multi-patch dual frequency antennas, and 3) reactively-loaded dual-frequency patch antennas.

In this section, design examples of some recent advances in regular-size Microstrip antennas, mainly with a single-feed, single-layer Microstrip structure, are presented. The dual-frequency designs presented are divided into two groups, depending on whether the two operating frequencies have the same polarization plane or orthogonal polarization planes.

5.3 Dual Frequency Operation with a Simple Rectangular Patch

Here, we present a simple design for a single-layer, single-feed rectangular Microstrip patch antenna to achieve dual-frequency operation with orthogonal polarization [47]. In this design, the two operating frequencies are mainly determined from the rectangular

patch dimensions and the substrate permittivity. The feed position is selected such that the TM_{01} and TM_{10} modes are excited, respectively, at the first and second resonant frequencies. Figure 5.1 shows the geometry of a rectangular Microstrip patch antenna. The rectangular patch has length L and width W . The substrate has thickness h and relative permittivity ϵ_r . Based on the cavity-model approximation, we can express the resonant frequencies for the TM_{mn} mode as

$$f_{mn} = \frac{c}{2\sqrt{\epsilon_r}} \sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2} \quad 5.1$$

Where, c is the speed of light in air. The resonant frequencies f_{01} and f_{10} depend on W and L , respectively. By choosing the feed position (point A) along the y axis, we can excite the patch in the TM_{01} mode only. In this case, the excitation of the TM_{m0} mode, $m = 1, 3, 5, \dots$, is eliminated. On the other hand, when we select the feed position (point B) along the x axis, the TM_{10} mode can be excited without the excitation of the TM_{0n} mode, $n = 1, 3, 5, \dots$. By first adjusting so that the input impedances seen by the probe at feed positions A $(0, y_A)$ for the TM_{01} mode and B $(x_B, 0)$ for the TM_{10} mode are 50Ω , dual-frequency operation (f_{01} and f_{10}) can be obtained when the patch is excited at (x_B, y_A) (point C).

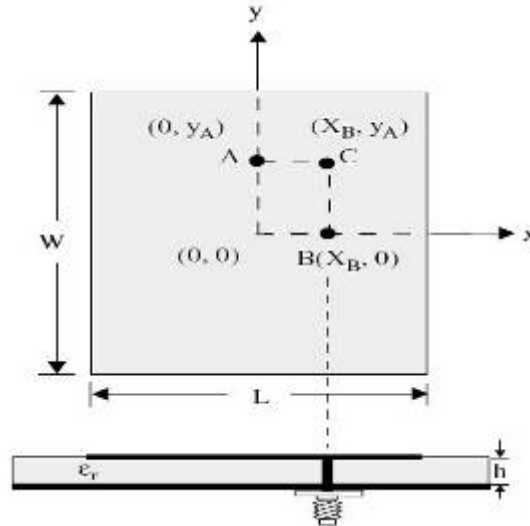


Figure 5.1 Geometry of Rectangular Patch Antenna for Dual Frequency Operation

An antenna with dual frequency operation resonating at 1.86 GHz and 2.34 GHz is designed and simulated. The height and relative permittivity of substrate material is 1.6mm and 4.4 respectively. The ground dimension is $40 \times 50 \text{ mm}^2$. To operate at dual

frequency 1.86GHz and 2.34 GHz, the patch size is chosen to be 28.83x37.30 mm². By moving the feed position along the x axis, one can find a 50- input impedance at (4.5 mm, 0) (point B) for the excitation of the TM₁₀ mode; by selecting a feed position at (0, 3.66 mm) (point A), a 50- input impedance is obtained for the TM₀₁ mode. Simulated return loss is shown in Figure 5.2. It is clear that only one resonant mode is excited in the frequency band of interest for both feed positions. By changing the feed position to (4.5 mm, 3.66 mm) (point C), two resonant modes are excited at about 1.86GHz and 2.34GHz with a good matching condition (see Figure 5.3).

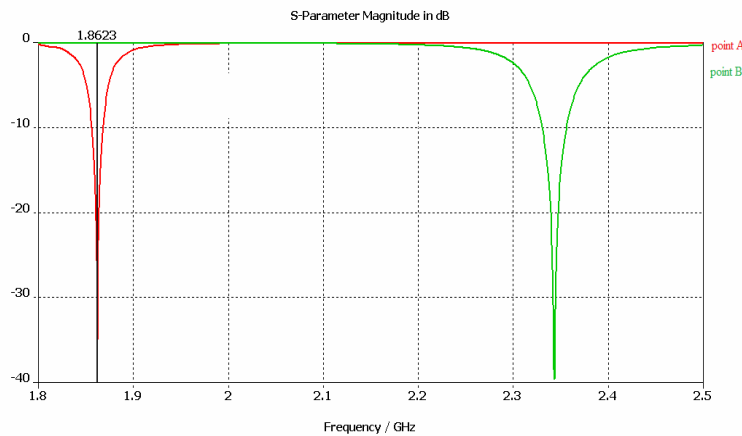


Figure 5.2 Simulated Return Loss for Feed Position at Point A, B

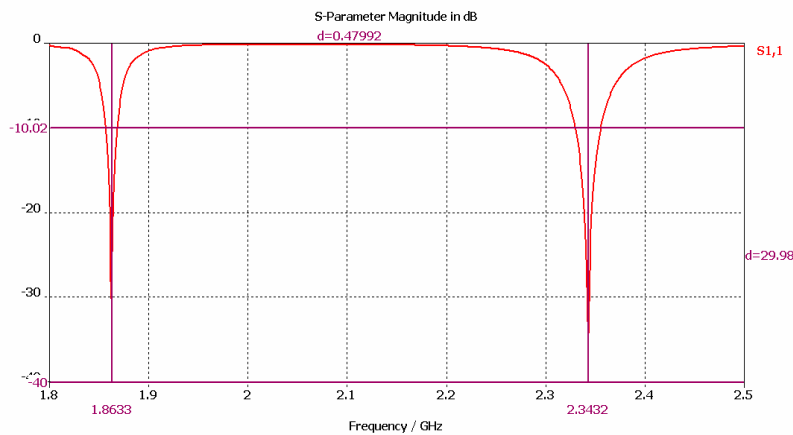


Figure 5.3 Simulated Return Loss at Feed Point C.

The simulated VSWR plot of the proposed patch antenna fed at point C is shown in figure 5.4 which depicts that the voltage standing wave ratio at two resonating frequencies is below 2. The input impedance at these two resonating frequencies is almost real and equal to 50Ω. Thus, there is a good impedance match between the patch antenna and the coaxial feed line.

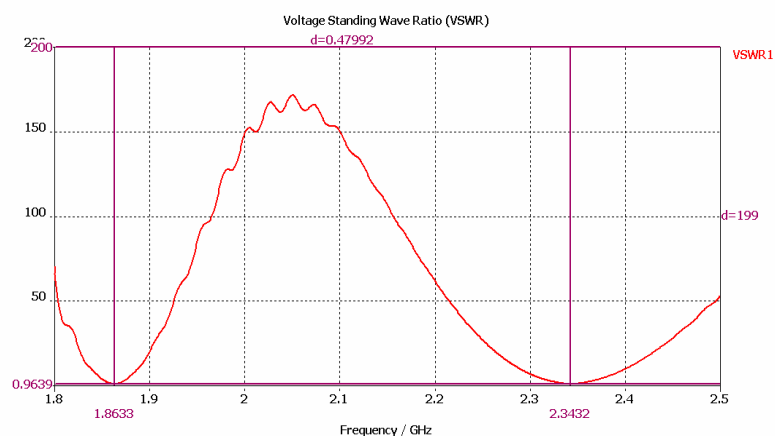


Figure 5.4 Simulated VSWR Plot

5.4 Dual Frequency Microstrip Patch Antenna with Cross Slot

In this section, rectangular Microstrip antennas with embedded slots or inserted slits for achieving compact dual-frequency operation are described. The first two resonant frequencies for these designs are found to have orthogonal polarization planes, and are both greatly lowered with increasing dimensions of the slots or slits. Dual-frequency operation of Microstrip antennas with a compact size is thus obtained.

Figure 5.5 shows the antenna geometry. The rectangular patch has dimensions $L \times W$, and the cross slot has equal slot lengths ℓ (Slot width w_s) and is centered at point B in the rectangular patch. The patch is fabricated on the top of substrate material having the dimensions of $L_g \times W_g$. Point A in the patch is the feed position for dual-frequency operation for the case without a cross slot, which is determined from the optimal feed positions of the TM_{01} and TM_{10} mode excitations. By choosing an equal-length cross slot, the optimal feed position for dual-frequency operation can easily be chosen between points A and B , as shown in the figure. Another reason for choosing an equal-length cross slot instead of using an unequal-length cross slot is that the frequency ratio of the two excited frequencies are mainly determined by the aspect ratio of the rectangular patch, which makes the dual-frequency design much simpler. In addition, by increasing the cross-slot length, both excited frequencies can be lowered with the frequency ratio almost unchanged. So, by using a cross-slot in the patch, dual-frequency operation of Microstrip antennas with a compact size is obtained. Table 5.1 shows the designed parameter of patch antenna.

Table 5.1 Dimensions of Dual Band Patch Antenna with Cross-Slot

L(mm)	W(mm)	h(mm)	ϵ_r (mm)	ℓ (mm)	L_g (mm)	W_g (mm)	w_s (mm)
37.70	28.4	1.6	4.4	10	50	40	1

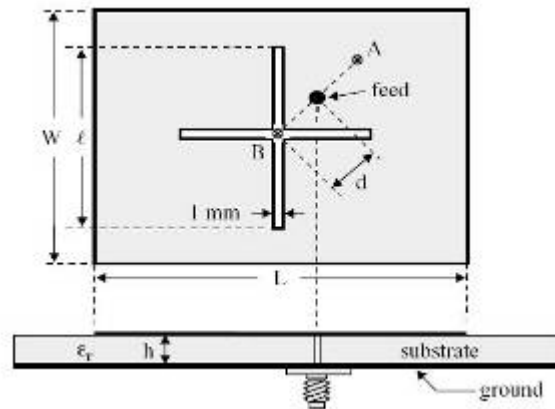


Figure 5.5 Geometry of Dual Frequency Rectangular Microstrip Patch Antenna with Cross-Slot

This proposed antenna is simulated and the performance of the patch antenna has been studied by comparing the Return loss, VSWR, Z parameter, Gain, azimuthal and elevation plane patterns.

The simulation result for return loss parameter is shown in figure 5.6. This shows that the patch antenna with cross-slot is resonating on 1.804GHz and 2.327GHz frequencies with a return loss of -20.59dB and -33.9dB respectively.

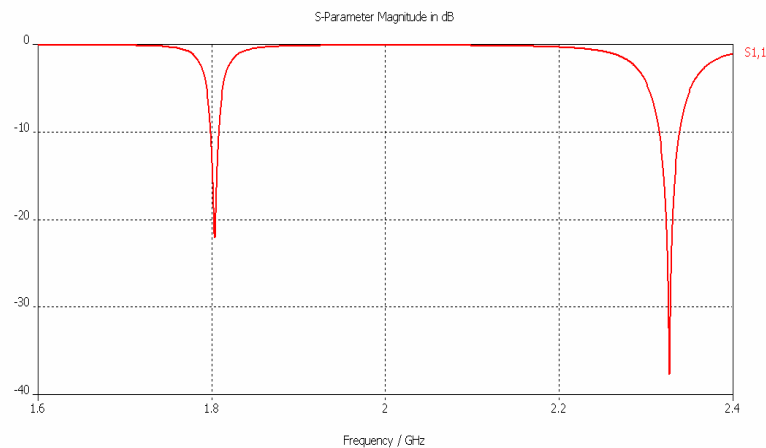


Figure 5.6 Return Loss Vs Frequency Plot

The simulation result for VSWR is shown in figure 5.7 for the frequency range 1.6GHz to 2.4GHz. The value of VSWR at these two resonating frequencies (1.804GHz and

2.327GHz) is below 2. So, there is a good impedance matching between the patch antenna and coaxial cable (50Ω) at these resonating frequencies.

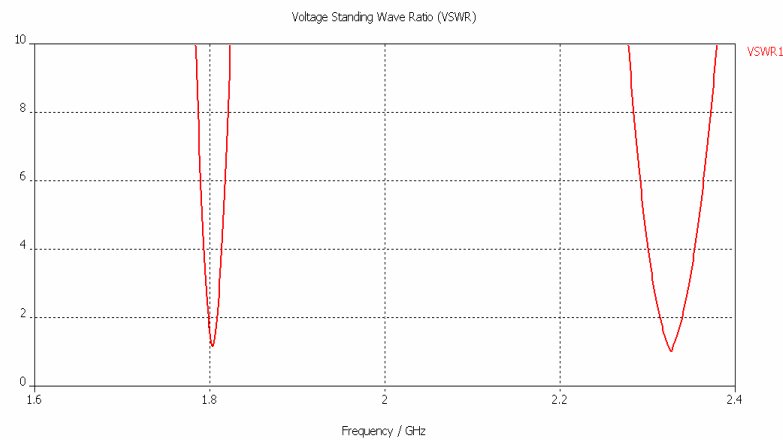


Figure 5.7 VSWR Plot

Microstrip antennas have very poor gain. But in order to be used in real life applications the gain should be more than 5dBi. The simulation result for the antenna gain in dB is shown in figure 5.8. The approximate value of gain in dB at the two central frequencies is obtained to be 6.5dBi at 1.804GHz and 6.19dBi at 2.327GHz.

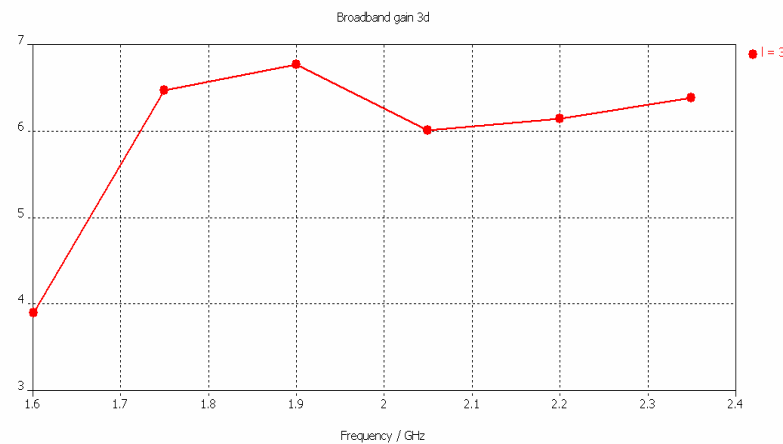


Figure 5.8 Gain Vs Frequency Plot

5.5 Slot Loaded Patch Antenna for Dual Band Applications

In this section, the design of a coaxially fed single layer single patch wideband Microstrip antenna in the form of slot loaded rectangular patch antenna is presented. The

slot loaded patch antenna resonates at 2.43 GHz and 3.5 GHz frequencies. It has been developed to be used in future WLAN/Wi-MAX technologies. The proposed antenna is simulated using Computer Simulation Technology (CST) Microwave Studio. This slot loaded patch antenna is suitable for the 2.39 GHz to 2.49 GHz WLAN applications and 3.33 GHz to 3.849 GHz Wi-MAX applications.

The geometry of patch antenna is shown in figure 5.9. The structure consists of a rectangular patch fed by co-axial probe of 50 Ω . The design specifications for patch antenna are listed in Table 5.2.

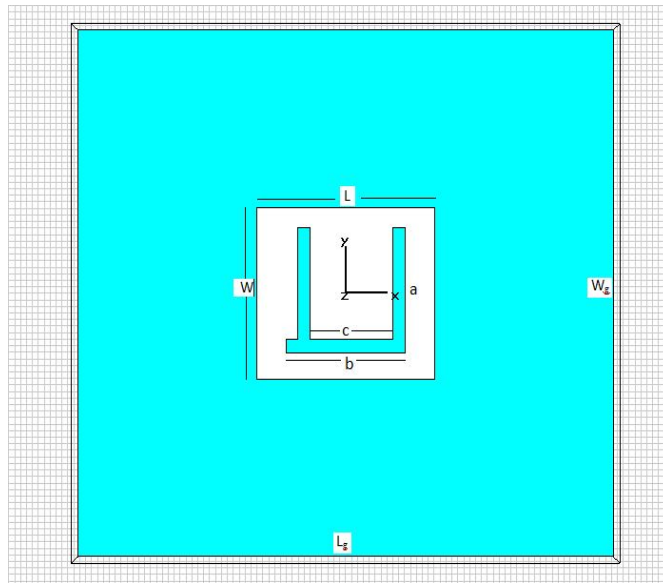


Figure 5.9 Geometry of Slotted Patch Antenna.

Table 5.2 Design Specifications of Slotted Patch Antenna

L(mm)	W(mm)	L _g (mm)	W _g (mm)	h(mm)	ϵ_r	a(mm)	b(mm)	C(mm)
30	26	90	80	8	2.33	19	20	14

The width of each slot is 2mm. The antenna structure is fed with a co-axial probe (50 Ω). The inner and outer radius of co-axial probe is 1.5 mm and 3 mm respectively.

Effect of Design Parameters

In order to study the effect of the various design parameters on the antenna performances, the parameters were varied one at a time keeping the others fixed at the value given in Table 5.2.

Effect of Variation in Vertical Slot Length (a)

As the proposed patch antenna is operated in two bands, thus variation in a affects both bands; lower as well as upper band. From figure 5.10, it is cleared that increasing a , the return loss parameter for lower band becomes poor while better for upper frequency band. Table 5.3 shows that how the vertical slot length (a) affects the return loss parameter and bandwidth of slotted patch antenna.

Table 5.3 Effect of slot length 'a' on antenna performances

A	S_{11L} (in dB)	BW_L (in MHz)	S_{11U} (in dB)	BW_U (in MHz)
18	-32.7	96	-16.4	900
19	-22.6	100	-20.26	519
20	-15.69	93	-25.73	442

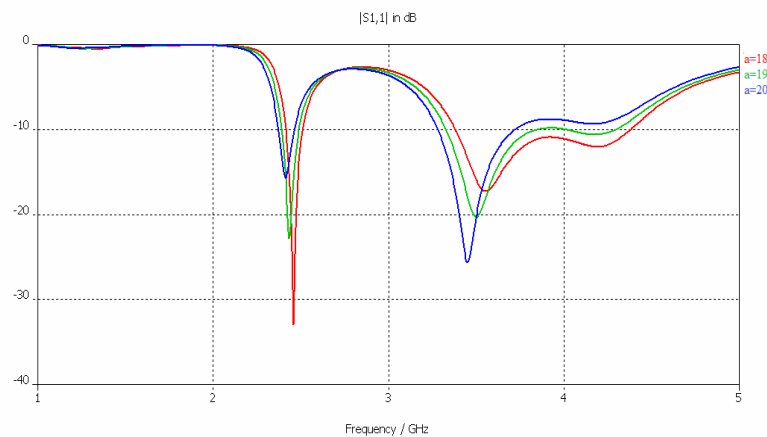


Figure 5.10 Effects of Vertical Slot Length (a) on Antenna Performances

Effects of Variation in Horizontal Slot Length (b)

The affects of horizontal slot length b on antenna performance (return loss) is shown in figure 5.11. As the slot length b decreases, the return loss parameter improves i.e. impedance matching between patch antenna and feed line improves.

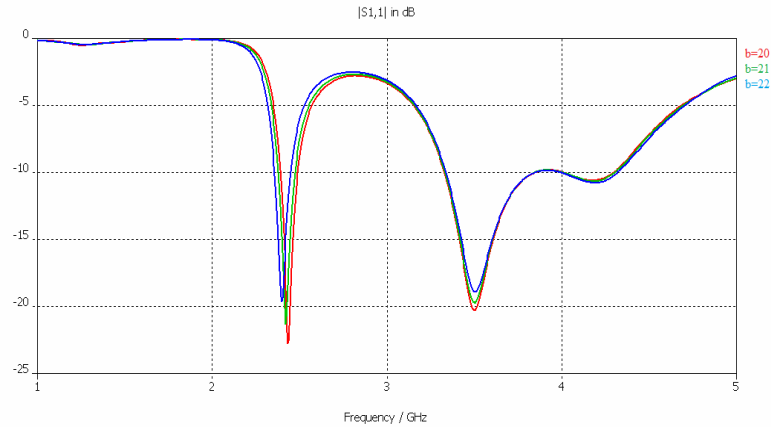


Figure 5.11 Effects of Variation in b on Antenna Performances.

Effects of Variation in ‘c’

The variation in c affects the return loss parameter as well as resonant frequency both for lower frequency band and upper frequency band. As c increases, the resonant frequency decreases and return loss parameter improves as shown in figure 5.12.

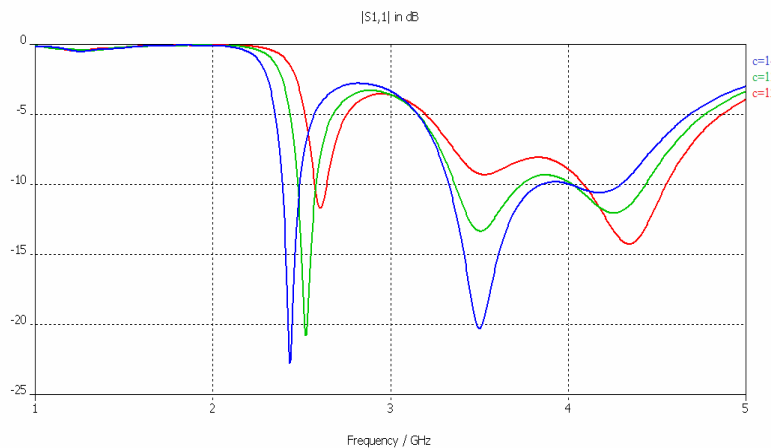


Figure 5.12 Effects of Variation in c on Antenna Performance.

Based upon the above parametric study, the optimum value of a, b and c is selected. And finally the performance of the antenna has been studied by comparing the Return loss, VSWR, Gain, azimuthal and elevation patterns.

The simulated results show that the designed patch antenna achieves impedance bandwidth of 4.1% and 14.8% for $VSWR < 2$, covering a frequency range from 2.39 GHz to 2.49 GHz and 3.33 GHz to 3.849 GHz respectively. The antenna exhibits the return loss (S11) below -10dB for frequency ranges mentioned. The gain of antenna at these two resonating frequencies is 5.3dBi and 8.6dBi respectively.

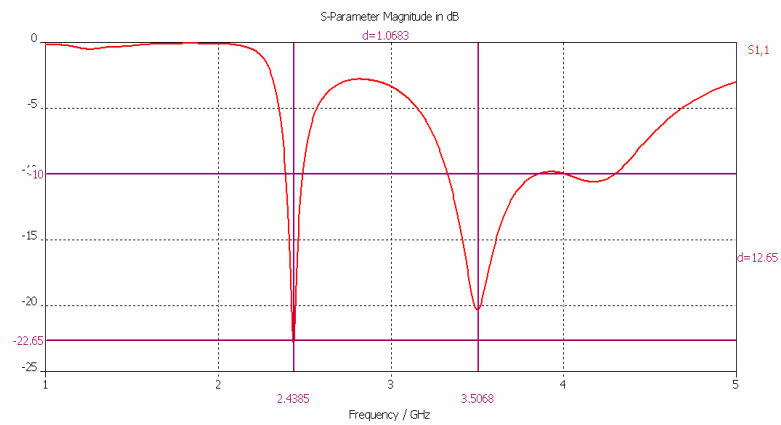


Figure 5.13 (a)

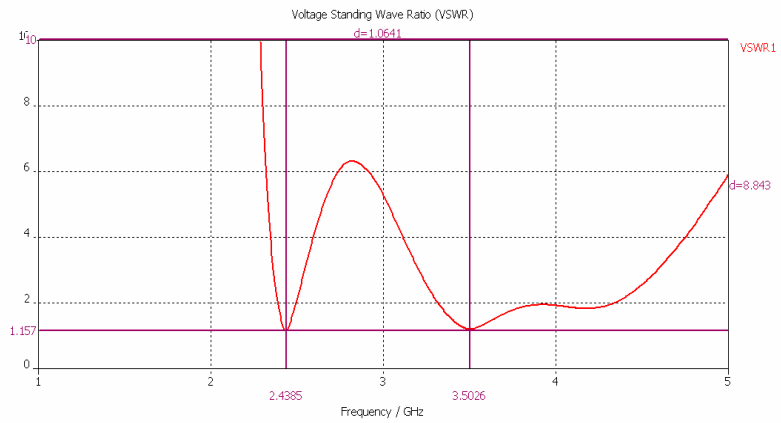


Figure 5.13 (b)

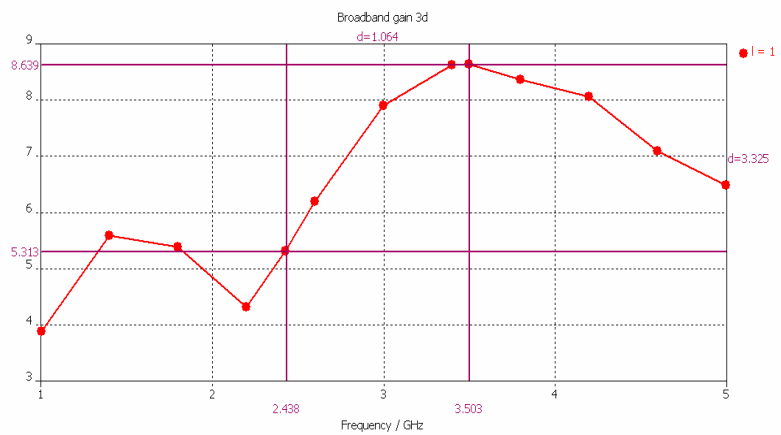


Figure 5.13 (c)

Figure 5.13 (a): Return Loss Plot for Proposed Antenna
 (b): Simulated VSWR Plot
 (c): Gain Vs Frequency Plot

5.6 E-Shaped Microstrip Patch Antenna

In this section, a dual band E-shaped Microstrip patch antenna has been designed for high-speed wireless local area networks (IEEE 802.11a standard) and other wireless communication systems covering 4.97GHz to 5.37GHz and 5.72GHz–5.86 GHz frequency bands. Two parallel slots are incorporated to perturb the surface current path, introducing local inductive effect that is responsible for the excitation of the second resonant mode. The length of the centre arm can be trimmed to tune the frequency of the second resonant mode without affecting the fundamental resonant mode. A comprehensive parametric study has been carried out to understand the effects of various dimensional parameters and to optimize the performance of the antenna. A substrate of low dielectric constant is selected to obtain a compact radiating structure that meets the demanding bandwidth specification. The reflection coefficient at the input of the optimized E-shaped Microstrip patch antenna is below -10 dB over the entire frequency band.

For the E-shaped patch antenna, two parallel slots are incorporated to introduce a second resonant mode, resulting in a dual band antenna. If the feed point is located at the tip of the centre arm as in [3–6], the second resonant mode will be introduced at a lower frequency than the fundamental resonant mode. If the feed point is moved to the base of the centre arm [7], the second resonant mode will be introduced at a higher frequency than the fundamental resonant mode.

The antenna geometry is shown in Figure 5.14. First, a rectangular Microstrip patch antenna is designed based on the standard design procedure to determine the length (L) and width (W) for resonant frequency at 5.25 GHz. It is fed by a coaxial probe at position (x_0, y_0) . Two parallel slots are incorporated to perturb the surface current path, introducing local inductive effect that is responsible for the excitation of a second resonant mode. The slot length (L_s), slot width (W_s), and the centre arm dimensions (W_t and L_t) of the E-shaped patch control the frequency of the second resonant mode and the achievable bandwidth.

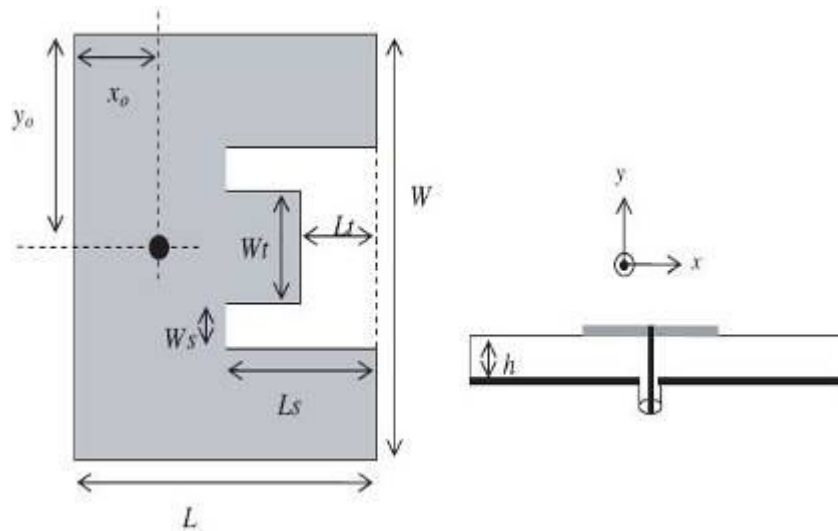


Figure 5.14 (a)

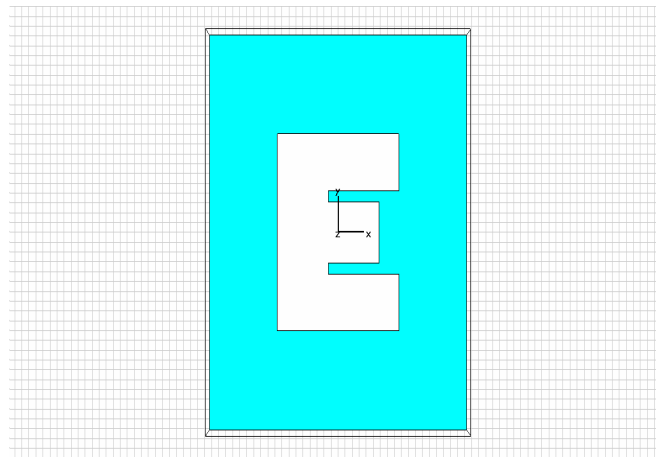


Figure 5.14 (b)

Figure 5.14 (a): Geometry of E-Shaped Microstrip Patch Antenna.
 (b): Front View of Designed Antenna on CST Microwave Studio.

The structure consists of a rectangular patch fed by co-axial probe of 50Ω . The inner and outer diameter of coaxial cable is 1.3mm and 4.7mm respectively. The design specifications for patch antenna are listed in Table 5.4.

Table 5.4 Design Specifications of E-shaped Patch Antenna

L(mm)	W(mm)	h(mm)	ϵ_r	W_t (mm)	L_t (mm)	W_s (mm)	L_s (mm)
17.2	20	3.2	2.2	6.2	2.8	1.12	10

In order to study the effect of the various design parameters on the antenna performances, the parameters were varied one at a time keeping the others fixed at the value given in Table 5.4. The four parameters (L_t , W_t , L_s , W_s) are set as variable and their effects on patch antenna performances are studied.

Effects of Variation in L_s

The slot length L_s is varied from 9.6mm to 10.4mm. On increasing the slot length, return loss parameter improves but does not affect on resonating frequency significantly. While the second resonating mode decreases.

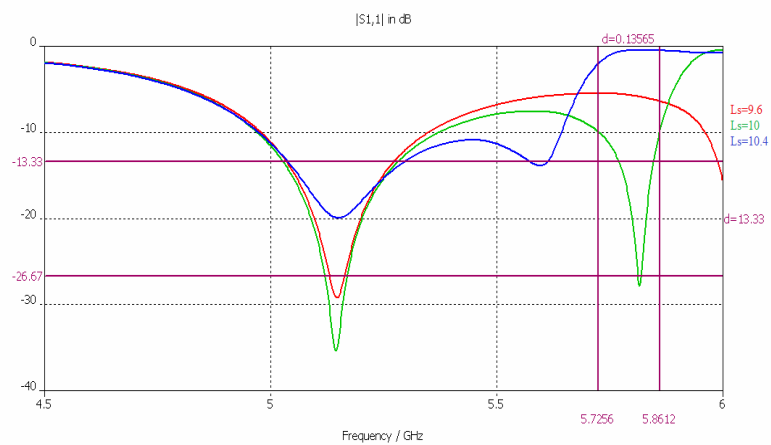


Figure 5.15 Simulated Return Loss for Various L_s .

Effects of Variation in W_s

The slot width W_s is varied from 0.5mm to 1.12mm. The wider is slot, the resonant frequency of second order resonating frequency decreases with wider slot. The fundamental resonating frequency is also affected. As we increase the slot width, the return loss parameter improves.

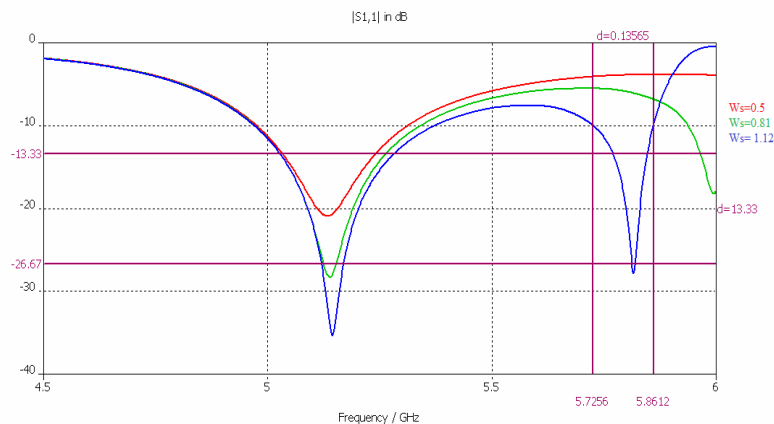


Figure 5.16 Simulated Return Loss for Various W_s .

Effect of Variation in L_t

As the centre arm length (L_t) increases, frequency of the second resonant mode increases as shown in figure 5.17. The centre arm slot length L_t does not affect significantly on fundamental resonating mode frequency.

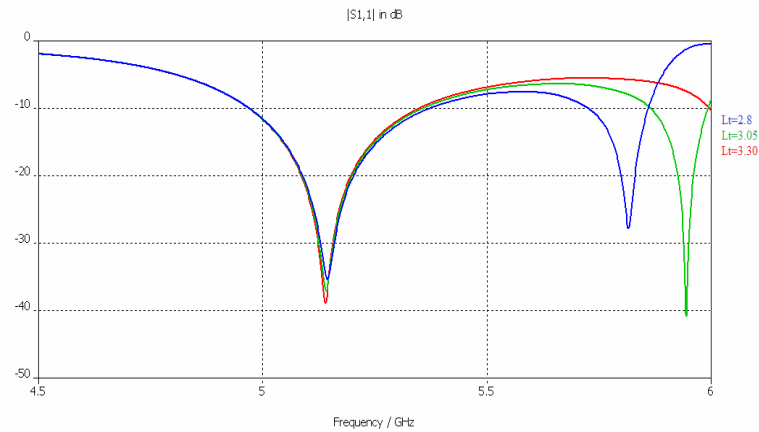


Figure 5.17 Simulation Return Loss for Various L_t

Effect of Centre Arm Slot Width W_t

Widening the centre arm will decrease the second resonating mode frequency but also affects the return loss performance of patch antenna at the fundamental resonating frequency.

The fundamental resonating frequency does not affect significantly by altering the centre arm width.

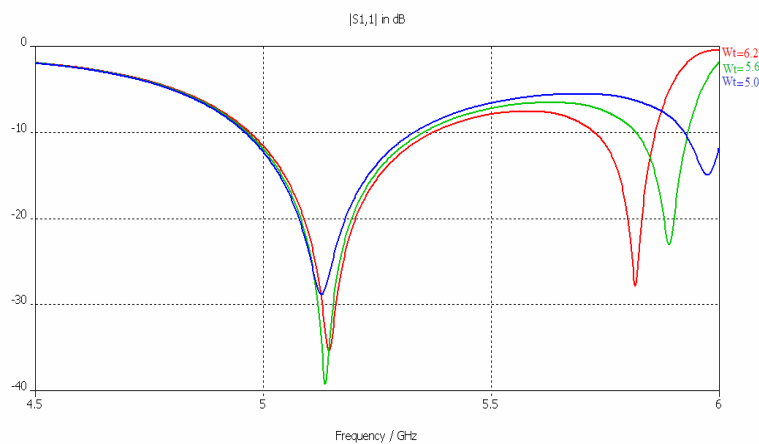


Figure 5.18 Simulated Return Loss for Various W_t

Based upon the above parametric study, the optimum value is selected for various parameters as mentioned in Table 5.4. The simulation results of E slotted patch antenna are shown in figure 5.19.

Figure 5.19(a) shows that the proposed patch antenna is resonating on two frequencies: 5.14GHz and 5.81GHz with return loss of -35dB and -27dB respectively. This slotted antenna is operating in two bands viz band 1 (4.97GHz to 5.37GHz) and band 2 (5.72GHz–5.86GHz). These bands are suitable for WLAN applications.

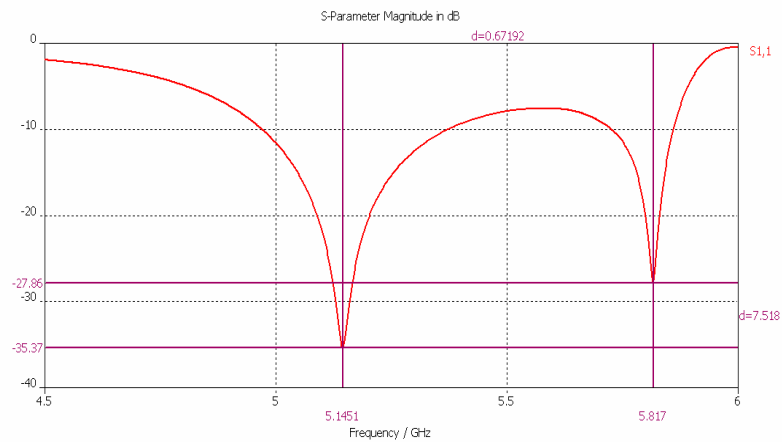


Figure 5.19 (a) Simulated Return Loss

The smith chart is shown in figure 5.19 (b). This chart indicates the behaviour of antenna impedance with frequency. The antenna impedance is almost real at both resonating frequencies.

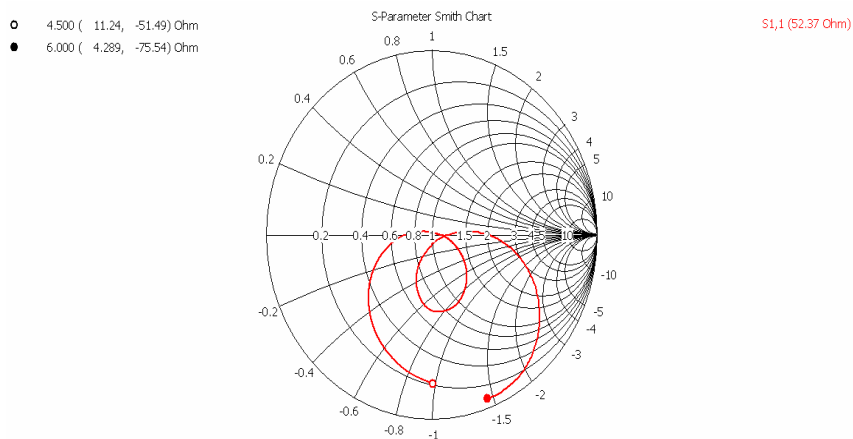


Figure 5.19 (b) Smith Chart

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Three configurations of Microstrip antennas have been studied in this thesis. The first is the design of typical single band rectangular Microstrip patch antenna, second is broadbanding of patch antennas and finally the design of dual band Microstrip patch antennas. The main concern of this thesis is to study of broad band dual frequency patch antenna using coaxial feeding techniques. The dual band Microstrip antenna is a more conventional approach for the implementation of a broadband antenna and for wireless communication.

Initially, single element rectangular Microstrip patch antenna is designed to operate at frequency 2.45 GHz. Their dimensions and simulation results are presented in chapter 3. It has been observed that the return loss parameter for the proposed antenna is approximately -35dB at the resonating frequency. The impedance bandwidth has been found to be approximately 2.9%. at -10dB return loss. This impedance bandwidth is not sufficient for practical applications. So, in the next chapter some techniques are proposed and simulated to increase the antenna impedance bandwidth.

In chapter 4, three techniques are discussed to increase the antenna impedance bandwidth namely: lowering the Q factor, introducing multiple resonances and by using impedance matching. The various antennas designed and simulated were compact broadband Microstrip patch antenna with chip resistor loading, patch antenna with stacked elements, U slot loaded patch antenna, patch antenna with reduced ground plane and E shaped broadband patch antenna. The simulation results of the design examples are summarised in Table 6.1. From this table it is clear that the patch antenna with reduced ground plane gives the maximum impedance bandwidth (87.3%).

Table 6.1 Simulation Results of Broadband Patch Antennas

Title	Resonating Frequency(GHz)	% Impedance Bandwidth	Return Loss(dB)
Compact Broadband Microstrip Patch Antenna with Chip Resistor Loading.	0.89748	7.6%	30.5
Patch antenna with stacked elements	2.43	3.6%	41.6
U slot loaded patch antenna	3.12	19.6%	45.85
Bandwidth enhancement by reducing ground size	2.84	87.3%	38.36
E shaped Broadband Patch Antenna	5.40	56.7%	46.92

And finally in chapter 5, dual band Microstrip patch antennas are designed for variety of wireless communication applications. The dual-frequency patch antenna designs presented are divided into two groups, depending on whether the two operating frequencies have the same polarization plane or orthogonal polarization planes. The dual band antenna shows that with correct selection of slot dimensions and positions, a desired dual frequency response can be achieved.

A simple design for single layer, single feed rectangular Microstrip patch antenna is designed to achieve dual frequency operation with orthogonal polarization. The simulation results show that the proposed antenna is resonating at 1.86GHz and 2.34GHz with a good impedance matching condition.

By embedding a cross slit in the patch, the performance of patch antenna improves as compared to rectangular patch antenna without cross slit.

In this chapter two more antennas named: slot loaded patch antenna and E shaped Microstrip patch antenna are modelled and simulated. Also the parametric study is carried out for both the antennas.

6.2 Future Scope

Based on gathered observations while completing this thesis; topics were identified which would benefit for further investigation.

- At present, facility for fabrication of patch Antenna is not available in our institute; the same work will be performed later. The simulated and experimental

results will be compared. So, on the basis of experimental verification of results, one can fabricate the antenna.

- In this thesis, optimization of parameters has been done manually. One can optimise the parameters using optimization techniques.
- Multiband patch antenna can be designed for various wireless applications like WLAN, WiMAX etc.
- Wideband and ultra-wideband patch antenna can be designed which is helpful in telecommunication, and high speed data transmission system.
- Defected ground structures (DGS) can be used for the miniaturization of the designed dual band antennas and to reduce mutual coupling between elements in the array.

PUBLICATIONS

- [1]. Rakesh Kumar Tripathi, Rajesh Khanna, Jaswinder Kaur, “Compact Broadband Microstrip Patch Antenna with Chip Resistor Loading”, Indian Stream Research Journal, vol. 1, June 2011.
- [2]. Rakesh Kumar Tripathi, Rajesh Khanna, “A Broadband Multilayered Stack Antenna for WLAN Applications”, National Conference on Converging Technologies Beyond 2020, Vol.6, No-5, pp 671-673, April 2011.
- [3]. Rakesh Kumar Tripathi, Rajesh Khanna, “Slot Loaded Patch Antenna for WLAN/Wi-Max Applications”, National Conference on Microwave ,Antenna & Signal Processing sponsored by DST, New Delhi, pp.43-45, April2011.

REFERENCES

- [1]. Kin-Lu Wong, Wen-Hsiu Hsu, "A broad-band rectangular patch antenna with a pair of wide slits", IEEE Transaction on Antennas and Propagation, vol.49, pp- 1345-1347, 2001.
- [2]. Sheng- Ming, M. -D. Wu and P. Hsu, "Analysis of coplanar waveguide-fed Microstrip antenna", IEEE Transaction on Antennas and Propagation Letters, vol. 43, No. 7, July 1995.
- [3]. <http://en.wikipedia.org/wiki/WiMAX/Wlan>.
- [4]. C.A. Balanis, "Antenna Theory Analysis and Design", third edition, Wiley, New Jersey, 2005.
- [5]. J. Van densande, H. Poes, A.V.de Capelle, "Calculation of the bandwidth of Microstrip resonator antenna", Microwave Conference, pp-116-119, 1979.
- [6]. Poes H., Vande Capelle A., "accurate transmission-line model for the rectangular Microstrip antenna", Microwaves, Optics and Antennas, IEEE Proceedings H, vol-131, pp-334-340, 1984.
- [7]. Nazifa Mariam, "Design of Coaxial Fed Microstrip Antenna for LEO Satellites", Wireless and Optical Communications Networks, IEEE Conference, pp1-5, 2008.
- [8]. Adil Hameed Ahmad and Basim Khalaf Jar'alla, "Design and Simulation of Broadband Rectangular Microstrip Antenna", Eng. Tech. Vol-26, No-1, 2008.
- [9]. Akhilesh Verma, Bevan D. Bates, "Microstrip Patch Antenna with Polypyrrole Ground Plane", IEEE Conference, pp-424-429, 2008.
- [10]. Tlili Boutheina, "Design of C-slot Microstrip patch antenna for WiMAX application", in Proceeding LAPC, pp-521-524, 2009.
- [11]. K. L.Wong and K. P. Yang, "Small dual-frequency Microstrip antenna with cross slot," Electron. Lett. Vol. 33, pp 1916–1917, Nov. 6, 1997.
- [12]. S. Maci and G. BifJi Gentili, "dual frequency patch antennas", IEEE Antennas and Propagation Magazine, Vol. 39, No. 6, pp 13-20, December 1997.

- [13]. Vedaprabhu. B and K.J. Vinoy, “A Double U-slot Patch Antenna with Dual Wideband Characteristics”, National Conference on Communications, pp 1-4, 2010.
- [14]. Yuehe Ge, Karu P. Esselle, Trevor S. Bird, “E-Shaped Patch Antennas for High-Speed Wireless Networks”, IEEE Transactions on Antennas and Propagation, vol. 52, no. 12, pp-3213- 3219, December 2004.
- [15]. R.Garg, P. Bhartia, I. Bahl, A. Itipiboon, “Microstrip antenna design handbook”, Artech House, Boston –London, 2000.
- [16]. J. Bahl and P. Bhartia, Microstrip Antennas, Artech House, Dedham, MA, 1980.
- [17]. D. M. Grimes and C. A. Grimes, “Bandwidth and Q of antennas radiating TE and TM modes”, IEEE Transactions on Antennas and Propagation, vol. 43, no. 2, pp. 217–226, 1995.
- [18]. R. E. Collin and S. Rothschild, “Evaluation of antenna Q”, IEEE Transactions on Antennas and Propagation, vol. 29, no. 1, pp. 23–27, 1964.
- [19]. R. L. Fante, “Quality factor of general ideal antenna”, IEEE Transactions on Antennas and Propagation, vol. 17, no. 2, pp. 151–155, 1969.
- [20]. J. W. Howell, “Microstrip antennas”, IEEE Transactions on Antennas and Propagation, vol. 23, no. 1, pp. 90–93, 1975.
- [21]. D. M. Pozar and D. H. S. (Ed.), Microstrip Antennas: Analysis and Design. New York: John Wiley & Sons, Inc., 1995.
- [22]. R. Q. Lee, T. Huynh and K. F. Lee, “Experimental study of the cross-polarization characteristics of rectangular patch antennas”, IEEE International Symposium on Antennas and Propagation, vol. 2, pp. 624–627, June 1989.
- [23]. N. Jayasundere and T. S. M. Maclean, “Omni directional radiation patterns from body-mounted Microstrip antennas”, IEEE Sixth International Conference on Antennas and Propagation, vol. 1, pp. 187–190, 4–7 April 1989.
- [24]. M. I. Aksun, S. L. Chuang and Y. T. Lo, “On slot-coupled Microstrip antennas and their applications to cp operation: theory and experiment”, IEEE Transactions on Antennas and Propagation, vol. 38, no. 8, pp. 1224–1230, 1990.

- [25]. M. A. G. de Aza, J. Zapata and J. A. Encinar, "Broad-band cavity-backed and capacitive probe-fed Microstrip patch arrays", *IEEE Transactions on Antennas and Propagation*, vol. 48, no. 7, pp. 784–789, 2000.
- [26]. M. A. Khayat, J. T. Williams and S. A. L. D. R. Jackson, "Mutual coupling between reduced surface-wave Microstrip antennas", *IEEE Transactions on Antennas and Propagation*, vol. 48, no. 10, pp. 1581–1593, 2000
- [27]. S. Hudson and M. D. Pozar, "Grounded coplanar waveguide-fed aperture-coupled cavity-backed Microstrip antenna", *Electronics Letters*, vol. 36, no. 12, pp. 1003–1005, 2000.
- [28]. B. Lee and F. J. Harackiewicz, "Miniature Microstrip antenna with a partially filled high- permittivity substrate", *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 8, pp. 1160–1162, 2002.
- [29]. K. P. Ray, G. Kumar and H. C. Lodwal, "Hybrid-coupled broadband triangular Microstrip antennas", *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 1, pp. 139–141, 2003.
- [30]. R. Q. Lee, K. F. Lee, and J. Bobinchak, "Characteristics of a two-layer electromagnetically coupled rectangular patch antenna," *Electron. Lett.*, vol. 23, no. 20, pp. 1070–1072, 1987.
- [31]. W. Chen, K. F. Lee, and R. Q. Lee, "Spectral-domain moment method analysis of coplanar Microstrip parasitic subarrays," *Microw. Opt. Technol. Lett.*, vol. 6, no. 3, pp. 157–163, 1993.
- [32]. K. H. Pan, J. T. Bernhard, and T. Moore, "Effects of lossy dielectric materials on Microstrip antennas," in *Proc. IEEE AP-S Conf. Antennas and Propagation for Wireless Communications*, Nov. 2000, pp. 39–42.
- [33]. J. T. Aberle, M. Chu and C. R. Birtcher, "Scattering and Radiation Properties of Varactor- tuned Microstrip antennas", *IEEE antennas propagaion. Soc. Int. Symp. Digest*, vol. 4, pp. 2229–2232, 1992.
- [34]. K. Guney, "Resonant frequency of a tunable rectangular Microstrip patch antenna", *Microw. Opt. Tech. Lett.*, vol. 7, no. 12, pp. 581–585, Aug. 20, 1994.
- [35]. S.-C. Pan and K. L. Wong, "Dual-frequency triangular Microstrip antenna with a shorting pin", *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 1889–1891, Dec. 1997.

- [36]. T. Huynh and K. F. Lee, "Single-layer single-patch wideband Microstrip antenna", *Electron. Lett.*, vol. 31, no. 16, pp. 1310–1312, Aug. 3, 1995.
- [37]. D. R. Jackson and N. G. Alexopoulos, "Simple approximate formulas for input resistance bandwidth and efficiency of a resonant rectangular patch", *IEEE Transactions on Antennas and Propagation*, vol. 39, no. 3, pp. 407–410, 1991.
- [38]. N. K. Das and D. M. Pozar, "Multiport scattering analysis of general multilayered printed antennas fed by multiple feed ports Part II: Applications", *IEEE Transactions on Antennas and Propagation*, vol. 40, no. 5, pp. 482–491, 1992.
- [39]. J. R. M. S. A. Bokhari and F. E. Gardiol, "Radiation pattern computation of Microstrip antennas on finite-size ground planes", *IEEE Proceedings: Microwave, Antennas and Propagation*, vol. 139, no. 3, pp. 278–286, 1992.
- [40]. W. F. Richards, S. E. Davidson, S. A. Long, "Dual-Band Reactively Loaded Microstrip Antenna", *IEEE Transactions on Antennas and Propagation*, AP-33, 5, May 1985, pp. 556-560.
- [41]. E.O. Hammerstad, "Equations for microstrip Circuit Design", *Pro. Fifth European Microwave Conference*, page 268-272, 1975.
- [42]. Microstrips patch antennas, "A designer's guide", by Rodney B. Waterhouse, 1999.
- [43]. S. S. Zhong and Y. T. Lo, "Single Element Rectangular Microstrip Antenna for Dual-Frequency Operation", *Electronics Letters*, 19, 8, pp. 298-300, 1983.
- [44]. S. Maci, G. Biffi Gentili, G. Avitabile, "Single-Layer Dual- Frequency Patch Antenna", *Electronics Letters*, 29, 16, August 1993.
- [45]. P. Piazzesi, S. Maci, G. Biffi Gentili, "Dual-Band Dual-Polarized Patch Antennas", *Znt. MiMiCAE Jour.*, 5, 6, pp. 375-384, December 1995.
- [46]. R. Waterhouse, "Small Microstrip patch antenna," *Electron. Lett.*, Vol.31, pp. 604-605,1995.
- [47]. J. S. Chen and K. L. Wong, "A single-layer dual-frequency rectangular Microstrip patch antenna using a single probe feed", *Microwave Opt. Technol. Lett.* **11**, 83–84, Feb. 5, 1996.

- [48]. Minh Tuan Nguyen, Byoungchul Kim, Hosung Choo, and Ikmo Park, "Effects of Ground Plane size on a Square Microstrip Patch Antenna Designed on a Low-Permittivity Substrate with an Air Gap", International Workshop on Antenna Technology, pp.1-4, 2010.
- [49]. Howell, J. Q., "Microstrip Antennas", IEEE AP-S int. Symp.digest, pp177-180, 1972.
- [50]. Munson, R.E., "conformal Microstrip antennas and Microstrip phased arrays", IEEE transaction on antennas and propagation, vol-AP22, pp74-78, 1974.