DESIGN AND DEVELOPMENT OF STACKED MICROSTRIP ANTENNA ARRAY FOR MIMO APPLICATIONS

Submitted towards the partial fulfilment of requirement for the award of degree of

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in

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Submitted by

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CANDIDATE'S DECLARATION CERTICICATE

I hereby certify that the work which is being presented in the Project entitled "**Design and Development of Stacked Microstrip Antenna Array for MIMO Applications**" in partial fulfilment of requirement for the award of degree of ME (Wireless Communications) at Thapar University, Patiala, is my own work carried out under the supervision of **Mrs. Amanpreet Kaur** (Assistant Professor), **ECED** during 4th semester, 2015-2016.

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

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ABSTRACT

There has been a wide and rapid growth in the field of wireless communication systems in the las two decades. Nowadays every modern wireless equipment is implemented with Wi-Fi (Wireless WLAN). As the wireless field is growing day by day it aims at providing better image, speed, and data communications. For the same we need broad-band and multi-band antennas to cover the various applications in a same terminal device. In order to have better transmitting and receiving rate broadband antennas are required. In addition, for miniaturising the wireless communication system, the antennas must be small enough to be placed inside the system. The microstrip antennas have various advantages that make them a good candidate for the use in wireless communication systems.

In this thesis work firstly a stacked microstrip antenna is theoretically studied using transmission line model. Stacking is a technique used for improving the bandwidth. In stacking a layer of dielectric etched with a metallic patch (known as driven patch) is electromagnetically coupled to the fed patch. The antenna is fed using aperture coupling. The designed antenna resonates at 6 GHz with 656 MHz bandwidth. The antenna characteristics like return loss, bandwidth, directivity, and gain are simulated using CST MWSv'14. Then a dual band aperture coupled microstrip antenna with stacking technique is simulated. The antenna resonates at two frequencies of 3.2 GHz and 4.5 GHz. Hence it finds application in C-band and WiMAX communication systems.

Wireless radio links are most affected by the fading. The fading can be combat by using multiple antennas at the communication link ends. When multiple antennas are employed at both or either sides of the communication system, the signals travelling through multiple paths can be used in an advantageous ways by employing various diversity schemes. The system having multiple antennas at both the transmitting and receiving ends is known as MIMO system. To employ the antenna in MIMO system, array of stacked microstrip patch antennas is simulated and fabricated in this thesis. In this context firstly a triple band stacked antenna array is designed and simulated. The antenna is energised using aperture feed. The antenna array has three resonances at 4 GHz, 5.8 GHz, and 6.2 GHz with -25 dB, -22 dB, and -19 dB return losses respectively.

The antenna array structure simulated can be installed in C-band, WiMAX and STM1 systems. Thereafter a dual-band antenna array is simulated. The structure consists of a reduced ground plane to reduce the back radiations. Slits are cut in the lower patches to improve the bandwidth. To further enhance the performance of the structure, slot is cut in the upper patches as well. Various parameters like return loss, directivity, gain, envelope correlation coefficient, and diversity gain are also discussed. The antenna offers a return loss of -20dB, and -30dB at resonances of 3.6GHz, and 5.2GHz respectively. The bandwidth offered by the structure is 228.3MHz, and 232MHz. System can be fabricated for WLAN applications.

Lastly the triple-band and dual-band antenna arrays simulated are then fabricated and tested using VNA. The tested results and the comparison of tested and simulated results are also shown.

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List of Abbreviation

WLAN	Wireless Local Area Network
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
MISO	Multiple Input Single Output
MIMO	Multiple Input Multiple Output
SDMA	Space Division Multiple Access
MAC	Multiple Access Channel
BC	Broadcast Channel
LTE	Long Term Evolution
OFDM	Orthogonal Frequency Division Multiple
HSPA+	High Speed Packet Access plus
WIFI	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave
GPS	Global Positioning System
MSA	Microstrip Antenna
FDTD	Finite Difference Time Domain
CST MWS	Computer Simulation Tool Microwave Studio
RF	Radio Frequency
DGS	Defected Ground Structure
STM-1	Synchronous Transport Module level-1
ACSMPA	Aperture Coupled Stacked Microstrip Antenna
ECC	Envelope Correlation Coefficient
SRS	Split Ring Resonator Structure
EBG	Electromagnetic Band Gap

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Chapter 1

Introduction

Communication, the activity of transmitting information from one point to other is the distinguishing ability which made human society to evolve. James Maxwell's discovery on electromagnetic waves made wireless communication possible, on the move connectivity demanded for more important data and information to be transferred, and led to the various developments in the field of wireless cmmunications.

1.1. Wireless Communication:

Wireless communication is one of the fastest growing zones of the communication sector. It uses EM waves to transmit data between two distant users. It has now become the backbone of the modern society. From satellite transmission, television and radio broadcasting to the modern mobiles, it has revolutionised the entire communication sector. There are some basic advantages of wireless communication like portability, flexibility, and coverage [1]. Portability means the freedom that a hand-held device provides such as cell-phone. Flexibility includes the freedom to add/remove the devices in any existing network without any alteration in the hardware. Wireless applications include voice, web browsing, paging, internet access, messaging, file transfer, subscriber information services, entertainment, video teleconferencing, and sensing. These applications have been made possible with the help of wireless service like LANs, cellular system, satellite system, wide area wireless data system, and ad-hoc wireless network [1].

In a wireless communication system, a transmitter creates electromagnetic waves that are then sent to the receiver through space. Transmitter is nothing but an electronic circuit with the facilitation of an antenna. These waves then promulgate through a channel (free space, buildings etc.). The signal is then received by the receiver. The receiver must have the knowledge of the nature of discrepancies introduced within the channel to successfully interpret the message sent by the transmitter [2]. Wireless communication system suffers from some disadvantages too. As the signals travel through the channel they gets distorted during the propagation. The distortions occurred in the transmitted signal due to multipath reception at the receiver is known as fading [1][2]. Fading is one of the major disadvantages of wireless communication.

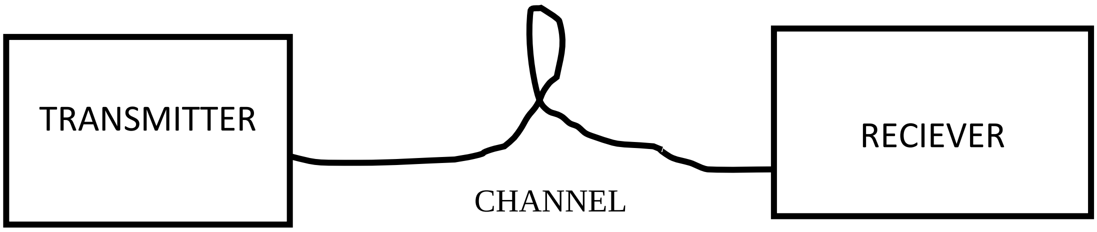


Figure 1.1 Communication Block Diagram

1.2. Fading:

In wireless telecommunications, the receiver receives the radio signals by two or more paths, this propagation phenomenon is known as multipath. Multipath can occur due many reasons some of them includes ionospheric reflection and refraction, atmospheric ducting, and reflection from objects like buildings and mountains. The multipath can cause interference, and phase shift in the transmitted signal. The interference could be constructive or destructive based on how signals are interacting. In digital radio frequency wireless communications (for example GSM) multipath signals are received as they are being affected by the terrestrial environment which can cause errors and affect the characteristics of communication. When there are different ways of propagation the signals received by the receiver arrives through a variety of paths. Therefore multipath interference will be there, which in turn causes multipath fading. The movement of either the transmitting unit or receiver or the surrounding clutter, causes the received signal's amplitude or phase to change over a small time contributing to the main cause of fading [1].

1.2.1. Fading Effects:

The effects can be summarized as:

- Signal strength changes rapidly over a small time interval or distance.
- Multipath propagation delays causes time dispersion or echoes. It also causes phase shifting, and interference (constructive or destructive) in the transmitted signal.
- When the user unit like mobile is in movement the relative motion between it and the transmitting unit (base station) results in varying Doppler shifts on different multipath signals which in turn can cause random frequency modulation and this results in change in the received signal.

- When the surrounding bodies in the radio wireless channel are in motion, their speed can inject a time varying Doppler shift on the transmitted signal's multipath components. If their speed is greater than the mobile, then it dominates fading.
- The received signal will get distortions if the transmission bandwidth of the signal is greater than the multipath channel bandwidth.

1.2.2. Types of Fading:

In wireless communication channel estimation is required to neutralize the effects of channel noise on the signal. The wireless channel is basically characterised by the variations of the channel strength over frequency and time. The type of fading being experienced by the signal transmitted in a wireless channel is dependent on the relationship of the signal parameters and the channel parameters. Signal parameters include symbol period and bandwidth, and channel parameters include Doppler and RMS delay spread. According to the time dispersive nature of the channel the types of fading can be characterized as [1].

- **Large-scale fading:**
  When path loss of the transmitted signal occurs as a function of distance and shadowing by large objects such as buildings and hills, it is known as large-scale fading.
- **Small-scale fading:**
  When the multiple path signals are interfered constructively or destructively in the radio link, fading occurs and is known as small-scale fading.

Various techniques can be implemented at the receiver side to overcome the effects of fading.

1.2.3. Channel Models:

To counter the effects of multipath signal fading various techniques are designated at the receiver side. For this various mathematical models are used to speculate the general behaviour of the concerned channel. Some important channel models are [3]:

- **Rayleigh channel:**
  This model is applied to a communication scenario when there are many scatters present, which means that Rayleigh fading is useful in the case of no line-of-

sight. For example in heavily built-up city centres Rayleigh Fading is a reasonable model as there is no line of sight between the transmitting and the receiving unit and there are many objects and buildings in the environment which attenuate, reflect, scatter, refract and diffract the signal before it reaches the receiver.

- **Riciean channel:**
  The Riciean fading channel model is quite similar to the Rayleigh, except that in Riciean fading a strong ascendant component is present. This component is due to the line-of-sight wave. It is basically a transmission channel having a line-of-sight component and several scattered of multipath components.
- **Nakagami channel:**
  The sum of multiple independent and identically distributed Rayleigh-fading signals can be modelled using Nakagami distributed signal amplitude. This is particularly relevant to model interference from multiple sources in a cellular system.

Depending upon the type of communication scenario, a channel can be modelled and various diversity schemes can be used to overcome fading.

1.3. Multiple Antenna System to Overcome Fading:

When the signal is transmitted it can take many paths before arriving at the receiver. When the antennas are moved even a small distance these paths get changed. The multiple paths available are a result of the number of obstacles appearing in the direct path or even in the side path between the transmitting and the receiving unit. Earlier these multiple paths only contributed to the interference, but in modern wireless systems these multiple additional paths can be employed to advantage. They can provide robustness to the radio wireless link by elevating the link data capacity and improving the signal to noise ratio. When the signal is transmitted towards the receiver it gets faded. Fading may affect the channel and can impact the signal to noise ratio. But in multiple antenna system, it increases the data rate by multiplexing and improves the performance through diversity [2][4].

The principle of diversity is to give receiver the multiple different versions of the transmitted signal. If the transmitted signal is affected in different ways by the signal path, the probability of getting them affected at the same time is considerable reduced.

In this way, diversity improves and stabilizes the link performance, thus reducing error rate. Several diversity schemes are [4]:

- **Time Diversity:**
  In this scheme, the message is transmitted at different time slots example using different time slots and channel coding. So multiple copies of the transmitted signal are received at the receiver and can be combined in best possible manner at the receiver.
- **Frequency Diversity:**
  In this scheme different frequencies are used for transmission which could be in the form of different channels or technologies like spread spectrum/GSM.
- **Space Diversity:**
  This scheme uses antenna located at different positions at the transmitter and receiver in order to take advantage of the different radio paths. Same signal is transmitted using different transmitters and multiple antennas at the receiver can be used to intercept those signals, and thus forms the basis of MIMO system too.

1.4. Types of Multiple Antenna Systems:

There are different forms of antenna technology that concerns to single or multiple inputs and outputs. Here input refers to the transmitter as it transmits into the RF wireless link, and the output is the receiver as it is at the output end of the wireless link. Therefore the different forms of single / multiple antenna links can be classified as:

1.4.1. Single Input Single Output (SISO):

It is the simplest form of the radio link. The transmitter as well as the receiver utilizes the single antenna. Its forte is its simplicity. It does not require any additional processing or diversity scheme. But this in turn limits its performance. In this system interference and fading influences more as compared to any other MIMO system with diversity gains.

Figure 1.2 SISO System

1.4.2. Single Input Multiple Output (SIMO):

In this scheme there is a single antenna at the transmitter side while receiver has multiple antennas. These systems are basically employed for short wave listening and receiving stations to revert the effect of fading and interference caused by ionosphere. One of the advantages of SIMO is that its implementation is relatively easy, but processing is required at the receiver side. There are two types of SIMO.

- **Maximum ratio combining SIMO:**

  In this form of SIMO, the two signals received at the receiver are summed by multiplying each signal by a weight that corresponds to channel weighing factor

- **Switched diversity SIMO:**

  This form of SIMO searches the strongest signal as it switches the antenna to the strongest signal out of the received signal.

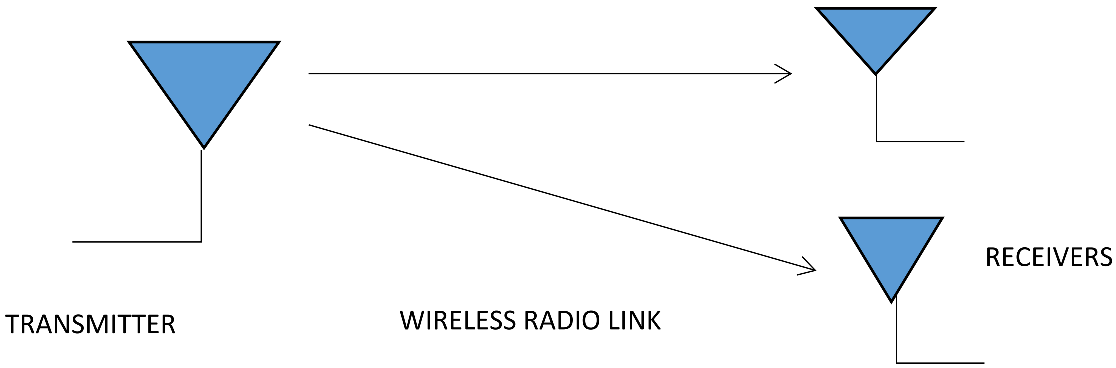


Figure 1.3 SIMO System

1.4.3. Multiple Input Single Output (MISO):

As the name suggests the system has multiple antennas at the source and a single antenna at the destination. It has application in digital television, WLANS.

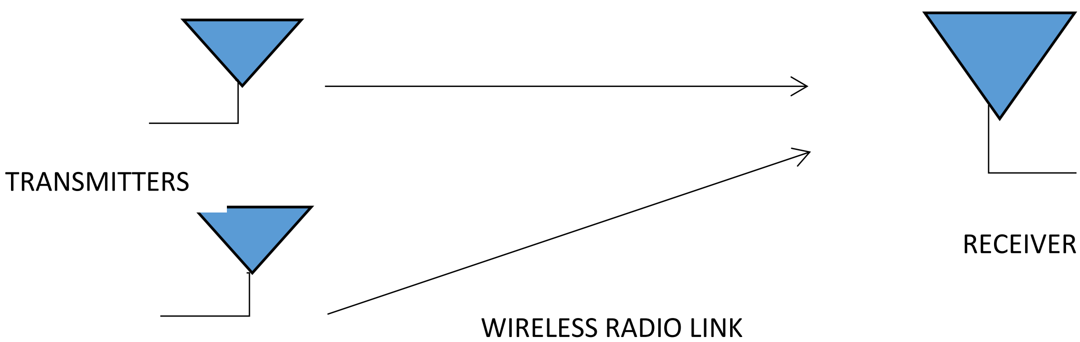


Figure 1.4 MISO System

The redundancy and coding is implemented at the receiver side here. In this scheme less power and processing is required at the user end. In this system the power consumption at receiver side is quite less. This has s positive affect on cost, battery life, and size as less processing requires lower level of battery consumption.

1.4.4. Multiple Input Multiple Output (MIMO):

In MIMO multiple (two or more) antennas are present at either end of the radio link. This improves both the channel robustness and channel throughput. Coding is used on the channel to fully utilize the MIMO technology. Multiple data streams follow different paths that are used in an advantageous way.

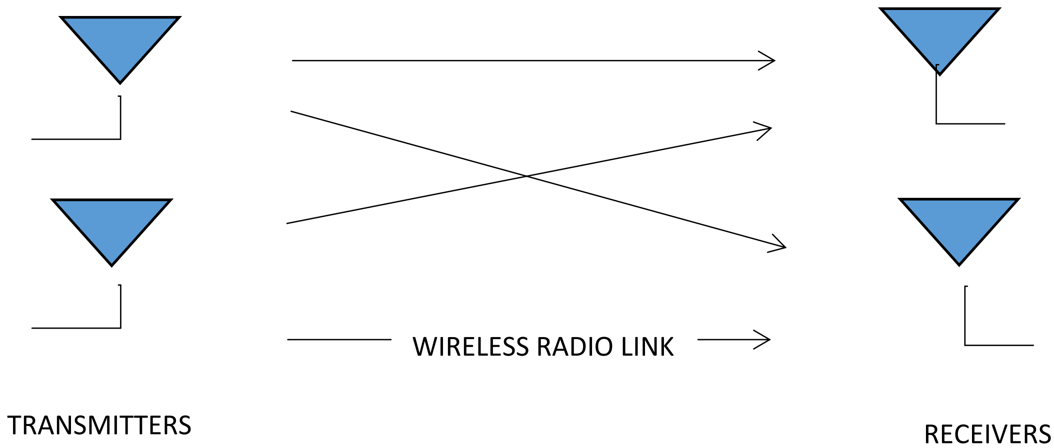


Figure 1.5 MIMO System

In 1984, Jack Winters patented a wireless communication system using multiple antennas and presented a study on the fundamental limits on the data rate of multiple antenna systems in a Rayleigh fading environment. Since then various work has been done for example Arogyaswami Paulraj and Thomas Kailath in 1983 proposed spatial multiplexing, Greg Rayleigh and Gerard Joseph Foschini invented approaches of space-time coding techniques. But the first commercial MIMO system was developed in 2001 by IOS pan Wireless Incorporation. Since 2006, several companies like Intel and Broadcom have introduced MIMO technology in various novel communication systems. Some of the latest technologies that depend upon MIMO systems are IEEE 802.11, Third Generation (3G), and Long Term Evolution (LTE).

The ever increasing demand for higher capacity, increased coverage, and higher reliability that too at a reduced cost has been achieved by MIMO systems. The block diagram of a general MIMO system is shown in Figure1.6. In MIMO wireless system space-time signal processing time is complemented with the spatial dimension provided by the spatially distributed multiple antennas. In this way MIMO allows the increased capacity and reliability without additional power or bandwidth [5].

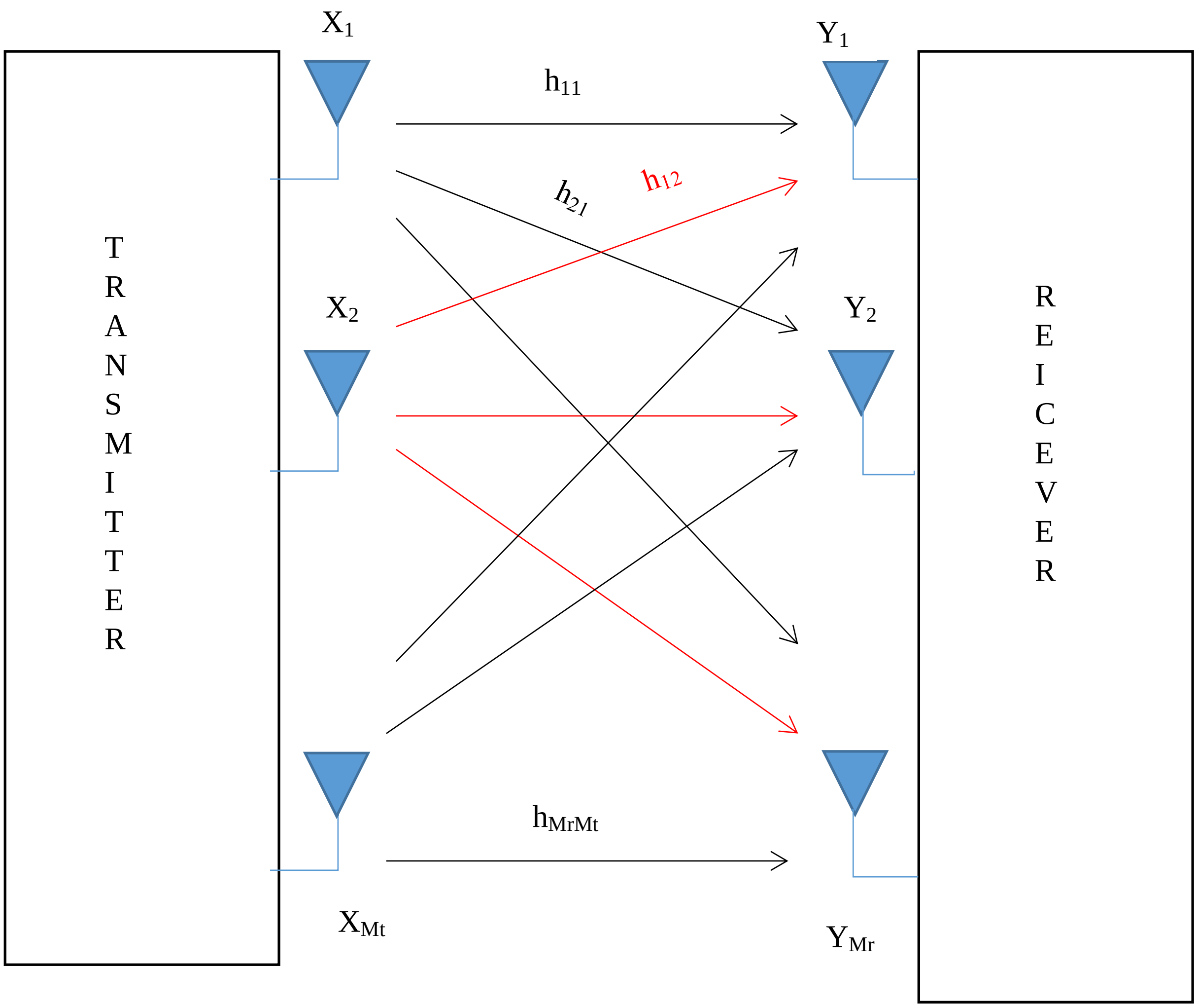


Figure 1.6 Block System of MIMO Architecture

The capacity of the system increases linearly with the minimum number of antenna deployed at the transmitting and the receiving side. In the Figure1.6 X ($X_1, X_2 \ldots X_{Mt}$) is the transmitted signal and Y ($Y_1, Y_2 \ldots Y_{Mr}$) is the signal received by the receiver and h (h_{ij}) represents the channel matrix.

1.4.4.1. Functions of MIMO:

The output obtained from a MIMO system can be optimised using following techniques:

- **Precoding:**

  In the shortest definition it can be said that precoding is multi-stream beamforming. All the spatial processing occurring at the transmitter comes under this function. In beamforming, the signal transmitted from each of the transmitter has considerable phase and gain weights to maximise the signal power at the receiving unit. As the signals transmitted from each antenna are constructively added it reduces the multipath fading effect which in turn increases the received signal gain. When there are multiple antennas at the receiver, it is not possible even with the transmit beamforming to simultaneously maximize the signal level of all the receive antennas, then precoding with multiple streams is beneficial.

- **Spatial Multiplexing:**

  In this scheme, a high-rate signal is split into multiple lower-rate streams and each of the low rate streams are transmitted via different transmitter in the same frequency channel. The receiver array receives the signals having different spatial signatures and then separates these streams into parallel channels. It is a very useful technique to increase the channel capacity at higher signal-to-noise ratios (SNR).

- **Diversity Coding:**

  In diversity methods, a single stream of coded signal is transmitted. Coding is done with a technique known as space-time coding. Diversity coding makes the use of independent fading in the multiple antenna radio wireless links to enhance signal diversity.

1.4.4.2. Advantages of MIMO:

- **Array gain:**

  It can be defined as the average increase in the signal to noise ratio present at the receiver arising from the coherent combination of multiple antennas. The signals that arrive at the receive antenna have different amplitudes and phases. The receiver then combines the received signals coherently which enhances the resultant signal. This results in improved reliability, and the capacity of the system [4].

- **Spatial diversity gain:**

  When signal power drops notably the channel is said to be suffering with fade. The diversity is used to nullify fading. Spatial diversity makes the use of independent copies of the transmitted signal at the receiver. In this scheme the rich scattering nature of the channel is exploited, hence the probability of all the transmitted signals undergoing deep fade becomes very less.

- **Spatial multiplexing:**

  In this scheme with the same bandwidth transmission rate can be increased and no additional power is also needed for the same. The bit stream at the transmitter is de-multiplexed into sub-streams, modulated and then transmitted simultaneously from each transmit antenna. The co-channel signals are then extracted and demodulated by the receiver. Demodulation then yields the original sub stream and then combined to get back the original signal.

- **Interference reduction:**

  Frequency reuse is used in wireless channels to effectively transmit the data, this causes co-channel interference. With the multiple antennas at both the ends the spatial signatures of the desired signal and co-channel signals can be easily differentiated and can be used to reduce the interference [4].

1.4.4.3. Applications of MIMO System:

With the MIMO technology there is an added complexity for multi-dimensional signal processing. To fully understand the multipath signals, a mathematical model is needed. The model consists of channel matrix. The model represents the received signal in terms of summation of channel noise and weighted transmitted signal in the matrix form.

MIMO technology is often combined with Orthogonal Frequency Division Multiple Access (OFDM) to combat the multi-path channel problems. MIMO-OFDM is incorporated in IEEE 802.16e. Recent standards like 3GPP and 3GPP2 also employs MIMO. 3GPP includes High Speed Packet Access plus (HSPA+) and Long Term Evolution (LTE). Most of the applications of MIMO system needs an antenna to be installed in a small hand held devices. For the same small antennas are needed.

1.4.4.4. MIMO Channel Matrix:

As shown in Figure1.6 a MIMO system consists of M_t transmit and M_r receive antennas. This system can be mathematically represented as [2]-

$$Y = hX + n \qquad 1.1$$

$$\begin{bmatrix} y_1 \\ \vdots \\ y_{Mr} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1Mt} \\ \vdots & \ddots & \vdots \\ h_{mr1} & \cdots & h_{MrMt} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{Mt} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{Mr} \end{bmatrix} \qquad 1.2$$

Where; x: M_t dimensional transmitted signal

n: M_r dimensional noise vector

h: M_r X M_t channel matrix and h_{ij} represents the gain from transmit antenna j to receive antenna i.

1.5. Need of Antenna:

Today's researches are focusing on the application of MIMO technique to the small devices like mobile, WLAN, Wireless Fidelity (WIFI), Worldwide Interoperability for Microwave Acess (WiMAX), where space or volume of the device is to be restricted. All the MIMO systems discussed above cannot use large protruding antennas. These systems are basically employable with small hand held devise like laptops, mobile phones, WLANs etc. which require planar antennas of small dimensions. Hence one of the best available choices is microstrip antenna. Microstrip antennas are extremely compatible for embedding in different RF devices like mobile phones, laptops, tablets, and computers. With the advancement in modern telecommunication systems there is a need of wider bandwidth antenna. Not only must an antenna possess larger bandwidth they must also be compact and possess a multi-band behaviour to suit various applications like Global Positioning System (GPS), WLAN, WIFI, GSM. A good gain is also desirable for good range property. Because of the compactness issue wireless world requires a microstrip antenna for most of the integrated operations.

1.6. Microstrip Patch Antenna:

The idea of microstrip antenna came into being in 1950's, but in 1970's microstrip antenna received much attention [6]. The basic structure of microstrip antenna comprises of a metallic patch etched on a thin ground dielectric substrate. Figure1.7

shows a basic microstrip patch antenna. The radiating element and the feed lines are normally printed on the dielectric substrate. The radiating element may be square, rectangle, circle, thin strip (dipole). For a rectangular patch, the dimensions usually taken are: length (L) in the range $0.3333\ \lambda_o < L < 0.5\ \lambda_o$, where λ_o is the free-space wavelength, thickness of patch (t) is generally chosen as $t << \lambda_o$, and height of the dielectric substrate (h) is taken in the range $0.003\ \lambda_o \leq h \leq 0.05\ \lambda_o$.

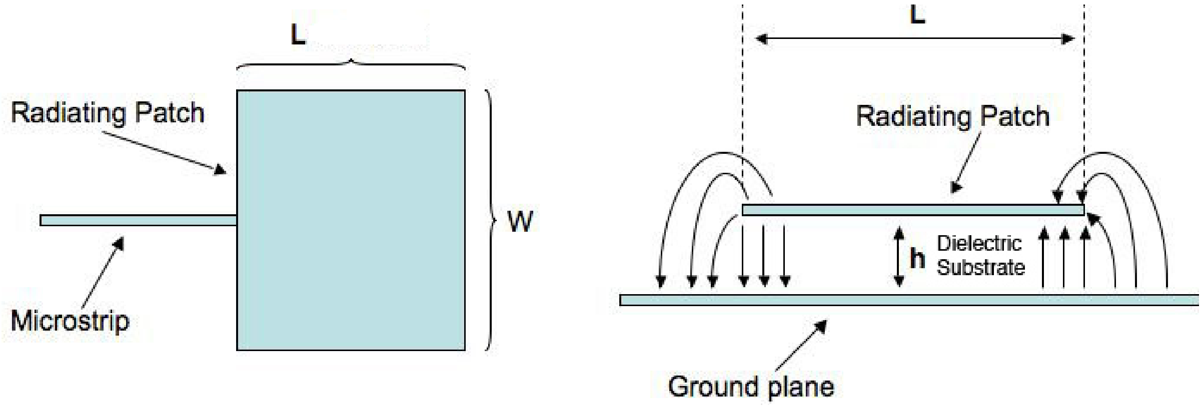


Figure 1.7 Microstrip Patch Antenna [6]

For better scanning capabilities and improved directivities arrays of microstrip elements, with single or multiple feeds can used. Dielectric constants of the numerous substrates that can be used usually fall in the range of $2.2 \leq \varepsilon r \leq 12$. Thick substrates having low dielectric constants are more desirable as low dielectric constant ensured loosely bounded fields which in turn provide larger bandwidth [6]. This provides better efficiency but at the cost of increased height. In microstrip antenna the pattern maximum is always normal to the patch. This can be accomplished by properly exciting the patch and decently choosing the mode (field configuration). The microstrip antenna (MSA) is a broadside antenna.

1.6.1. Advantages:

MSAs have several advantages compared to the conventional microwave antennas. The main advantages of MSAs are listed as follows:

- They have lightweight and small volume and can be used in low-profile planar configuration.
- Versatility in terms of electromagnetic characteristics (input impedance, radiation pattern, polarization) [7].

- They can easily be made conformal to the host surface.
- They can be easily mass produced using printed-circuit technology which leads to low fabrication cost.
- Both linear and circular polarization can be easily achieved [8].
- Easy fabrication into linear and planar array [9].

1.6.2. Disadvantages:

Although microstrip antenna has various advantages but there are some disadvantages associated with it namely:

- They have narrow impedance bandwidth.
- Low power-handling capability.
- Their efficiency is very less.
- High Q value.
- Poor polarization and scan performance.
- Excitation of surface waves.

1.6.3. Methods to Overcome Disadvantages:

Some of the limitations like low gain and low power handling can be overcome with an array configuration. But the increment of bandwidth and the achievement of multi band frequency remains a major issue. This can be improved by:

- **Increasing the Substrate Height:**
  Increasing the substrate height can improve the efficiency up to 90 percent (when there are no surface currents) and can improve the bandwidth bout 35 percent [6]. But as the substrate height is increased, undesirable surface waves gets introduced. These are undesirable as they withdraw power from the total available power for space waves. The waves travelling within the substrates are surface waves. They gets scattered at surface discontinuities and bends, which includes truncation of the ground plane, and dielectric substrate. This modifies the antenna characteristics.
- **Slot in the Patch:**
  Slot can be cut in the patch to improve the bandwidth. As the current flows in the patch, the patch can be represented as LC circuit. And as slot is cut, it can be represented as the LC circuit. As the current flows around the slot, the length of

the current path is increased. This effect can be modelled as an additional series inductance ΔL. The antenna changes from a single LC resonant circuit to dual resonance circuit. The two resonant circuits couple together and form a wide bandwidth. The effect of slot is different at different resonances. This is the key reason the slots can extend the bandwidth.

- **Stacked Microstrip Antenna:**
  Stacking can nullify the limitations associated with the substrate height increment. In stacking a patch is fabricated over the driven patch known as parasitic patch. Both the parasitic and feed patches are electromagnetically coupled to each other. By optimising both the patches so that they produce the resonant frequency close to each other, wider bandwidth can be obtained. There are various parameters that are needed to be optimised to have the same [10].

1.6.4. Feeding Methods:

There are many configurations available to energise the microstrip antenna. The four most popular are:

- **Microstrip Feed:**
  In this method a microstrip feed which is a conducting strip is photoetched on the substrate. Its thickness is much less as compared to the patch. This feed is simple to fabricate and easy to model. But as the substrate height is increased, it limits the bandwidth by introducing spurious feed radiations.

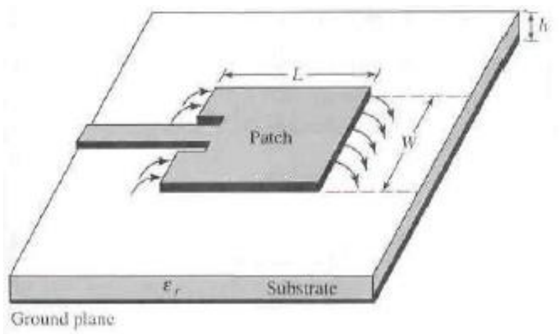


Figure 1.8 Microstrip Feed [6]

- **Coaxial Line:**
  In co-axial feed there are two conductors, inner conductor is connected to the patch and the outer one is attached to the ground. Fabrication of this

configuration is easy but it is difficult to model. Its modelling becomes more difficult as the substrate height increases.

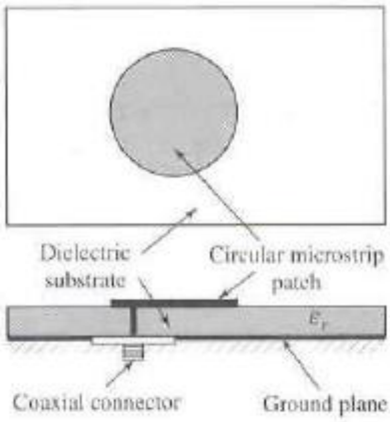


Figure 1.9 Coaxial Feed [6]

- **Aperture Coupling:**

There are some disadvantages of above two feeds like asymmetries and cross-polarization radiation. These are somewhat overcome in aperture coupling. This feeding method employees two dielectric material that are separated by the ground plane between them. Dielectric constant of bottom material is usually higher than the upper dielectric.

Feedline is etched on the lower side of the bottom substrate. The feedline is coupled to the patch through a slot in the ground plane. This is the most tedious of all four to fabricate. But its modelling is quite simple. This arrangement allows independent optimization of various parameters like feedline width, substrate electrical parameters, slot position and size. This feed is shown in figure 1.10.

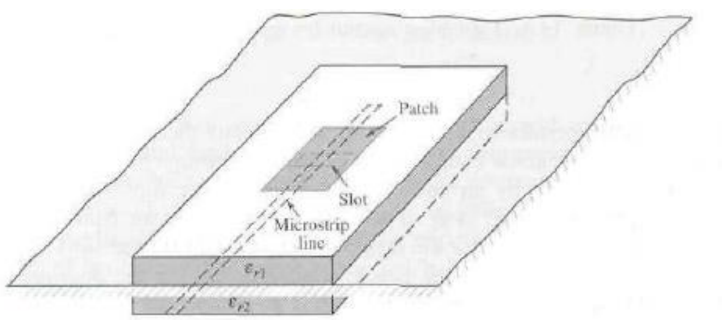


Figure 1.10 Aperture Coupling [6]

- **Proximity Coupling:**

  It also employs two dielectric materials. But in this design the ground plane is present at the bottom side of the lower substrate. It allows the maximum bandwidth. This configuration has low spurious radiations and is quite difficult to fabricate but its modelling is simple

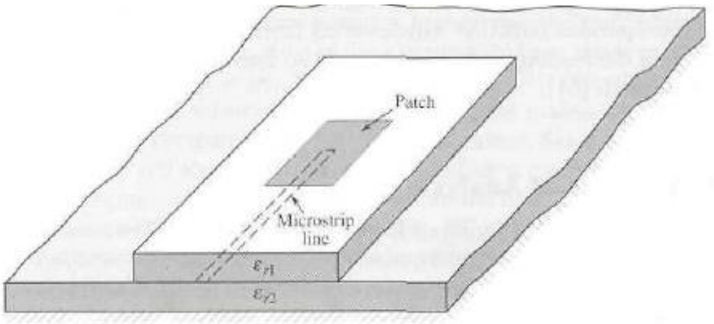


Figure 1.11 Proximity Coupling [6]

1.6.5. Comparison of Various Feeding Techniques:

Every feeding technique has its advantages and disadvantages. The four feedings explained above are compared in table 1.1.

Characteristics	**Microstrip Feed Line**	**Coaxial Feed**	**Aperture Coupled Feed**	**Proximity Coupling**
Spurious feed radiation	More	More	More	More
Reliability	Better	Pure due to soldering	Good	Good
Impedance Matching	Easy	Easy	Easy	Easy
Bandwidth	2-5%	2-5%	13%	21%

Table 1.1 Comparison of Feeding Techniques for MSA

From the above table it can be inferred that aperture coupled feed is more reliable and gives good impedance matching. Also the bandwidth offered by it is better than the microstrip feed line and coaxial feed. For these reasons aperture coupling is used.

1.6.6. Microstrip Antenna Analysis:

To fully understand the concept of MSA, there are number of methods available for microstrip antenna analysis. But the four most popular are transmission line model, cavity model, and full-wave analysis.

1.6.6.1. Transmission Line Model:

Transmission line model is the easiest of all and gives good physical insight but is not much versatile. According to this model antenna can be represented with two transmission line of length L and separated by low impedance Z_c.

Fringing Effects:

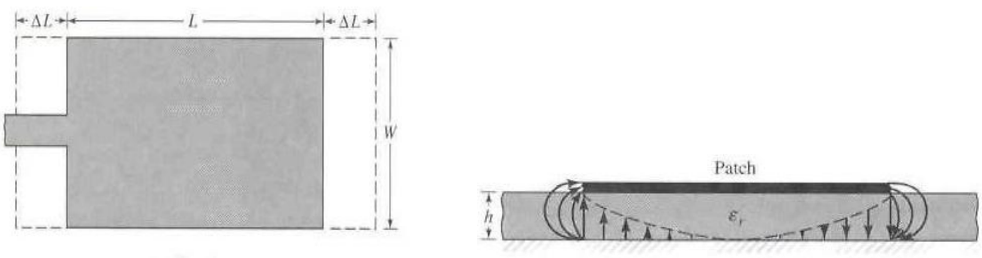
As the dimension i.e. width and length of the patch is finite, the fields at the edge of it undergoes fringing. Due to the abruption in the geometries, all the fields are not able to get transmitted into the space, and some gets trapped on the surface of the dielectric. These surface waves contribute to fringing fields. Fringing is the function of the height of substrate and dimension of the patch [11]. As most of the fields appear on the substrate, it makes the patch look wider electrically as compared to its physical dimensions. In this way an effective dielectric constant ε_{reff} is introduced. It has values in the range of $1 < \varepsilon_{reff} < \varepsilon_r$. when dielectric constant of the substrate is much greater than the unity ($\varepsilon_r >> 1$) then ε_{reff} is close to the actual ε_r. mathematically [6]

for W/h >1

$$\varepsilon reff = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1 + 12\frac{h}{w}\right]^{\frac{-1}{2}} \qquad 1.3$$

Effective Length, Resonant Frequency, and Effective Width:

As the fringing fields causes the patch to look electrically wider, the length of the patch gets extended on each side by a distance ΔL. as shown in figure 1.12.



(a) (b)

Figure 1.12 (a) Top View of Rectangular Patch (b) Side View of Rectangular Patch

An approximate relation can be given as [6]:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon reff+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon reff-0.258)\left(\frac{w}{h}+0.8\right)} \qquad 1.4$$

Due to the extension of ΔL, effective length becomes:

$$L_{eff} = L + \Delta L \qquad 1.5$$

Resonant function of the structure is a function of its length given by [6]:

$$f_r = \frac{1}{2L\sqrt{\varepsilon r}\sqrt{\mu_o \varepsilon_o}} = \frac{v_o}{2L\sqrt{\varepsilon_r}} \qquad 1.6$$

$\boldsymbol{v}_o$: Speed of light

Design:

The design procedure assumes that the resonant frequency, dielectric constant and substrate height is known.

- First step is to specify the known resonant frequency f_r, the substrate height h, and dielectric constant ε_r.
- Next is to determine width of the patch using equation given below [6]:

$$W = \frac{1}{2f_r\sqrt{\mu_o \varepsilon_o}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad 1.7$$

- Next is to determine the effective dielectric constant using equation 1.3.
- Once W has been calculated ΔL is too be calculated.
- Now the actual physical length of the patch is calculated.

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_o \varepsilon_o}} - 2\Delta L \qquad 1.8$$

1.7. Antenna Parameters Used to Characterize its Performance:

CST MWS analyses antenna's performance on the basis of a few characteristic parameters. There various antenna parameters are needed to be analysed before the simulations.

1.7.1. Return Loss:

It is a measure of how well the lines or devices are matched. It can be defined as the loss of signal power being reflected by a discontinuity in a transmission line. If P_i is incident power and reflected power is represented by P_r, then return loss is given by [6]:

$$RL = 10log_{10}\frac{P_i}{P_r} \qquad 1.9$$

For maximum power transfer return loss must be as small as possible. Return loss tells about how much power is being reflected by the antenna, hence it is known as the reflection coefficient (┌ or return loss).

1.7.2. Bandwidth:

It can be defined as the range of frequencies within which a predefined given return loss is maintained. The bandwidth can be considered to be the range of frequencies, on either side of a resonant frequency. Within this frequency range antenna characteristics like radiation pattern, beam direction, input impedance are within the comparable value.

1.7.3. Directivity:

It is a figure of merit. It measures the radiation by an antenna in the direction of its strongest emission vs the power density radiated by an ideal isotropic antenna. It can also be defined as the ratio of radiation intensity in a given direction to averaged radiation intensity over all the directions. Mathematically it can be represented as [6]:

$$D = \frac{U}{U_o} = 4\pi\frac{U_{max}}{P_{rad}} \qquad 1.10$$

Where; U: Radiation intensity (W/unit solid angle)

Uo: Radiation intensity of an isotropic antenna (W/unit solid angle)

Umax: Maximum radiation intensity (W/unit solid angle)

Prad: total power radiated (W)

1.7.3. Efficiency:

It can be defined as the power given to the antenna and the power radiated or dissipated in the antenna. Power can be dissipated due to the following reasons:

- When the transmission line and the antenna are mismatched, reflection occur which causes power dissipation.
- Conduction and dielectric losses.

1.7.4. Gain:

It describes how much power is transmitted in the direction of peak radiation to that of the isotropic source. In general it can be described as:

$$\text{Gain} = \text{Directivity X Efficiency.}$$

1.7.5. Smith Chart:

In 1905-1987 Phillip H. Smith invented Smith Chart. It is a graphical aid that helps to solve problems of matching circuits and transmission lines. Smith Chart specializes in radio frequency (RF) engineering. Normalised scaling helps usage of Smith Chart for any characteristic or system impedance. It helps to read the impedance shown by antenna at a desired frequency of operation.

1.8. Research Gaps:

An extensive literature survey has been carried out in chapter 2 on the development of MSAs for various wireless applications. It was observed that MIMO system propose an increased data rate in the wireless application where these are employed. But not much work is reported in the literature that focuses on the MSA arrays for being used in wireless communication system. Typically stacked patch antennas that can lead to an increased bandwidth can greatly affect the system performance. So in this thesis, design and fabrication of various stacked microstrip antenna array is presented for wireless applications.

1.9. Objectives:

It is shown that stacking is oven of the better options available to achieve greater bandwidth at much denser space as compared to conventional microstrip antennas. Also on comparing the various feeding techniques, aperture coupling was found to be good. So, following are the objectives for future research in this regard

Analysis of MSA

- Design and simulation of a stacked microstrip antenna for wireless applications.
- Design, simulation, and testing of a stacked aperture coupled multi band microstrip antenna array for MIMO application.
- Design, simulation, and testing of a stacked aperture coupled dual band microstrip antenna array with defected ground structure for MIMO application.
- Applicability of antennas in practical environment.

This thesis work focuses on the use of stacked microstrip antennas for MIMO applications. Due to the ever increasing demand of higher capacity, gain, and bandwidth for MIMO applications, the wireless world needs compact and efficient antennas. And due to the advantages provided by the micrsotrip antennas, arrays of the same can be implemented in MIMO applications. Firstly stacked microstrip antenna is theoretically analysed using transmission line equation. Then the stacked antenna is designed and simulated using CST MWSv'14. Then in the following chapters the arrays are designed and fabricated. To integrate multiple MIMO applications in the same equipment, multiple-band antennas are needed. For the same firstly a triple band stacked microstrip antenna array of two patches with aperture coupling feed is designed for C-band, WiMAX, and STM1 applications. Then the dual band aperture coupled stacked array is simulated. The antenna resonates at the frequency applicable for WLAN application. Finally the two arrays are fabricated and tested using VNA and the comparison of the two are also shown.

1.10. Thesis Organisation:

The thesis is divided into following chapters.

- **Chapter 1:** Overview of wireless communication, MIMO communication and Microstrip antenna.
- **Chapter 2:** The literature survey.
- **Chapter 3:** Theoretical analysis of stacked antenna and **a** single band stack antenna is designed.
- **Chapter 4:** A dual single band stacked antenna with aperture coupling is optimized.
- **Chapter 5:** A multi band stacked antenna array with aperture coupling is optimized.
- **Chapter 6:** A dual band stacked aperture coupled antenna array with slits on the lower patch and slots on the upper patch is simulated and optimized.
- **Chapter 7:** The antennas optimized in chapter 5 and 6 are fabricated and tested.
- **Chapter 8:** Conclusion and the future work.

Chapter 2

Literature Survey

Microstrip gained popularity in 1970s. Since then a lot of research has been presented by scientists. A comparison between different feeding techniques shows that aperture coupling is the best of all four techniques. So the current chapter presents a literature survey on aperture coupled MSA, followed by stacked microstrip antenna and then array for the usage in MIMO system.

2.1 Aperture Coupled Antenna:

F. Croq *et al.* [21] in 1991 presented a study on aperture-coupled stacked microstrip antenna. The effects of varying physical parameters of the structure were investigated. Then two antennas were simulated and fabricated. Good agreement was observed between the theoretical and tested results.

D. M. Pozar *et al.* [7] in 1992 presented the brief study of the basic characteristics of the microstrip antenna. Each of the feeding techniques was also studied briefly. Microstrip antenna was analysed using reduced analysis and full-wave analysis. Various advanced anetenna configurations including arrays were also presented.

D. M. Pozar *et al.* [8] in 1997 designed and tested an aperture-coupled antenna with circularly polarization antenna for GPS applications. Antenna operates on two resonances of 1575 and 1227 MHz. Prototype was then fabricated and tested.

F. Yang *et al.* [20] in 2001 presented a novel E-shaped wide band patch antenna. Slots were cut to provide larger bandwidth. Slot parameters like length, width, and position were optimized. Finally, an E-shaped antenna with resonance of 1.9 and 2.4 GHz was designed, measured, and characterized in detail. Comparing to conventional antennas it provided bandwidth increase of 30.3%.

2.2. Stacked Microstrip Patch Antenna:

Stacking is a method of using multiple antennas in layers. This method helps to increase the bandwidth and gain of MSA.

H. Legay *et al.* [22] in 1994 presented a new radiating antenna structure consisting of four identical coplanar patches electromagnetically coupled to a driven patch etched on a lower substrate. The antenna presented a large bandwidth, and a high gain. The proposed structure overcomes the problem of grating lobes. Therefore can be used in large phased arrays.

Jiri SvaEina [23] in 1992 investigated multi-layered microstrip transmission lines. The conformal mapping method was used for the analytical investigation of effective permittivity of three-layered microstrips.

S. Egashira *et al.* [24] in 1996 presented a stacked microstrip antenna with two parasitic elements. Firstly the antenna was tested with only one parasitic element which provided impedance bandwidth alike single element antenna. Then a stacked three layer antenna was designed and tested which provided increase in gain. Stacked antenna with circular polarization was also studied.

R. L. Yadav *et al.* [12] in 2000 theoretically analysed a coaxially fed, electromagnetically coupled elliptical microstrip two-layered stacked antenna. Analysis was based on circuit theory. Various parameters like VSWR, return loss, impedance bandwidth were also investigated.

E. Nishiyama *et al.* [13] in 2004 theoretically calculated the antenna parameters like input impedance, radiation pattern and directivity using the FDTD method. Analysed the stacked antenna by varying the distance between the fed and driven patch and concluded that the antenna has wide bandwidth and high gain because of the two-frequency resonance and leaky resonant cavity formation due to stack technique.

K. Shambavi [25] in 2007 designed and studied a stacked microstrip square patch antenna with an air gap to for WLAN applications. The proposed antenna has resonance of 2.45 GHz. The antenna showed an increase of 12.72% bandwidth.

A. A. Serra *et al.* [26] in 2007 presented a dual-polarized stacked patch antenna having a wide bandwidth. Antenna showed three resonances from 1920 to 2170 MHz (UMTS), 2.4 to 2.484 GHz (WLAN), and 2500 to 2690 MHz (UMTS II). A prototype was tested for various parameters like impedance bandwidth, gain, and cross-polarization level.

S. Shekhawat *et al.* [27] in 2010 designed and analysed a single-feed stacked rectangular patches antenna with circular polarization. The driven patch was truncated at the corner to provide the circular polarization. It also had a slot at the centre. Parameters like feed point location, size of slot, and the amount of corner truncation were optimized for the optimum results. The proposed antenna provided much greater impedance and axial ratio bandwidth when compared to single layer antenna

R. K. Vishwakarma *et al.* [28] in 2010 experimentally analysed a dual-band stacked rectangular microstrip antenna. The length and width of the parasitic patch was altered. The proposed antenna worked well in the frequency range from 2.86 to 4.63 GHz. Dual resonance was achieved it was observed that the upper resonance remained almost constant as the patch dimensions were increased. The input impedance, return loss, and VSWR were measured with the network analyser and found to be matching with the simulated results.

F. Zhang *et al*. [14] in 2010 proposed a stacked microstrip antenna with aperture coupling feeding. It provided the impedance bandwidth of about 25%. Then a broadband 8X8 stacked microstrip antenna array is designed and fabricated. Array showed an impedance bandwidth of 18%. Along with the impedance bandwidth, the gain of the antenna array was also investigated.

X. Lin *et al.* [29] in 2012 proposed a high gain three layered microstrip array with aperture coupling feed. The structure consists of 2X4 patches etched on the top most layer, middle layer is ground plane with rectangular slots, and bottom layer had feedline on to. Proposed antenna is analysed by FDTD algorithm. The fabricated prototype showed a gain and bandwidth of 15.7 dBi and 300 MHz respectively at 5.8 GHz.

P. R. Prajapati *et al.* [15] in 2012 proposed a compact stacked circular disc microstrip antenna (SCDMA) which is energised using proximity feed. The structure has Defected Ground Structure (DGS) that are dumbbell shaped with circular heads. DGS helped in improving the bandwidth and hence the radiation efficiency. The simulated antenna covers the frequency band from 5.20 to 5.94 GHz. Bands of WLAN (5.25 to 5.8 GHz) and WiMAX (5.725 to 5.8 GHz) were covered by the proposed antenna. The design and simulation of SCDMA with and without DGS were carried out using CSTMWSv'9.

S. V. Pushpakaran *et al.* [30] in 2013 presented a novel stacked metal slab antenna with directional broadside radiation coverage having resonance at 3.2 GHz suitable for wireless applications. The proposed antenna is analysed using HFSS software. The prototype was fabricated and tested, simulated, and FDTD computed results were presented and discussed.

H. Alias *et al.* [31] in 2013 proposed an aperture coupled microstrip antenna integrated with four dumb shell shaped DGS and four parasitic elements. Measure and simulated results were also presented which showed the reduction of back lobes from 4.6dB to 0.1331dB. Antenna showed the resonance at 5.8GHz with S_{11} of -27.50dB. The presented antenna design showed the effect of DGS on back lobe reduction thus improving the gain.

R. S. Kushwaha *et al.* [32] in 2013 designed and simulated a novel E-shaped slot loaded microstrip patch antenna with square shaped parasitic element. The antenna was simulated using IE3D software and showed a wide band covering 1.35 to 3.89 GHz frequency range. The proposed antenna covers the frequency bands of UMTS (1.92 to 2.17 GHz), WiMAX (2.2 to 3.4 GHz), WLAN (2.40 to 2.48 GHz), and UMTS II (2.50 to 2.69 GHz) frequency bands.

A. Agarwal *et al.* [10] in 2014 presented a review on stacked microstrip antenna. Various parameters of stacking technique were discussed for high gain and high bandwidth. Parameters studied were dielectric constant, dimension of the stacked patches, and distance between them.

A. Kaur *et al.* [33] in 2015 proposed a multi-layered dual band aperture coupled antenna with circular polarization. It shows the bandwidth of 250 MHz from 2.39 to 2.64 GHz and 370 MHz from 3.39 to 3.76 GHz. The proposed structure covers the application of WLAN (2.5-2.485), ZigBee (2.4-2.485), Bluetooth (2.4-2.485), WiMAX (3.4-3.69), and IMT (3.4-3.6). The gain observed was 4.08dBi and 5.024Dbi at the resonances of 2.4 GHz, and 3.51 GHz. Simulated parameters like return loss, smith chart, and gain were also presented. The simulated antenna was fabricated and tested for return loss.

A. Agarwal *et al.* [34] in 2015 presented a paper on theoretical analysis of electromagnetically coupled stacked microstrip antenna. Analysis was carried out using equivalent circuit technique. Stacked antenna was designed using CSTMWSv'14 which showed 11.7% bandwidth increase over 3.27% of single element antenna resonating at the same frequency.

A. Kaur [19] in 2015 presented parametric study of G-shaped microstrip antenna. The antenna was designed and optimized using CST MWSv'10. It showed two resonances at 3.6 GHz and 5.2 GHz. The prototype of the proposed structure was fabricated on FR4 substrate and both the simulated and tested results were also presented in the paper. The tested results were 80% matching to the simulated ones.

2.3. MSA for MIMO Applications:

To employ the microstrip antennas in a MIMO system array configuration is to be designed. Some of the work related to array design and fabrication is presented here.

J. Thaysen *et al.* [18] in 2006 derived a simple closed form equation for ECC in an MIMO system. The ECC was calculated from the S-parameter between two antennas which made the calculations less tedious as compared to radiation pattern approach. An example was also illustrated that indicated the high accuracy of the formula even when the radiation efficiency was low.

B. Clerckx *et al.* [35] in 2007 presented the impact of mutual coupling induced by two antennas present at the receiver side in 2 × 2 MIMO system. Analytically showed the detrimental impact of mutual coupling on correlation.

H. Zhang *et al.* [36] *in* 2008 presented an array of three equilateral triangular microstrip patch antenna and studied the effect of mutual coupling on radiation pattern and correlation coefficient. It was then observed that the antenna array has high diversity gain when the isolation between them was fair.

D. Piazza *et al*. [37] in 2009 proposed a reconfigurable circular patch antenna (RCPA) for MIMO systems. Then antenna was tested indoor for various parameters like scattering parameter, radiation pattern, and achievable channel capacity in a 2X2 MIMO system. It was then concluded that the proposed antenna provider higher channel capacity as compared to conventional non-reconfigurable antennas.

A. Öcalan *et al.* [38] in 2009 designed and analysed a compact stacked microstrip circular patch uniform linear antenna array. Stacked circular patch antenna was analysed for s-parameter and it showed the resonance at 5.8 GHz. Next the uniform linear array of stacked circular patch was evaluated for correlation and capacity analysis. Proposed antenna showed lower correlation, and higher spectral efficiency when compared to conventional single circular patch antenna array.

C. A. Tunc *et al.* [9] in 2010 designed various array configurations of rectangular patch and were tested in various multiple antenna configurations in an indoor environment.

Simulated and measured results were compared which provided a good agreement. The proposed antenna was tested to study the effects of mutual coupling and electrical properties on the MIMO system capacity.

A. Yavanoğlu *et al.* [39] in 2010 analysed compact multimode stacked circular microstrip patch antenna uniform linear arrays (SCP-ULA) for spectral efficiency, data rate and compactness gain. It also presented the use of low complex sub-optimal MIMO detectors in WLAN systems. Higher data rates were obtained when these detectors were used in conjunction to SCP-ULA with respect to using dipole ULA and circular patch ULA antenna arrays.

S. Mohanna *et al.* [16] in 2010 presented a novel 1X2 and 1X4 wideband array. 1X2 and 1X4 array showed a gain of 10dB and 12dB. To improve the gain 2X4 array was simulated which showed a gain of greater than 12dB. The fabricated, simulated, and measured results were also presented. The antenna finds application in Ku and K bands.

C. Votis *et al.* [17] in 2010 designed and fabricated a T- shaped antenna. Then used that antenna in an array configuration. Various array configurations were investigated for ECC in terms of S-parameter. It was shown by the measured results that ECC was low in rich scattering environment. For the proposed array configuration ECC didn’t get much affected by the distance between the antenna elements.

H. Nigam *et al.* [5] in 2014 designed an antenna having band-notched, and ultra-wideband characteristics and presented a novel design of UWB MIMO-OFDM system using the proposed antenna. The MIMO system showed capacity improvement over SISO system. The UWB antenna was designed on CST. Further using the result from CST, the data throughput for both single and multiple antenna system was compared for system performance.

C. Y. D. Sim *et al.* [40] in 2015 proposed a Long Term Evolution (LTE) antenna having ultra-wideband. The structure is designed as such to reduce the ground effects. The antenna has bandwidth of 13% and 37.6% at LTE bands (700/2300/2600 MHz). The proposed structure was then used as two element MIMO system. On the evaluation of array good ECC of less than 0.14 and 0.0022 at resonance was observed.

I. Mohamed *et al.* [41] in 2015 designed, fabricated, and measured 2X2 planar 60 GHz microstrip antenna array. The structure was simulated using CST. The proposed antenna showed a gain of 12.4 dB at 60GHz resonance which made it suitable for short range high speed wireless communication.

E. Rodriguez *et al.* [42] in 2015 presented an array of four compact patches with corrugated slots on the ground plane. The array operates at 2.6 GHz LTE. Then MIMO array was simulated and fabricated to investigate the radiation pattern and scattering parameters. Ground plane, and orientation of each patches were optimised to reduce the mutual coupling.

A. Agarwal *et al.* [43] in 2016 designed and simulated an array for C-band applications. The array used stacked patches as single antenna element. The proposed antenna structure resonates at 6 GHz with a bandwidth of 521 MHz. capacity of 1X2 MIMO system with the assumption of simulated array being installed at the receiver side was also presented.

S. Amit *et al.* [44] in 2016 designed a U-shaped bent dipole patch antenna resonating at 1.575 GHz for GPS application. The proposed antenna is then fabricated on FR4 epoxy substrate with ε_r=4.3 and height 1.52mm for two and six element antenna array. The return loss for one, two, and six element is -31.7dB, -20dB, and -17dB respectively. And gain observed is 2dB, 4.59dB, and 8.01dB. An increase in gain was observed for six element array.

D. F. Guan *et al.* [45] in 2016 designed and fabricated a 3X3 microstrip patch antenna array. The proposed structure consisted of nine coplanar patches with the centre patch as fed patch and the remaining eight patches as the parasitic patches. The fed patch is energised using a probe feed. All the elements were excited simultaneously by feeding them with the microstrip lines between them. The fabrication results showed the bandwidth of 15.4 % from 18 to 21 GHz and a gain of 14.8dBi.

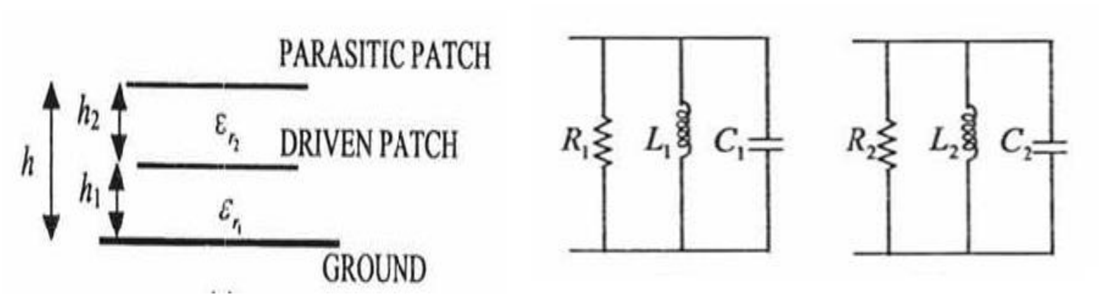
Chapter 3

Single Band Stacked Microstrip Antenna for Wireless Local Area Network (WLAN) and Synchronous Transport Module-1 (STM1) Applications

This chapter presents the electromagnetic analysis of stacked microstrip patch antenna. These concepts are used to design a single band stacked antenna for Wireless Local Area Network (WLAN) and Synchronous Transport Module-1 (STM1) application.

3.1. Theoretical Analysis of Stacked Microstrip Patch Antenna:

A stacked microstrip antenna consists of a driven patch and a parasitic patch above it. In the stacked configuration as shown in figure 3.1 the second patch known as parasitic patch is electromagnetically coupled on top of the driven patch. There are two resonances associated with the structure. One resonance is caused by the lower patch and the ground plane which controls upper resonant frequency and the second resonator is formed by the parasitic patch and lower patch which is associated with the lower resonant frequency.



(a) (b) (c)

Figure 3.1 (a) Side View of Stacked Microstrip Antenna (b) Equivalent Circuit of Lower Resonator (c) Upper Resonator

Due to the presence of two patches the effective dielectric constant of the structure gets changed and now the resonant frequency will be determined by the new dielectric constant. Figure 3.1 (b) and (c) shows the RLC circuits of the driven and parasitic patch respectively. The equivalent circuit of a stacked patch antenna is shown in figure 3.2. Due to the presence of two substrates the effective dielectric constant is given by [12]-

$$\varepsilon_{eff} = \varepsilon_{r1} q_1 + \frac{(1-q)^2}{\varepsilon_{r2}(1-q_1-q_2)+q_2} \qquad 3.1$$

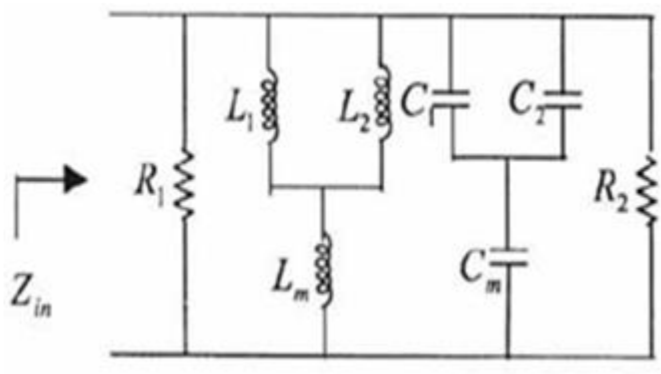


Figure 3.2 Equivalent Circuit of the Stacked Microstrip Antenna [12]

Here, q_i is the filling fractions given by:

$$q_1 = 1 - \frac{h_1}{2w_{1e}} \ln\left(\frac{\pi}{h_1} w_{1e} - 1\right)$$

Where, the effective width is given by:

$$w_{1e} = w_1 + \frac{2h_1}{\pi} \ln\left\{17.08\left(\frac{w_1}{2h_1} + 0.92\right)\right\}$$

$$q_2 = 1 - q_1 - q_3$$

$$q_3 = \frac{h_1 - g}{2w_{1e}} ln\left\{\pi \frac{w_{1e}}{h_1} \frac{cos\left(\frac{\pi g}{2h_1}\right)}{\pi\left(\frac{h}{h_1} - \frac{1}{2}\right) + \frac{\pi g}{2h_1}} + sin\left(\frac{\pi g}{2h_1}\right)\right\}$$

$$g = \frac{2h_1}{\pi} tan^{-1}\left\{\frac{\pi}{\frac{\pi w_{1e}}{2h_1} - 2}\left(\frac{h}{h_1} - 1\right)\right\}$$

Where, h_1: Height of lower substrate

q_1,q_2,q_3: Filling fractions

Using the dielectric constant given by equation 3.1, the superstrate microstrip antenna can be represented as a single patch antenna with dielectric constant equal to ε_{r1}' given by:

$$\varepsilon_{r1}' = \frac{2\varepsilon_{eff} - 1 + A}{1 + A} \qquad \text{Where, } A = \left(1 + 10\frac{h_1}{w_{1e}}\right)^{-1/2}$$

Resonant frequency of the fed patch can be written as.

$$f_{r1} = \frac{c}{2(l_1+\Delta l_1)\sqrt{\varepsilon_{eff}}} \quad 3.2$$

Here, l_1: Actual length of the lower patch

Δl1: fringing length given by:

$$\Delta l_1 = 0.412 l_1 \frac{(\varepsilon_{1e} + 0.3)\left(\frac{W_1}{h_1} + 0.264\right)}{(\varepsilon_{1e} - 0.258)\left(\frac{W_1}{h_1} + 0.8\right)}$$

Here, ε_{1e} is the effective dielectric constant

$$\varepsilon_{1e} = \frac{\varepsilon'_{r1}+1}{2} + \frac{\varepsilon'_{r1}-1}{2}\left(1 + 12\frac{h_1}{w_1}\right)^{-1/2} \quad 3.3$$

Similarly, for the second resonator:

$$f_{r2} = \frac{c}{2(l_2+\Delta l_2)\sqrt{\varepsilon_{2e}}} \quad 3.4$$

$$\varepsilon_{2e} = \frac{\varepsilon_{r2}+1}{2} + \frac{\varepsilon_{r2}-1}{2}\left(1 + 12\frac{h_2}{w_2}\right)^{-1/2} \quad 3.5$$

$$\Delta l_2 = 0.412 l_2 \frac{(\varepsilon_{2e}+0.3)\left(\frac{w_2}{h_2}+0.264\right)}{(\varepsilon_{2e}-0.258)\left(\frac{w_2}{h_2}+0.8\right)} \quad 3.6$$

There will be a mutual capacitance and inductance between the two resonators as they are electromagnetically coupled. Maximum radiation will be there when both the resonators are in action. At resonance, the response in the parasitic element can be written as:

$$\frac{V_2}{V_1} = \sqrt{\frac{L_2}{L_1}}\left(\frac{K_1}{K^2 + \frac{1}{Q_{T1}Q_{T2}}}\right)$$

Here, V_1, V_2 : Voltage across fed and parasitic patch

L_1, L_2: Inductance of fed and parasitic patch element

K_1: Actual coefficient of coupling

K: Critical coefficient of coupling

When the actual coefficient of coupling equals the critical coefficient of coupling ie K_1=K. Then,

$$\frac{d}{dK_1}\left(\frac{K_1}{K^2 + \frac{1}{Q_{T1}Q_{T2}}}\right) = 0$$

$$K = \frac{1}{\sqrt{Q_{T1}Q_{T2}}}$$

With inductive and capacitive coupling, the equivalent circuit of the stacked structure is shown in figure 3.2. The values of mutual inductance and capacitance are given by.

$$L_m = \frac{K^2(L_1 + L_2) + \sqrt{(K^2(L_1 + L_2)^2 + 4K^2(1 - K^2)L_1L_2)}}{2(1 - K^2)}$$

$$C_m = \frac{-(C_1 + C_2) + \sqrt{\left((C_1 + C_2)^2 - C_1C_2\left(1 - \frac{1}{K^2}\right)\right)}}{2}$$

Input impedance of the stacked antenna can be derived from the Figure 3.3

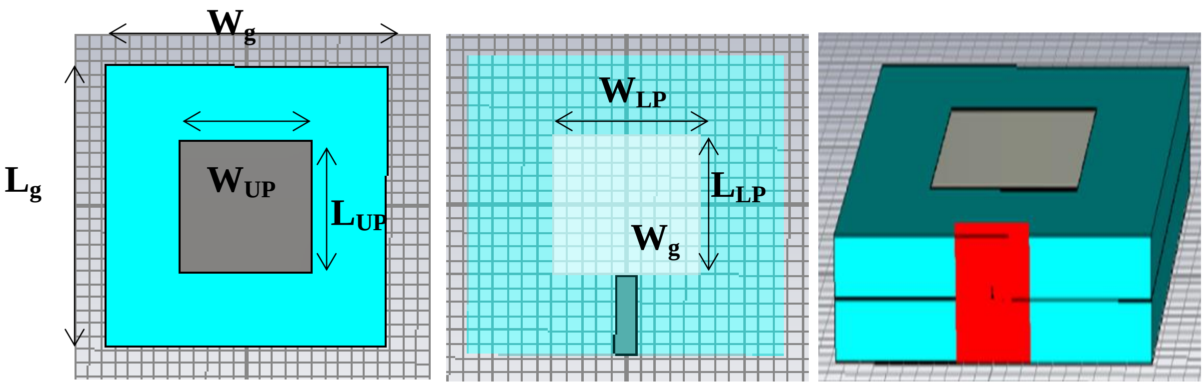
$$Z_{in} = \frac{\omega^2RL^2 + j\omega R^2L(1 - \omega^2LC)}{\omega^2(\omega^2R^2L^2C^2 - 2R^2LC + L^2) + R^2}$$

Where, $R = \frac{R_1R_2}{R_1+R_2}$, $L = \frac{L_1L_2}{L_1+L_2} + L_m$ and $C = \frac{(C_1+C_2)C_m}{C_1+C_2+C_m}$

These concepts are used to design a stacked single band antenna for STM1 application in next section.

3.2. Single Band Stacked Microstrip Antenna Simulation:

A single band stacked antenna is designed and simulated on an FR4 substrate with a dielectric constant of 4.4 and height of 1.57mm. The structure consists of two stacked layers. One FR4 layer is added over another as shown in figure 3.3(c). Both the substrates have patches of same dimensions printed on them. Therefore, both the patches are now electromagnetically coupled. There are two resonances associated with the structure. One resonator is formed by the lower patch and ground, and second resonance frequency is associated with the lower patch and the upper patch. Lower resonator controls the upper resonant frequency while the lower resonant frequency is controlled by the upper resonator.



(a) (b) (c)

Figure 3.3 Broadband Stacked Antenna (a) Top View, (b) Ground Pla-ne with Lower Patch and Feedline, (c) Side Siew

Dimension of the upper patch was optimized such that the resonance produced by it comes close to the resonant frequency of lower patch. This way both the resonant frequencies produce a wider bandwidth. Thus stacking is proposed as an efficient method for increasing the performance of a microstrip antenna in terms of bandwidth [13]. Although the volume occupied by the antenna increases but the lateral surface area occupied by the antenna remains the same. Hence, it is suitable for WLAN and STM1 wireless application. Various design specifications have been shown in table 3.1 and optimized parameters are shown in table 3.2. All the dimensions of the structure are calculated with the help of equation 3.1 to 3.6.

Table 3.1 Specified Antenna Parameters of the Broadband Stacked Antenna

Resonant frequency	6 Ghz
Patch substrate material	FR-4
Patch substrate thickness	1.57 mm
Dielectric constant of the material used	4.4
Thickness of PEC material	0.035 mm

Table 3.2 Optimized Antenna Parameters of the Broadband Stacked Antenna

Parameter	Description	Value
L_{LP}	Lower patch length	10 mm
W_{LP}	Lower patch width	10 mm
L_{UP}	Upper patch length	10 mm
W_{UP}	Upper patch width	10 mm
L_g	Ground plane length	21.34 mm
W_g	Ground plane width	21.34 mm
W_f	Feedline width	1.4 mm

3.2.1. Return Loss and Antenna Bandwidth:

Figure 3.4 shows the return loss versus frequency plot of the designed antenna. It is a wide band covering the frequency range from 5.7783 GHz to 6.4372 GHz having a bandwidth of 658.9 MHz with the return loss value of −23 dB at resonant frequency of 6 GHz. This frequency band covers the application of WLAN and STM1.

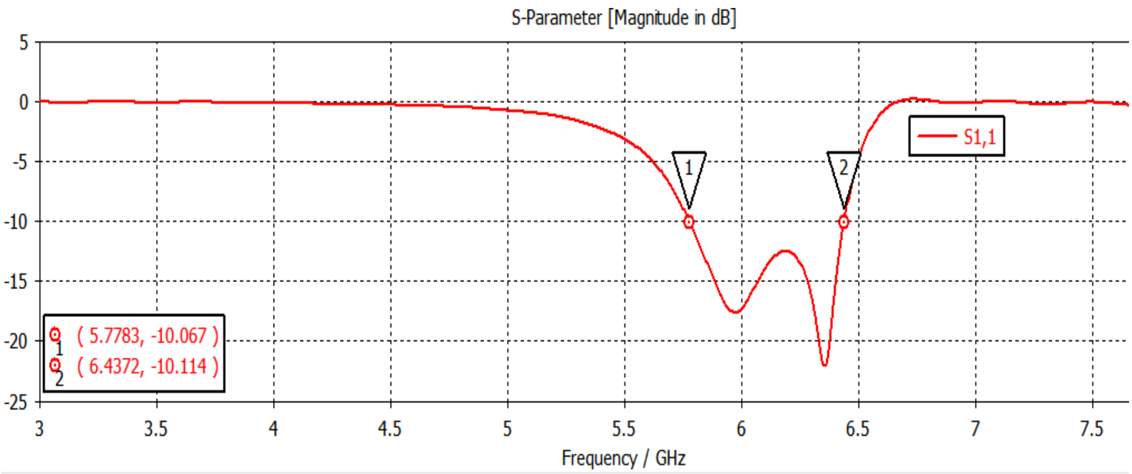


Figure 3.4 Return Loss S_{11} (dB) V/S Frequency Plot of the Broadband Stacked Antenna

3.2.2. Smith Chart and Antenna Impedance:

The smith chart represents variation of the antenna impedance with the frequency. It shows the complex impedance of the reflected S-parameter $S11$ within a specified frequency range. Bandwidth can be also determined from it by reading the frequencies at the points where the VSWR=2 circle and input impedance curve intersects. For proper matching conditions the locus of the smith chart must pass through its centre. The smith chart for the single band stacked antenna has been shown in Figure 3.5.

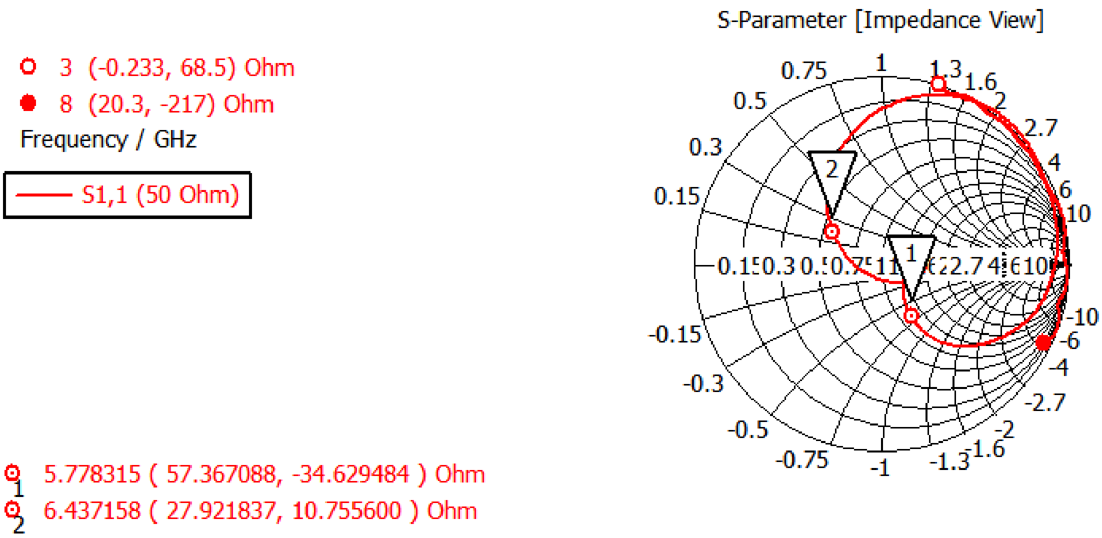


Figure 3.5 Smith Chart Showing the Characteristics Impedance of Broadband Stacked Antenna

3.2.3. Gain:

Figure 3.6 shows the radiation pattern plot of the simulated antenna with a stacked layer on top of the designed antenna Figure 3.6 shows that this antenna has gain of 6.100 dBi.

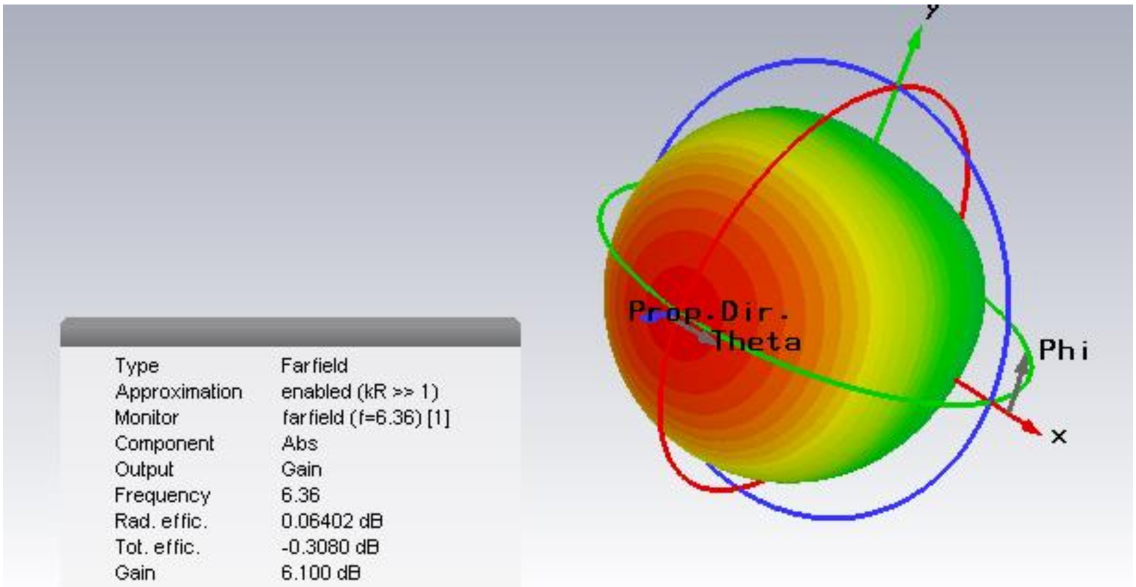


Figure 3.6 3D Radiation Pattern of the Gain of the Broadband Stacked Antenna

3.2.5 Surface Currents:

Figure 3.8 reveals the surface currents on the upper patch. From the figure it can be inferred that the maximum current distribution is achieved at the centre of the patch. Maximum current observed at 6.36 Ghz is 65.3 A/m.

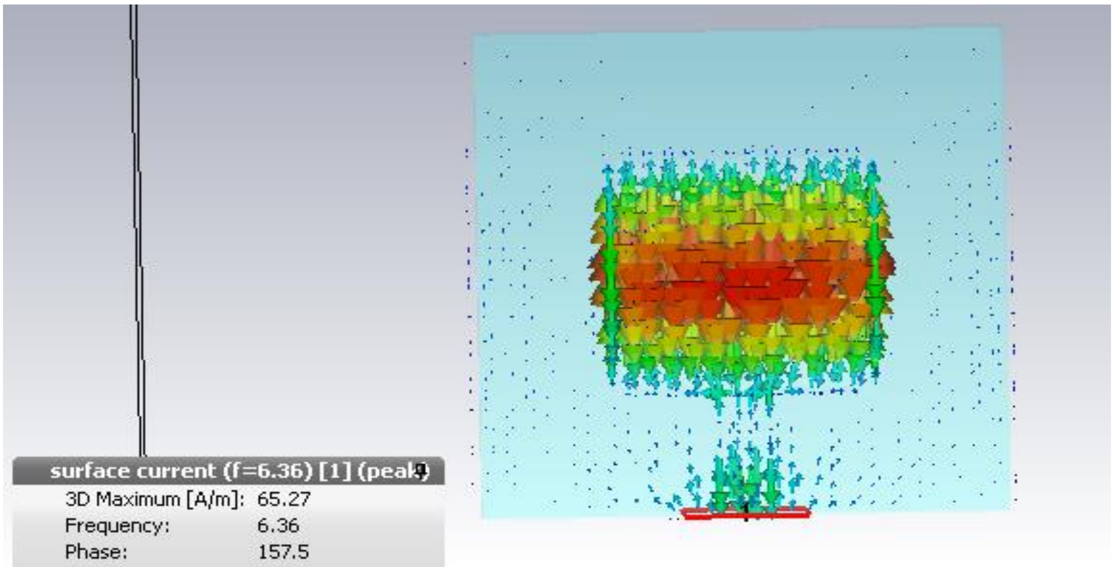


Figure 3.8 Surface Current Distribution of the Broadband Stacked Antenna

3.3. Conclusion:

This chapter presented the theoretical analysis of a stacked MSA and then those concepts are used to design a single band stacked MSA. The designed antenna shows a bandwidth of 658 MHz from 5.7783 GHz to 6.4372 GHz thereby allowing the antenna to be suitable for WLAN and STM1 wireless applications.

Chapter 4

Dual-band Aperture Coupled Stacked Antenna

In this chapter a dual band aperture coupled stacked microstrip antenna (ACSMPA) is designed and simulated using CST MWSv'14 for C-band and WiMAX applications.

4.1. Design and Simulation:

Stacking is a technique that can be used to either achieve the dual band behaviour or increase the impedance bandwidth of the antenna. The stacked structure is a multi-layered structure consisting of number of dielectric substrates and patches. The parasitic element (or stacked patch) is electromagnetically to the fed element (or the driven patch). The material used for both the substrates is FR-4. The material has a thickness (h) of 1.57 mm and dielectric permittivity ε_r of 4.4. The structure consists of two patches having same dimensions. The structure consists of three substrates as shown in figure 4.1.

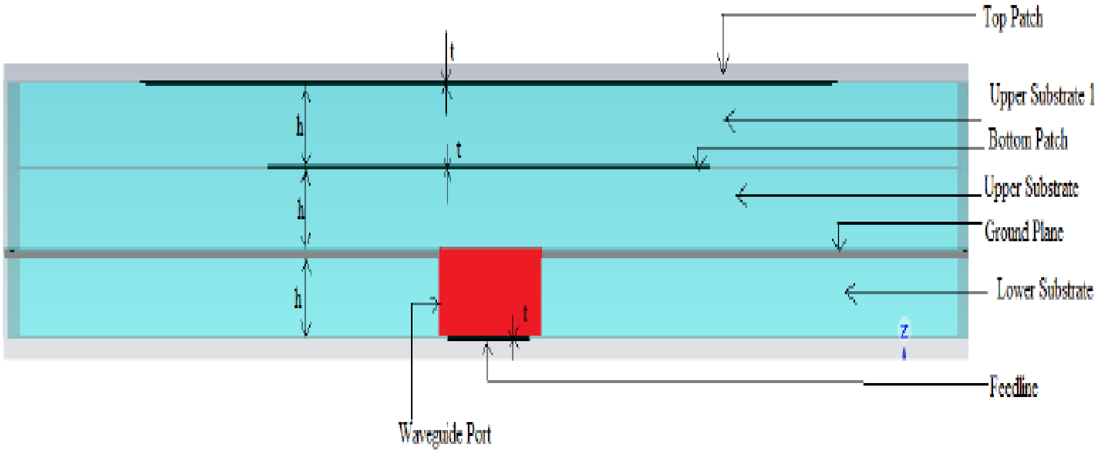


Figure 4.1 Side View of Dual Band ACSMPA

The upper two substrates contribute to antenna and the lowest substrate is for aperture feeding [14]. It has feedline etched on the lower part and ground plane with defected ground structure (DGS) is etched on its upper surface. The patches are energised by the feedline through the DGS present in the ground plane [15]. Figure 4.2 depicts the front view of every layer of the antenna with labelled dimensions. The design specifications of the dual band ACSMPA has been given in Table 4.1. Also the various dimensions of the antenna are calculated using equations from 3.1 to 3.6. The dimension of the patches, ground plane, substrate, and feedline of the designed dual band antenna has been given in Table 4.2.

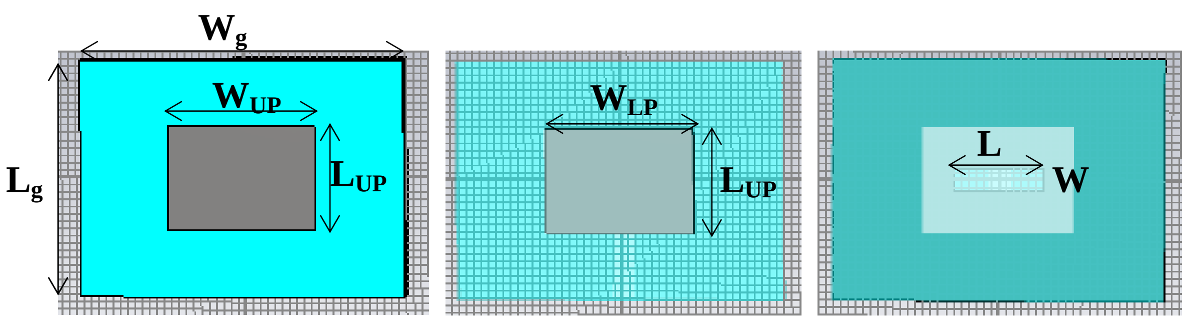
Table 4.1 Specified Antenna Parameters of Dual Band ACSMPA

Resonant frequency	3.2 GHz, 4.5 GHz
Patch(top as well as lower) substrate material, feed substrate material	FR-4
Patch (top as well as bottom) substrate thickness, feed substrate thickness, h	1.57 mm
Dielectric constant of the material used	4.4
Thickness of PEC material, t	0.035 mm

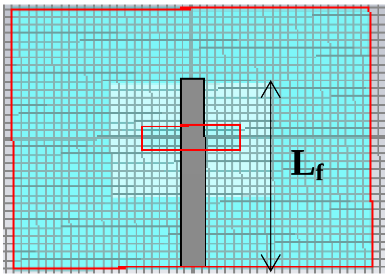
The various dimensions of antenna are labelled in figure 4.2 and values are mentioned in table 4.2.

Table 4.2 Optimised Antenna Parameters of Dual Band ACSMPA

Parameter	**Description**	**Value**
L_{LP}	Lower patch length	14 mm
W_{LP}	Lower patch width	20 mm
L_{UP}	Upper patch length	14 mm
W_{UP}	Upper patch width	20 mm
L_g	Ground plane length	32 mm
W_g	Ground plane width	44 mm
L_f	Feedline length	23 mm
W_f	Feedline width	3 mm
L	Length of the aperture in ground-plane	12 mm
W	Width of the aperture in ground-plane	3 mm



(a) (b) (c)



(d)

Figure 4.2 Dual Band ACSMPA (a) Front View Showing Top Patch, (b) Bottom Patch, (c) Slot in the Ground Plane, (d) Back View Showing Feedline

4.2. Simulation Results:

The proposed antenna is designed and simulated for various parameters like return loss, gain, and smith chart using CST MWSv'14.

4.2.1. Return Loss and Antenna Bandwidth:

The S_{11} parameter represents the power reflected from the antenna. The plot can also be used for the calculation of bandwidth. The bandwidth of the antenna can be defined as the range of frequencies over which the return loss is lesser than −10 dB. Figure 4.3 shows the S-parameter plot of the dual band ACSMPA. The S_{11} versus frequency plot of the antenna shows dual frequency operation of the antenna at the resonance frequencies of 3.2 GHz and 4.5 GHz. The simulated -10 dB bandwidth of the optimised antenna is 82.9 MHz and 293.2 MHz at the lower resonant frequency of 3.2 GHz and the upper resonant frequency of 4.5 GHz respectively. Both the frequencies can be used for C-band applications. 3.2 GHz band is useful in WiMAX. The return loss values are -16 dB and -19 dB at the corresponding resonance frequencies.

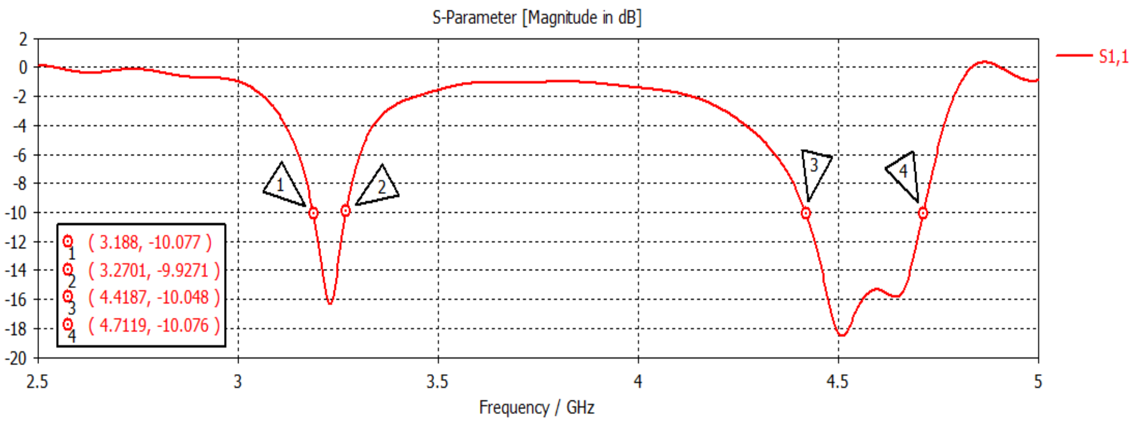


Figure 4.3 Return Loss S_{11} (dB) Versus Frequency Plot of Dual Band ACSMPA

4.2.2. Smith Chart and Antenna Impedance:

Smith chart is used to plot the graph of antenna impedance as a function of the frequency. The smith chart shows the characteristics impedance of 50 ohms for the antenna. The smith chart for the dual band ACSMPA is shown in figure 4.4 depicting the value of at the resonant frequencies.

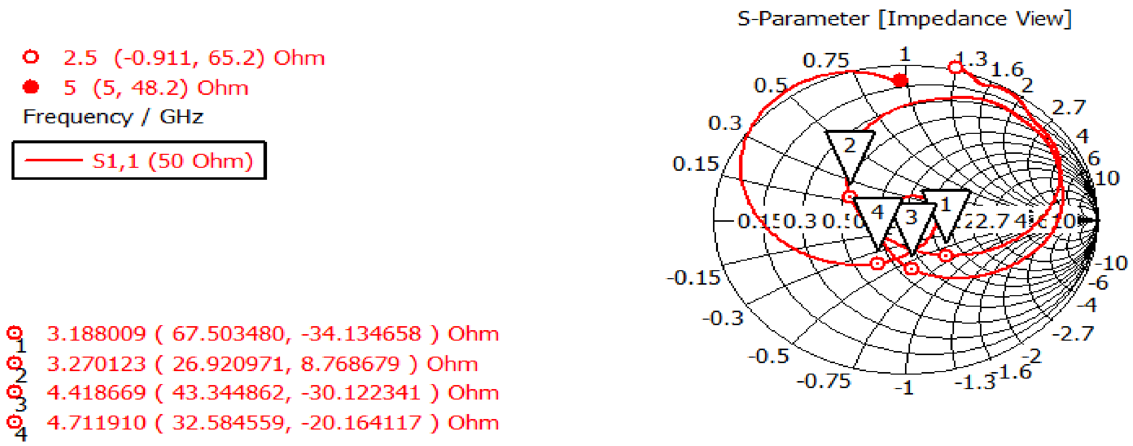
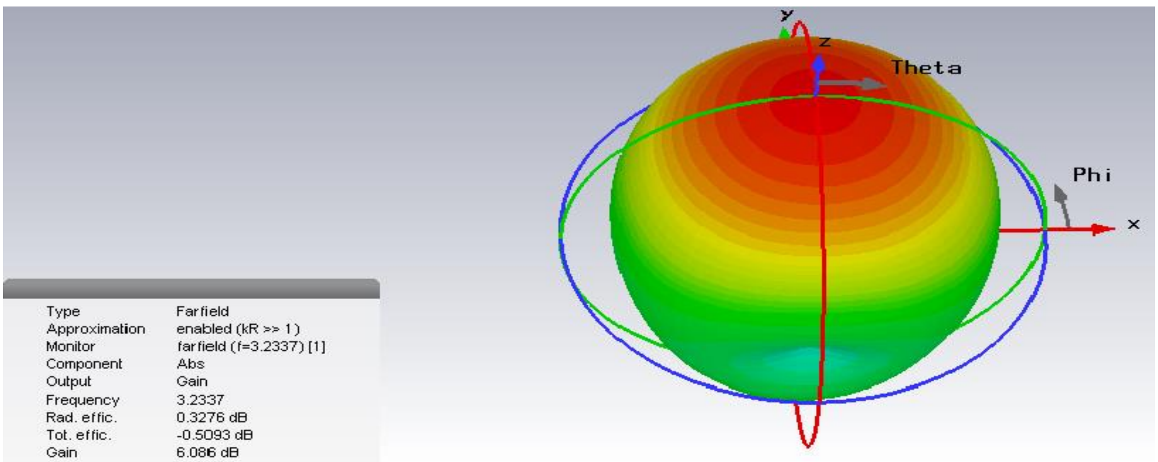


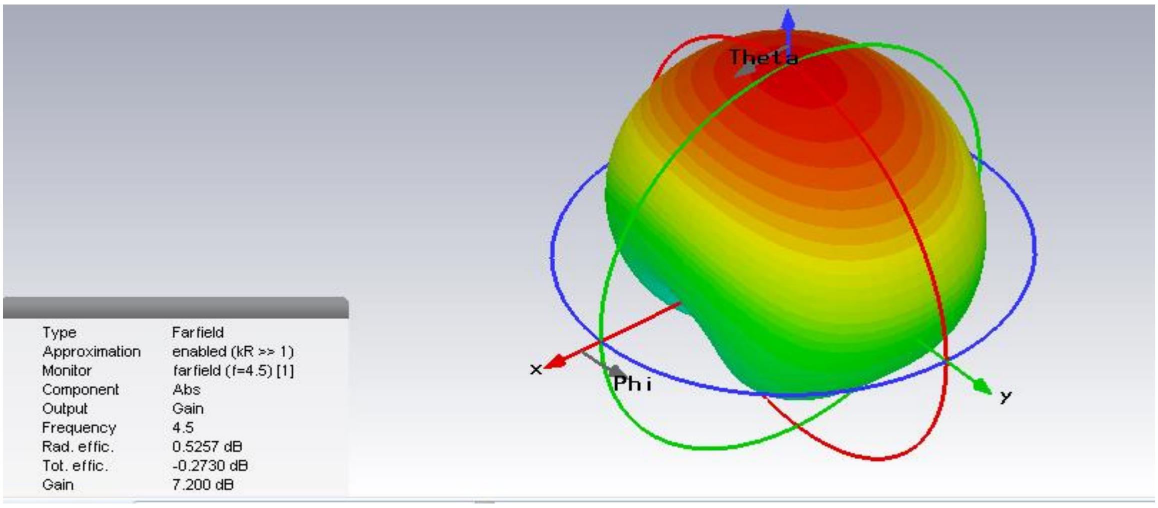
Figure 4.4 Smith Chart Showing the Characteristics Impedance of Dual Band ACMPA

4.2.3. Gain:

The gain of an antenna describes the power transmitted in the direction of peak radiation to that of an isotropic antenna. The polar plot of the gain at both the resonance frequencies of 3.2 GHz and 4.5 GHz is shown in Figure 4.5(a), (b). The dual band antenna has a gain of 6.086 dB at frequency 3.2 GHz and 7.2 dB at 4.5 GHz which means the power received far from the antenna would be 6.086 dB higher than that would be received from an isotropic antenna.



(a)

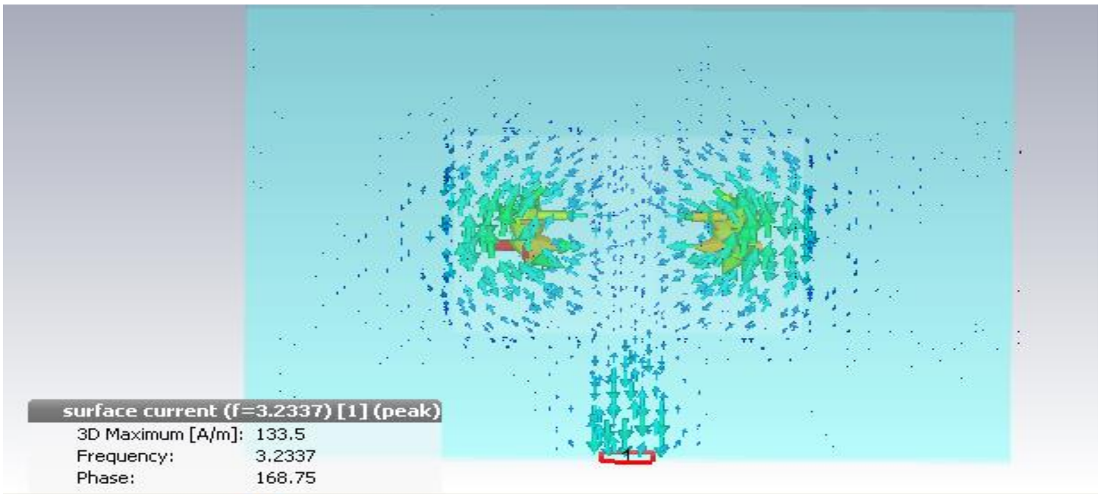


(b)

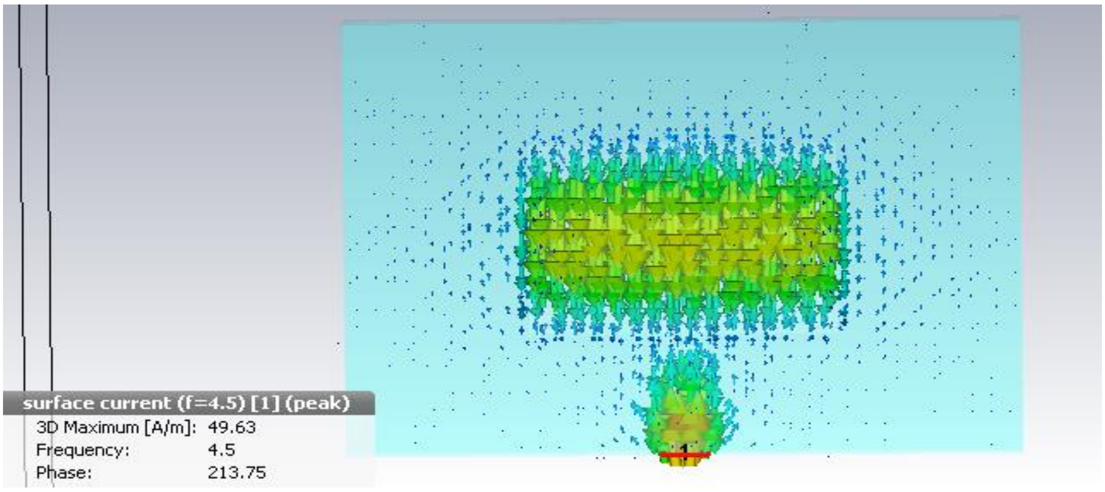
Figure 4.5 3D Radiation Pattern of Gain of the Dual Band ACSMPA (a) 3.2 GHz (b) 4.5 GHz

4.2.4. Surface Currents:

The surface current distribution of the top patch for the dual band microstrip patch antenna resonating at lower band frequency of 3.2 GHz is shown in Figure 4.6 (a). It depicts the current is flowing in almost the entire patch, but it has more magnitude near the rightmost and leftmost the patch. The surface current distribution at the top patch for the dual band microstrip patch antenna resonating at upper band frequency of 4.5 GHz is shown in Figure 4.6(b). It depicts the current is flowing in almost the entire patch, but it has more magnitude near the middle of the patch.



(a)



(b)

Figure 4.6 Surface Current Distribution of the Dual Band ACSMPA antenna (a) 3.2 GHz (b) 4.5 GHz

4.3. Conclusion:

In this chapter a stacked microstrip antenna was designed and simulated for C-band applications. Stacking is a technique which utilizes two electromagnetically coupled patches which helps in improving the bandwidth without the introduction of surface waves. To further enhance the performance of the antenna system aperture coupling feed was used. The proposed antenna resonates at two frequencies of 3.2 and 4.5 GHz with a bandwidth of 82.9 and 293.2 MHz. Gain of 6.086 and 7.200 dBi was observed at each resonances respectively.

Chapter 5

Multi-band Stacked Antenna Array with Aperture Coupling Feed

In wireless communication system signals are prone to fading due to multipath. The fading can be combat by using multiple antennas. When multiple antennas are employed at both or either ends, the signals travelling through multiple paths can be used in an advantageous way by employing various diversity schemes [16]. To employ antenna in MIMO applications an array is designed in this chapter. This chapter deals with the designing and optimisation of the multi-band aperture coupled stacked microstrip patch antenna (ACSMPA) array. The antenna resonates at three frequencies 4 GHz, 5.8 GHz, and 6.2 GHz. The structure finds application in C-band, WiMAX and Synchronous Transport Module level 1 (STM1) respectively.

5.1. Design and Simulation:

An array of two aperture coupled stacked microstrip antenna is designed in this section using CST MWSv'14. The antenna consists of three layers of substrate. The two feedlines are etched on the lower part of the lowest substrate. Each substrate is of FR4 material with dielectric constant of ε_r=4.4 and height h=1.57 mm. The structure is excited by energising the two feedlines simultaneously with two ports. Stacking and aperture coupling is used to improve the bandwidth and to reduce the back radiations respectively, hence improving the performance of the system. All the specified antenna parameters are given in table 5.1. The various parameters like patch dimensions, substrate and ground plane dimensions are calculated using equation 3.1 to 3.6 and are given in table 5.2

Table 5.1 Specified Antenna Parameters of Triple Band ACSMPA array

Resonant frequency	4.5 GHz, 5.8 GHz, 6.2GHz
Patch(top as well as lower) substrate material, feed substrate material	FR-4
Patch (top as well as bottom) substrate thickness, feed substrate thickness, h	1.57 mm
Dielectric constant of the material used	4.4
Thickness of PEC material, t	0.035 mm

Figure 5.1 shows the side view of the proposed antenna structure and figure 5.2 depicts the front view of each layer of the structure with labelled dimensions with the values mentioned in table 5.2.

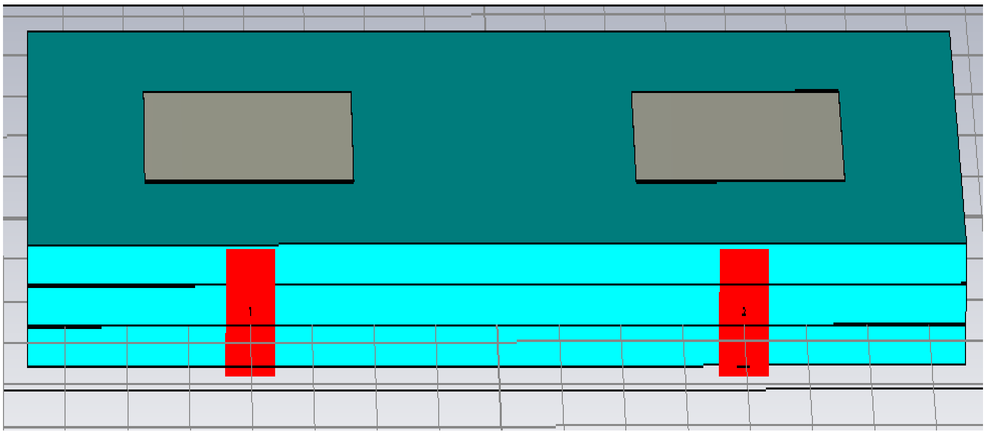


Figure 5.1 Side View of Triple Band ACSMPA Array

Table 5.2 Optimized Antenna Parameters of Triple Band ACSMPA Array

Parameter	Description	Value
L_{LP}	Lower patch length	11 mm
W_{LP}	Lower patch width	17 mm
L_{UP}	Upper patch length	11 mm
W_{UP}	Upper patch width	17 mm
L_g	Ground plane length	26 mm
W_g	Ground plane width	76 mm
L_f	Feedline length	20 mm
W_f	Feedline width	2 mm
L	Length of the aperture in ground-plane	2 mm
W	Width of the aperture in ground-plane	10 mm

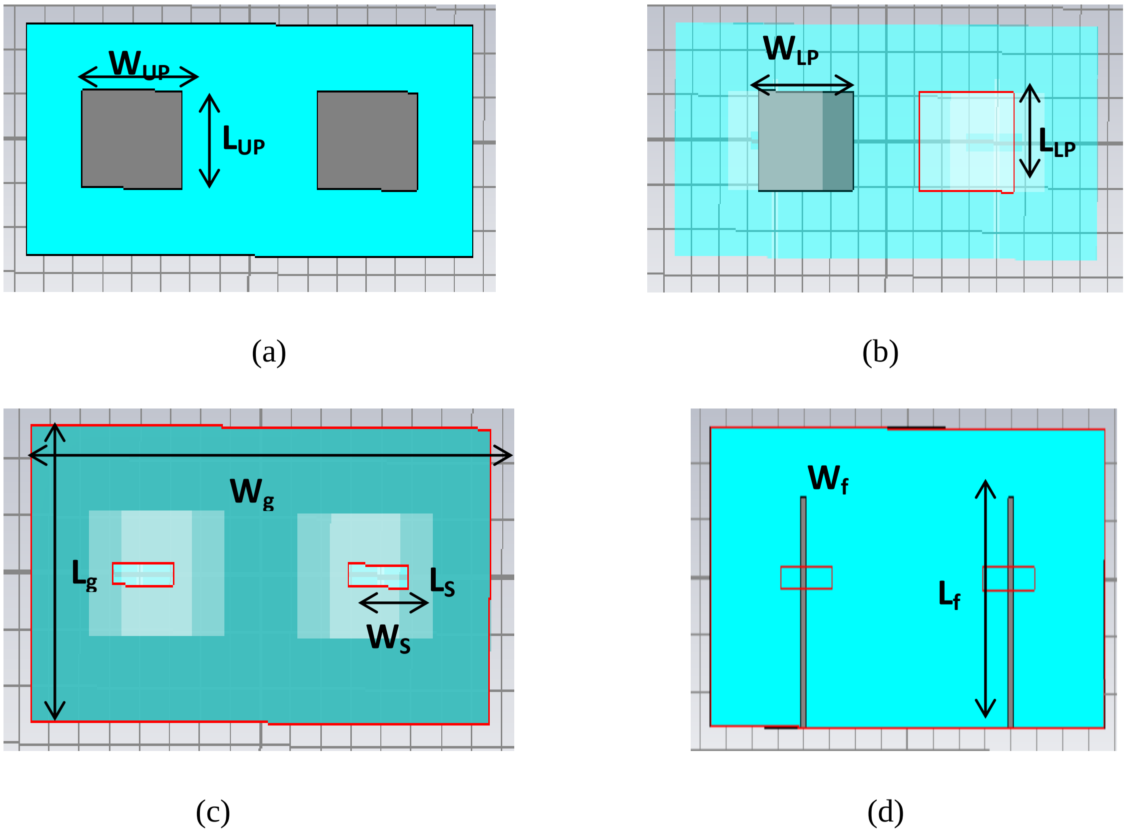


Figure 5.2 Triple Band ACSMP Array (a) Front View Showing Top Patches, (b) Bottom Patches, (c) Slots in the Ground Plane, (d) Back View Showing Feedline

5.2. Simulations:

All the simulations are carried out using CST MWSv'14.

5.2.1. Return Loss and Antenna Bandwidth:

Figure 5.3 shows the parameter plot of the antenna with S_{11}, S_{12}, S21, and S_{22}. From the figure 5.3 it can be observed that there are three dips indicating the triple band nature of the structure. Plot of S_{11} with respect to frequency shows three resonant frequencies at 4 GHz, 5.8 GHz, and 6.2 GHz. The bandwidth obtained is 130 MHz, 404.7 MHz, and 108 MHz at the respective resonances. The array of patches is excited by simultaneously energising the two feedlines. Hence some power gets transmitted from one port to another. S_{21} in the figure below represents the power transmitted from port 1 to port 2. For efficient transmission its value should be less than -10 dB. At all the three resonant bands the value of S_{21} is less than 0.5 as desired. S_{21} plotted with respect to frequency shows the same resonant bands and shows a low correlation by antenna two.

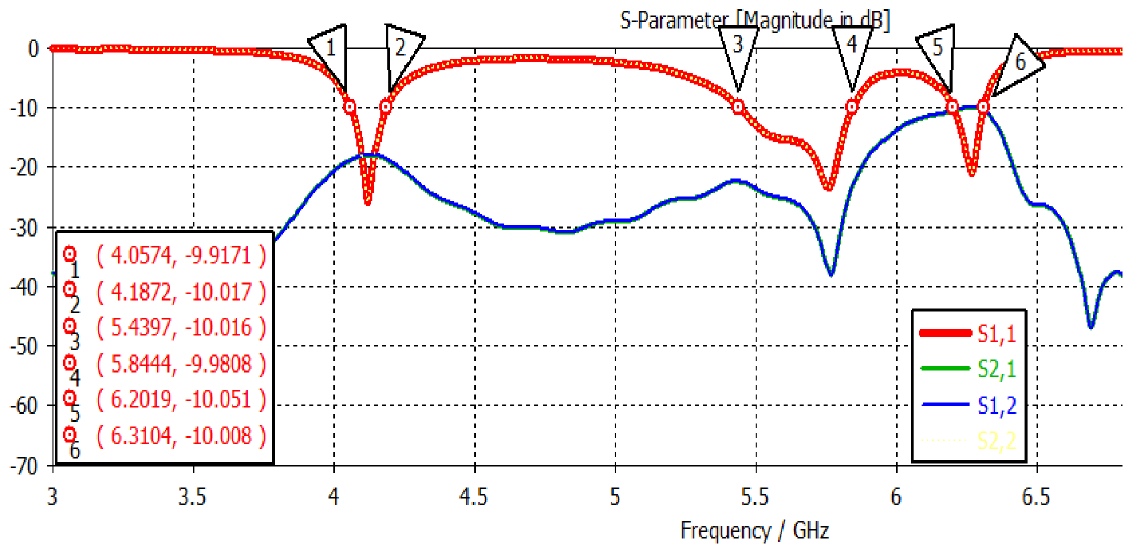


Figure 5.3 Return Loss S_{11} (dB) Versus Frequency Plot of Triple Band ACSMPA Array

5.2.2. Smith Chart and Antenna Impedance:

The smith chart for the triple band ACSMPA array is shown in Figure 5. 4. It represents the value of impedances at the marked resonant frequency.

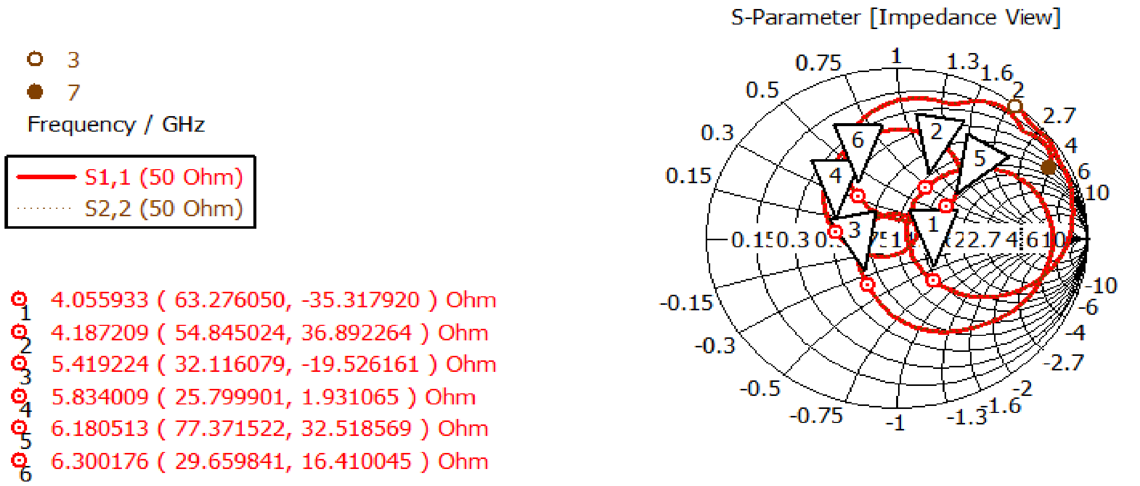
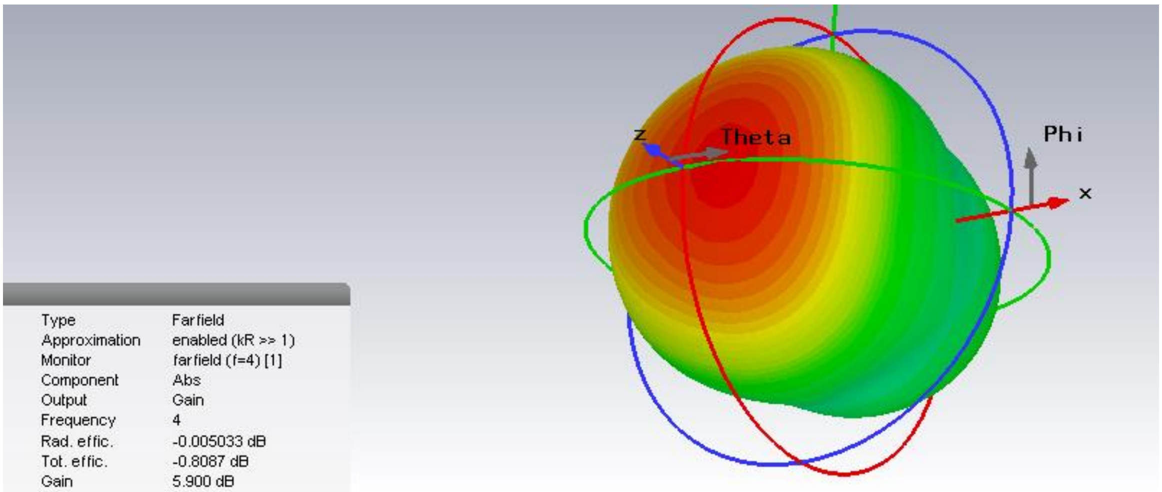


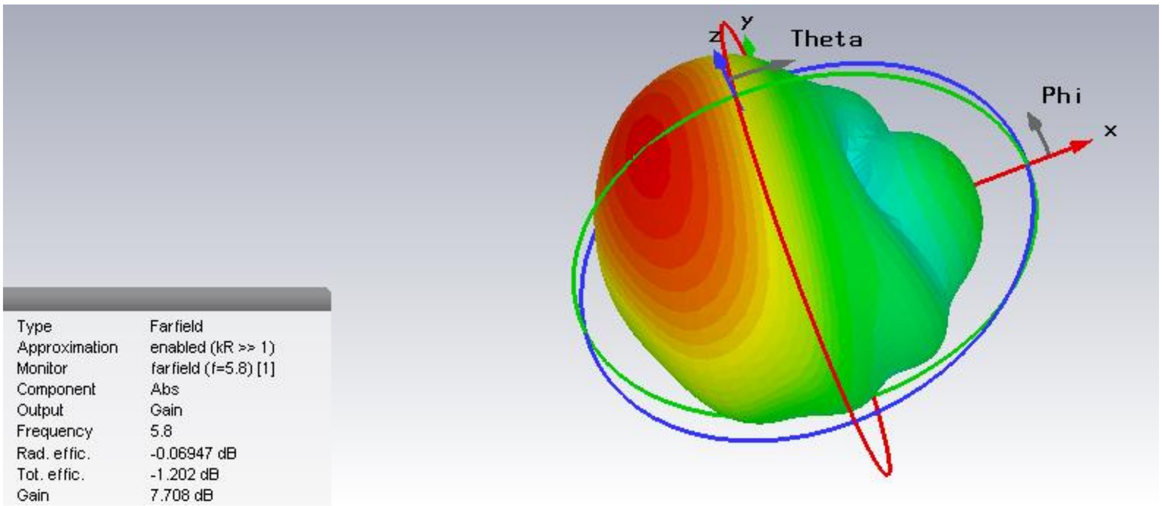
Figure 5.4 Smith Chart Showing the Characteristics Impedance of Triple Band ACMPA Array

5.2.3. Gain:

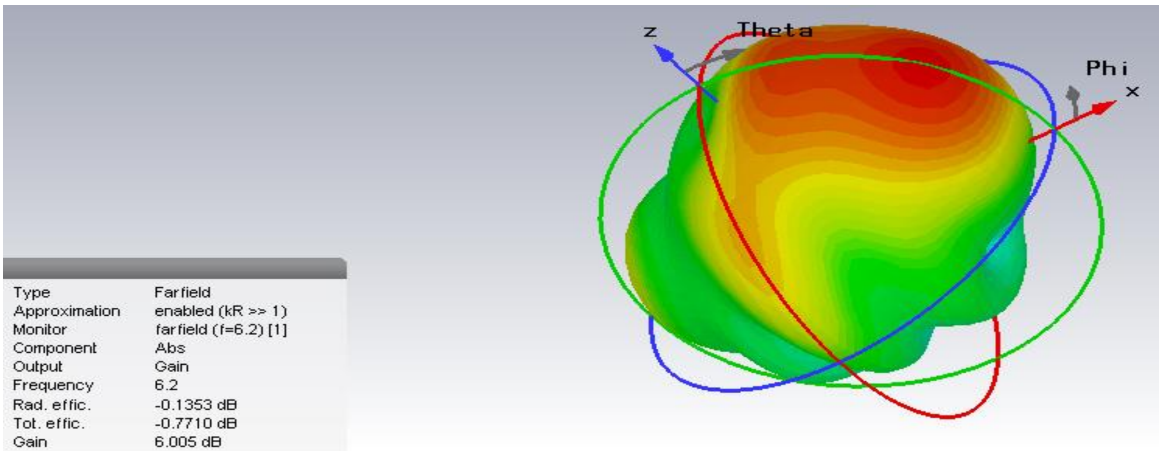
The gain of an antenna describes the power transmitted in the direction of peak radiation to that of an isotropic antenna. The polar plot of the gain at all the resonant frequencies of 4 GHz, 5.8 GHz, and 6.2 GHz is shown in Figure 5.5(a), (b), (c). The triple band antenna has a gain of 5.9 dB at frequency 4 GHz, 7.708 dB at 5.8 GHz, and 6.005 dB at 6.2 GHz.



(a)



(b)

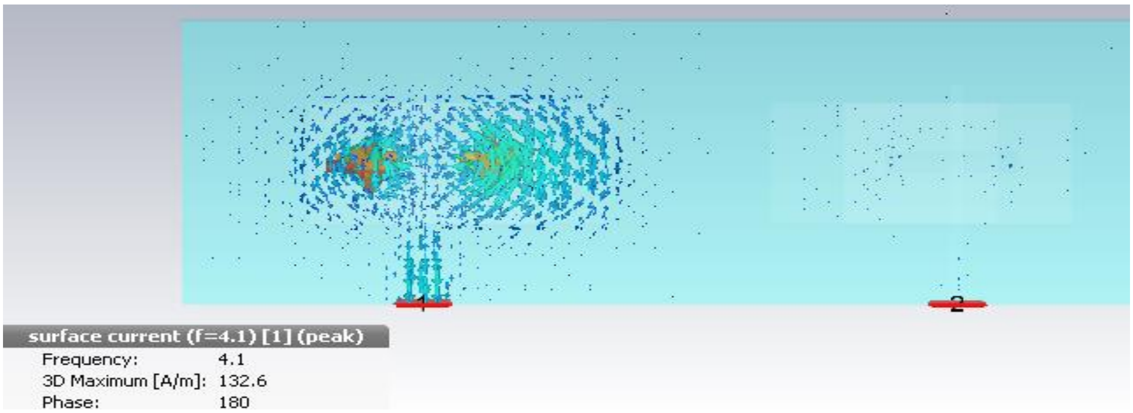


(c)

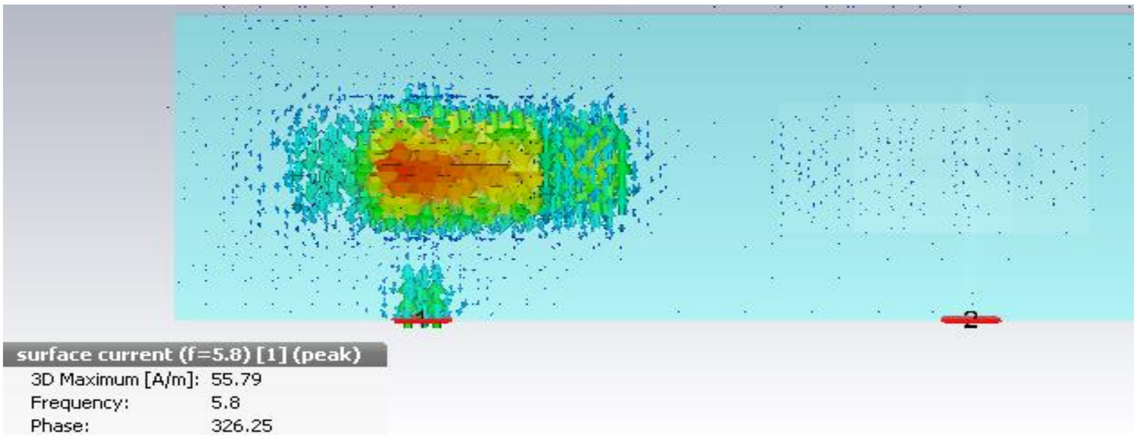
Figure 5.5 3D Radiation Pattern of Gain of the Triple Band ACSMPA Array (a) 4 GHz (b) 5.8 GHz (c) 6 GHz

5.2.4. Surface Currents:

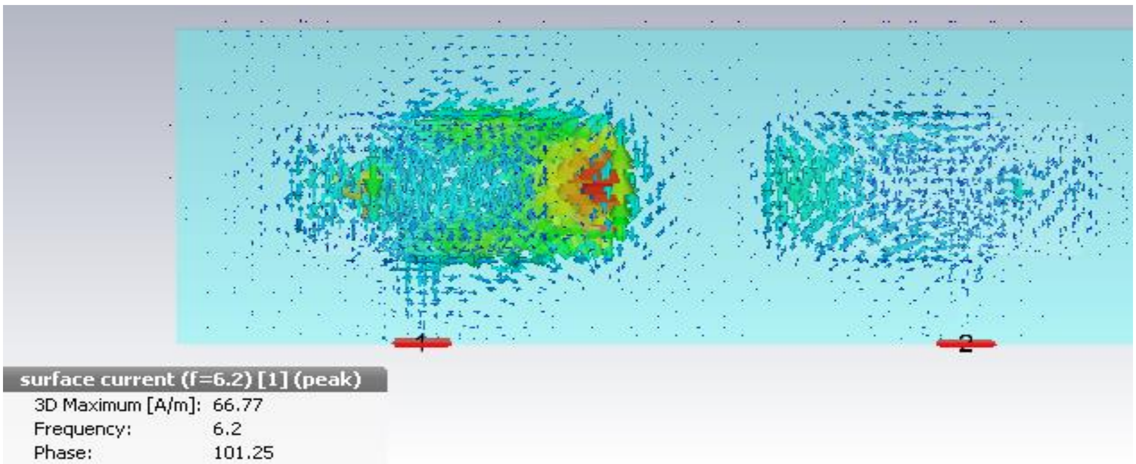
The surface current at the top patch is shown in figure 5.6 (a),(b), and (c). The figure shows the current distribution with port 1 energised. It can be observed that current is maximum at the center of the patch at 6.2 GHz.



(a)



(b)



(c)

Figure 5.6 Surface Current Distribution of the Triple Band ACSMPA Array antenna (a) 4 GHz (b) 5.8 GHz (c) 6.2 GHz

5.3. MIMO Parameters:

Since the array has to be implemented in a MIMO environment certain parameter calculations are required.

5.3.1. Envelope Correlation Coefficient (ECC):

It is a measure of the correlation between the radiation patterns of multiple antennas. It is one of the important parameters that needed to be taken care of in arrays. Its value falls in the range of 0 to 1. Ideal condition is achieved when this parameter approximates to zero. For the desirable result this value should be less than 0.4 in any MIMO system [17]. Antenna position has to be optimised to get optimum value of ECC. For two antenna elements equation of ECC can be written as [18]:

$$\rho = \frac{|S_{11}^{*}S_{12}+S_{21}^{*}S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)(1-|S_{22}|^2-|S_{12}|^2)} \qquad 5.1$$

Figure 5.8 shows the ECC of the simulated antenna system.

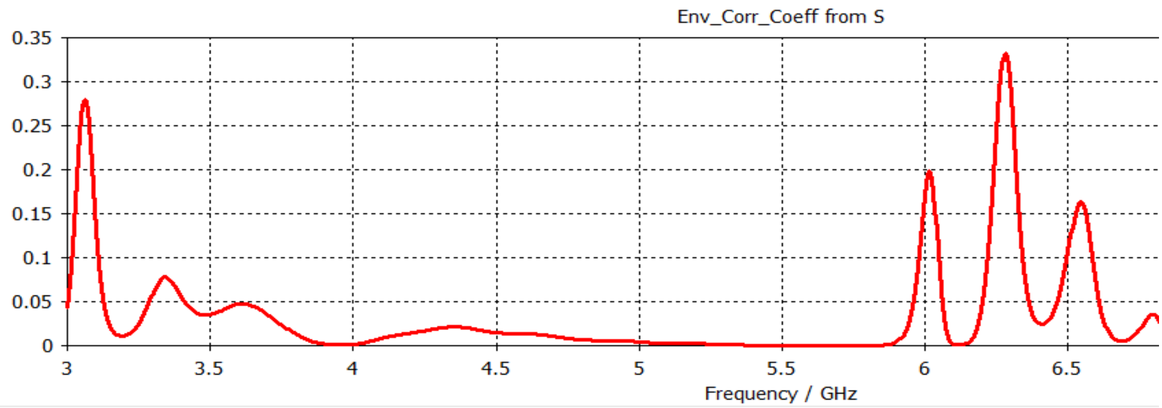


Figure 5.7 Envelope Correlation Coefficient of Triple Band ACSMPA Array

As can be seen from the figure 5.7 the antenna shows a correlation coefficient of less than 0.4 at all the three resonances, thereby allowing it to be suitable for MIMO applications.

5.3.2. Diversity Gain:

It can be defined as the increase in signal-to-interference ratio due to some diversity scheme. Figure 5.8 shows the graph of diversity gain vs frequency. A quite satisfactory performance is achieved when diversity gain is 10.

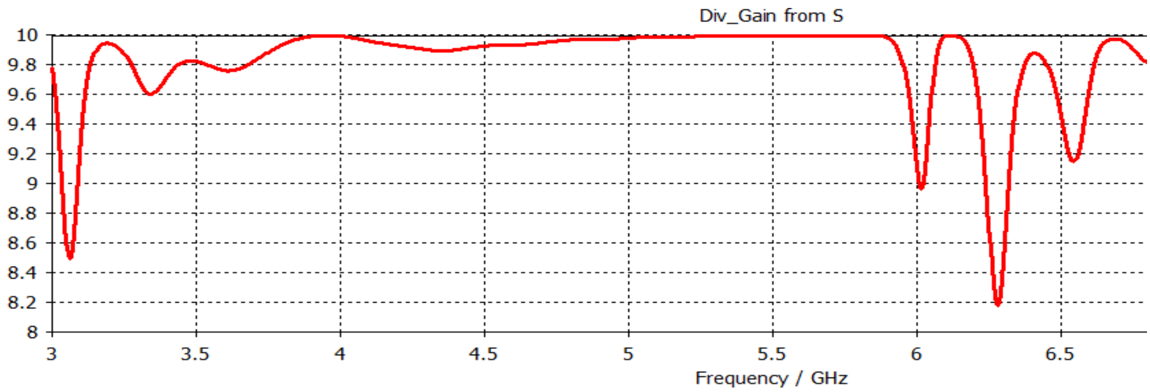


Figure 5.8 Diversity Gain of Triple Band ACSMPA Array

5.3.3. Capacity Analysis:

The antenna array designed in this chapter can be deployed at the receiver section. Consider a wireless communication scheme in which multiple antennas are present at the receiver and a single transmitting antenna at the source. The antenna simulated shows the resonance useful in WiMAX. The capacity analysis is carried out assuming Rayleigh fading environment. Figure 5.9 shows the plot of capacity vs bandwidth. And Equation used for plotting the graph is given below:

$$C = B.^{*}\, log_2\left(1 + \frac{P}{N_o{}^{*}B}\right) \qquad 5.2$$

Where, B: Bandwidth, P: Power transmitted, N_o: Noise in the channel. Figure 5.8 shows that firstly there is an exponential increase in capacity, after a limit the increase is linear. More bandwidth means more number of transmissions per second, hence increase in the capacity. Maximum achievable capacity by increasing bandwidth is 1.44 times the P/N_o value.

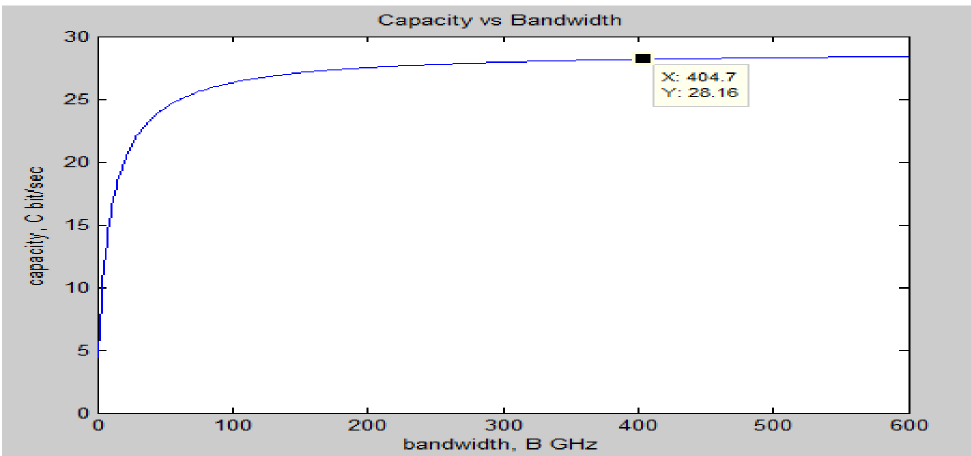


Figure 5.9 Capacity vs Bandwidth

5.5. Conclusion:

In this chapter to install antenna in a MIMO system an array of stacked microstrip patch was designed and simulated. The antenna resonates at three frequency bands of 4, 5.8, and 6.2 GHz with bandwidth of 130, 404.7, and 108 MHz respectively. Antenna showed the gain of 5.9, 7.708, and 6.005 dB at the respective resonances. Various MIMO parameters like ECC and diversity gain was also simulated using CST MWSv'14. In the last section analysis of capacity was also carried out using MATLAB.

Chapter 6

Dual-band Stacked Aperture Coupled Antenna Array with Reduced Groundplane and Defected Ground Structure

This chapter presents another antenna array for MIMO application in WLAN wireless communication. A dual band stacked antenna array is designed and simulated with aperture coupling feed for WLAN applications. The software used is CST MWSv'14.

6.1. Design and Simulation:

A dual band antenna array is designed on FR4 substrate with dielectric constant of 4.4 and height 1.57 mm. Dual-band is achieved using the stacking technique. The antenna is a multi-layered structure as shown in figure 6.1. The antenna has reduced ground-plane to reduce back radiations. To further improve the performance by decreasing the back radiations DGS is cut on the ground-plane. The antenna has array of two patches etched on the middle substrate known as fed patches and two patches are photo-etched on the uppermost substrate known as driven or parasitic patches. Fed patches have slits as shown in figure 6.2 to improve the bandwidth of the system [19]. To further improve the bandwidth resonant slots are cut on the driven patches. When slots with resonant frequency close to patch resonance are cut an increase in bandwidth is observed. All the parameters are calculated using equation 3.1 to 3.6. The specified and optimised parameters are given in table 6.1 and 6.2 respectively.

Table 6.1 Specified Antenna Parameters of Dual Band ACSMPA Array

Resonant frequency	3.6 GHz, 5.2 GHz
Patch(top as well as lower) substrate material, feed substrate material	FR-4
Patch (top as well as bottom) substrate thickness, feed substrate thickness, h	1.57 mm
Dielectric constant of the material used	4.4
Thickness of PEC mater-ial, t	0.035 mm

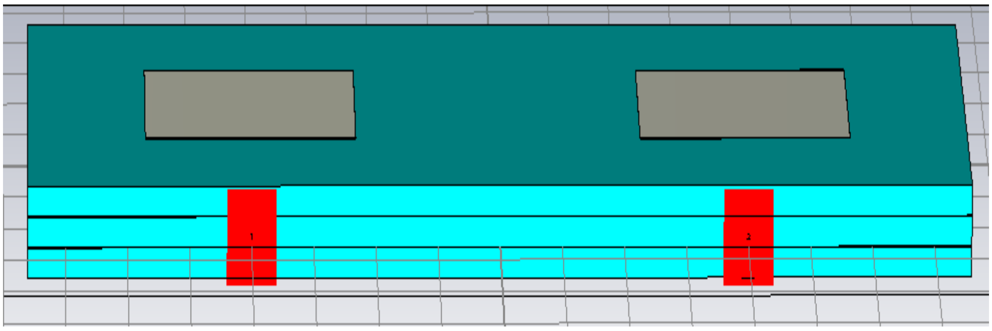
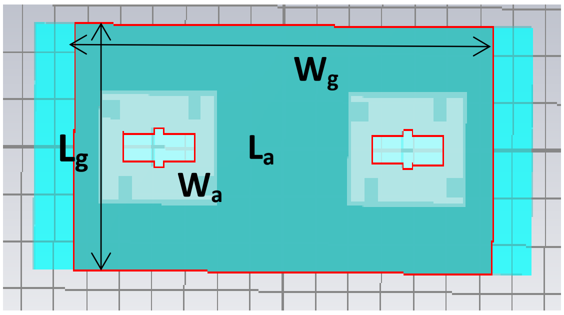
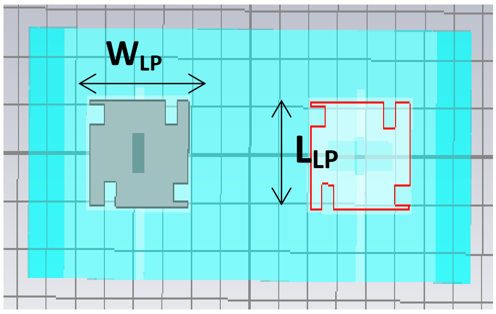


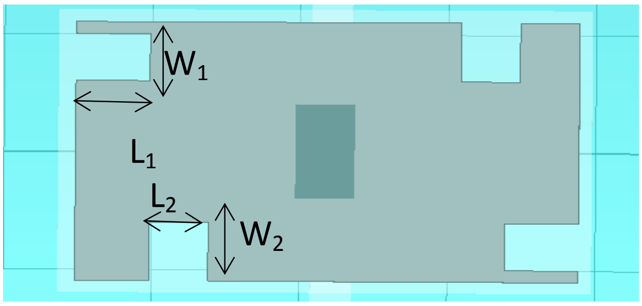
Figure 6.1 Side View of Dual Band ACSMPA Array



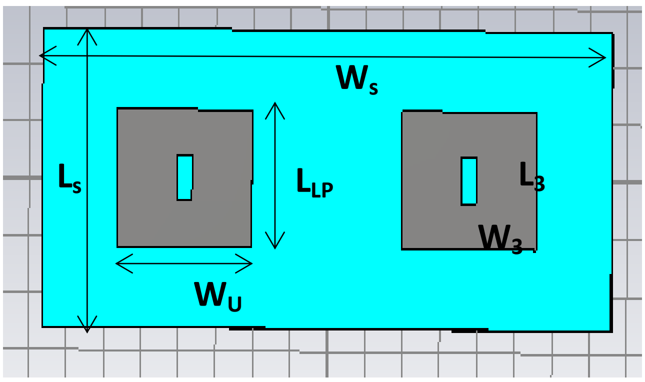
(a)



(b)



(c)



(d)

Figure 6.2 Dual Band ACSMP Array (a) Front View Showing Ground plane, (b) Bottom Patches, (c) Slits on Bottom Patch, (d) Slots on Top Patch

Figure 6.2 shows the labelled diagram of the designed antenna with the valu of all the parameters presented in table 6.2.

Table 6.2 Optimized Antenna Parameters of Triple Band ACSMPA Array

Parameter	Description	Value
L_{LP}	Lower patch length	11 mm
W_{LP}	Lower patch width	17 mm
L_{UP}	Upper patch length	11 mm
W_{UP}	Upper patch width	17 mm
L_g	Ground plane length	26 mm
W_g	Ground plane width	64 mm
L_f	Feedline length	20 mm
W_f	Feedline width	1.4 mm
L	Length of the aperture in ground-plane	3 mm
W	Width of the aperture in ground-plane	11 mm
W_s	Substrate width	76 mm
L_s	Substrate length	26 mm
L_1	Length of the slit in lower patch	2 mm
W_1	Width of the slit in lower patch	2.5 mm
L_2	Length of the slit in lower patch	2.5 mm
W_2	Width of the slit in lower patch	2 mm
L_3	Length of the slot in upper patch	4 mm
W_3	Width of the slot in upper patch	2 mm

6.2. Simulation Results:

The designed antenna is simulated using CST MWSv'14 and is presented in this section.

6.2.1. Return Loss and Antenna Bandwidth:

Figure 6.3 shows the return loss of antenna with respect to frequency. From the figure 6.3 it can be observed that there are two dips indicating the dual band nature of the structure. The array of patches is excited by simultaneously energising the two feedlines. The antenna shows two resonant frequencies at 3.6 GHz and 5.2 GHz with S_{11} -20dB and -30 dB. The bandwidth obtained is 228 MHz and 232 MHz at the respective resonances. This antenna finds application in WLAN. As the antenna is excited some power gets transmitted from one port to another. S_{21} in the figure below represents the power transmitted from port 1 to port 2. For efficient transmission its value should be less than -15 dB.

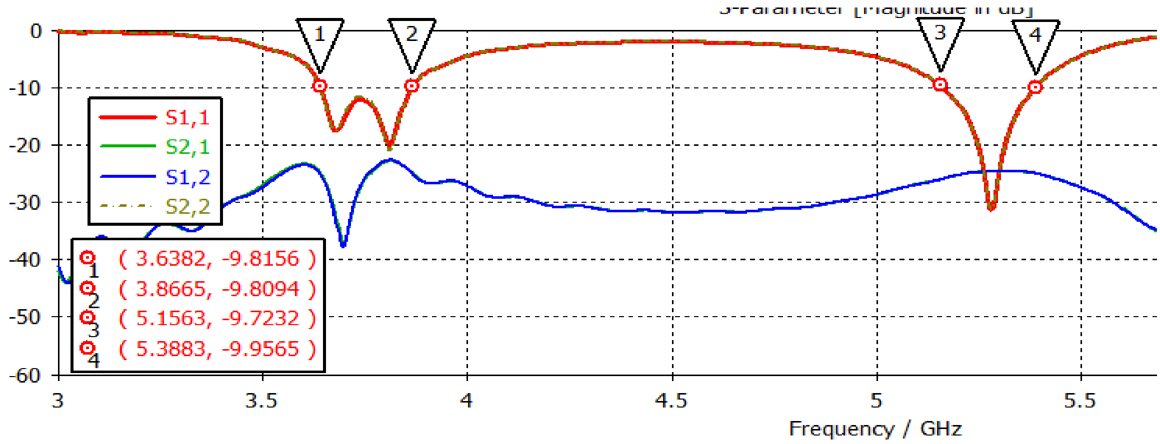


Figure 6.3 Return Loss S_{11} (dB) Versus Frequency Plot of Dual Band ACSMPA Array

6.2.2. Smith Chart and Antenna Impedance:

The smith chart of S_{11} for the optimised dual band ACSMPA array is shown in Figure 6.4. It represents the value of impedances at the marked resonant frequency.

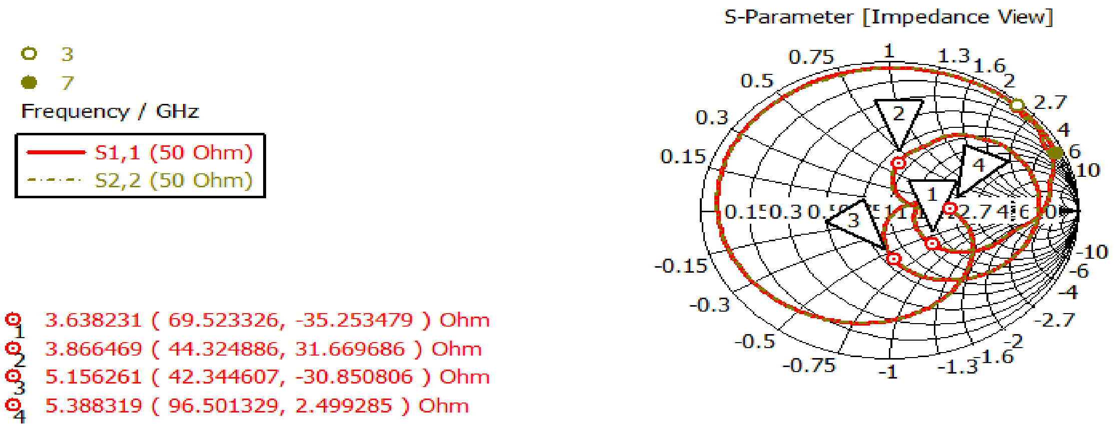
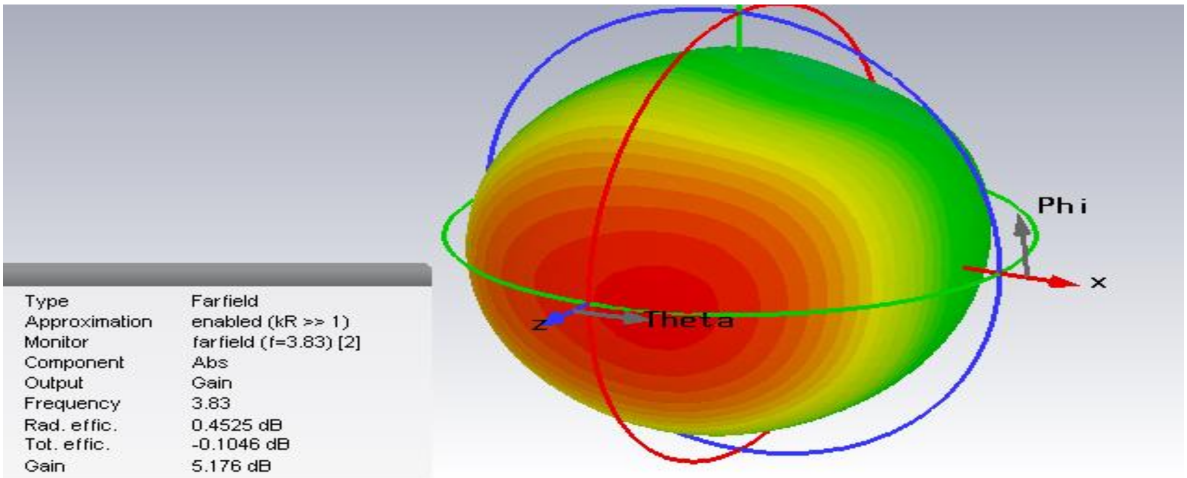


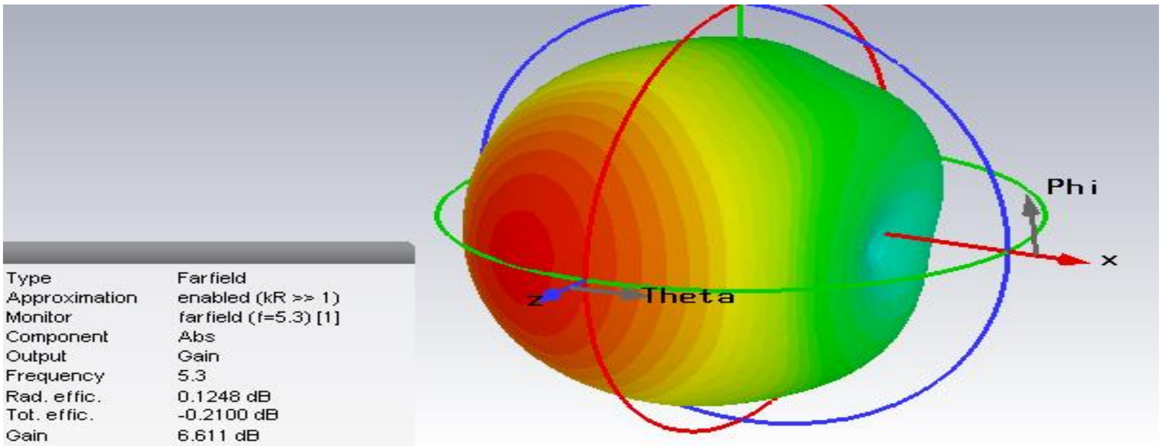
Figure 6.4 Smith Chart Showing the Characteristics Impedance of Dual Band ACMPA Array

6.2.3. Gain:

3D plot of the gain at two resonant frequencies of 3.6 GHz and 5.2 GHz is shown in Figure 6.5(a) and (b). The antenna array has a gain of 5.176 dB at frequency 3.6 GHz, 6.611 dB at 5.2 GHz. A good gain allows the antenna to be successfully used for long distance applications.



(a)

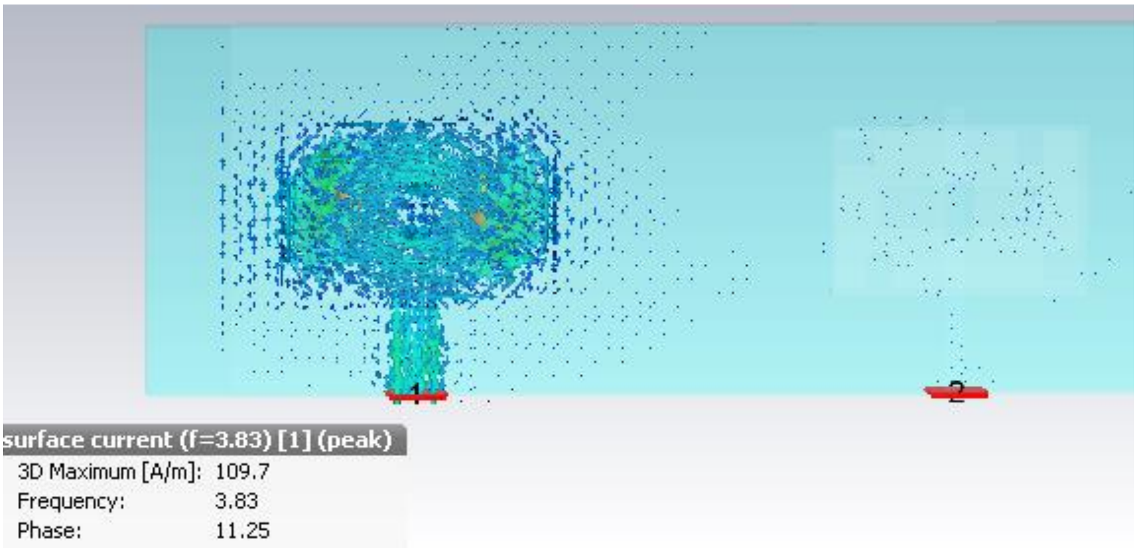


(b)

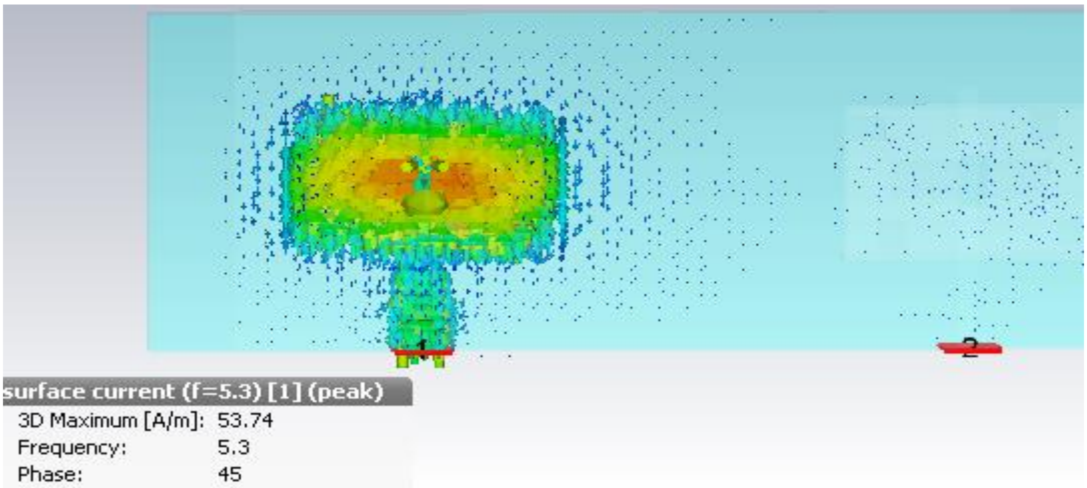
Figure 6.5 3D Radiation Pattern of Gain of the Dual Band ACSMPA Array (a) 3.6 GHz (b) 5.2 GHz

6.2.4. Surface Currents:

The surface current at the top patch is shown in figure 6.6 (a) and (b). The figure shows the current distribution with port 1 energised. It can be observed that current is maximum at the centre of the patch at 6.2 GHz.



(a)



(b)

Figure 6.6 Surface Current Distribution of the Dual Band ACSMPA Array (a) 3.6 GHz (b) 5.2 GHz

6.3. MIMO Parameters:

6.3.1. Envelope Correlation Coefficient (ECC):

It is a measure of the correlation between the radiation patterns of multiple antennas. Approximately it ranges from 0 to 1. Ideal condition is achieved when this parameter approximates to zero. That is the outputs of multiple antenna array should not interfere each other. For the desirable result this value should be less than 0.4 in any MIMO system. Distance between the patches optimised to get optimum value of ECC. Figure

6.7 shows the ECC of the simulated antenna system. For the operation bands of 3.6 GHz and 5.2 GHz the ECC is found to be 0.002.

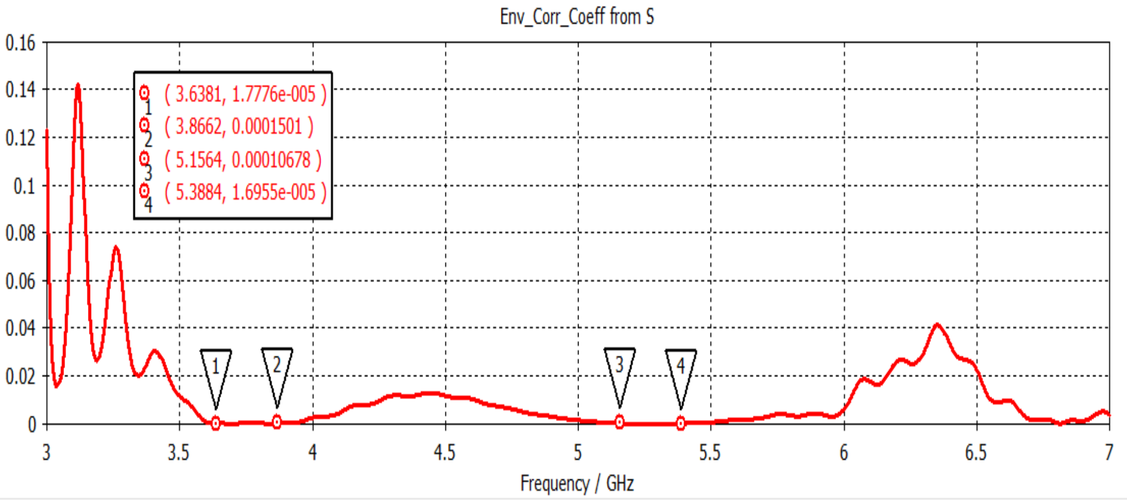


Figure 6.7 Envelope Correlation Coefficient of Dual Band ACSMPA Array

6.3.2. Diversity Gain:

It can be defined as the increase in signal-to-interference ratio due to some diversity scheme. Figure 6.8 shows the graph of diversity gain vs frequency. It can be seen that for operation frequency band of 3.6 and 5.2 GHz the diversity gain achieved is 10.

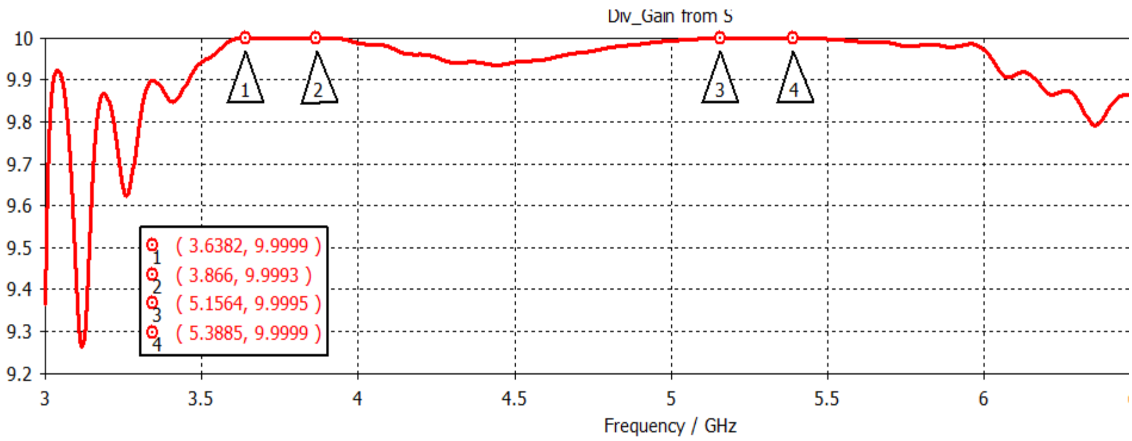


Figure 6.8 Diversity Gain of ACSMPA Array

6.3.3. Capacity Analysis:

The antenna array designed in this chapter finds application in WLAN. The antenna is designed to be deployed at the receiving side. The capacity analysis is carried out assuming Rayleigh fading environment. The graph is plotted using MATLAB v'11. Figure 6.9 (a) shows the plot of capacity vs bandwidth. And 5.9 (b) shows the zoomed view of the graph with the marked desirable frequencies. Equation 5.2 is used for plotting the graph. Figure 5.8 shows that firstly there is an exponential increase in capacity, after a limit the increase is linear. More bandwidth means more number of transmissions per second, hence increase in the capacity. Figure 5.9 (b) infers the increase in capacity with the frequency. It shows the capacity 0f 10.65 bits/sec.

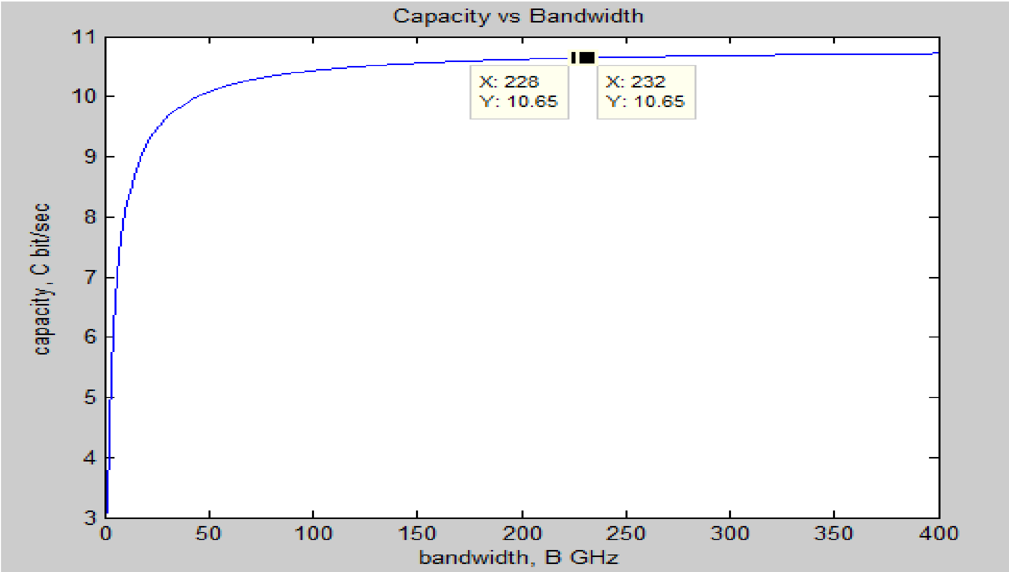


Figure 6.9 (a) Capacity vs Bandwidth

6.4. Conclusion:

In this chapter a stacked antenna array with reduced ground is optimised. To further enhance the bandwidth slots are cut on the patches. The antenna shows a dual frequency. The antenna offers a return loss of -20dB, and -30dB at resonances of 3.6GHz, and 5.2GHz respectively. The bandwidth offered by the structure is 228.3MHz, and 232MHz. System can be fabricated for WLAN applications. In the last section graph of capacity with the increasing bandwidth is also shown that depicts the linear rise in capacity with increase in frequency bandwidth as the number of channels for data transfer also increases.

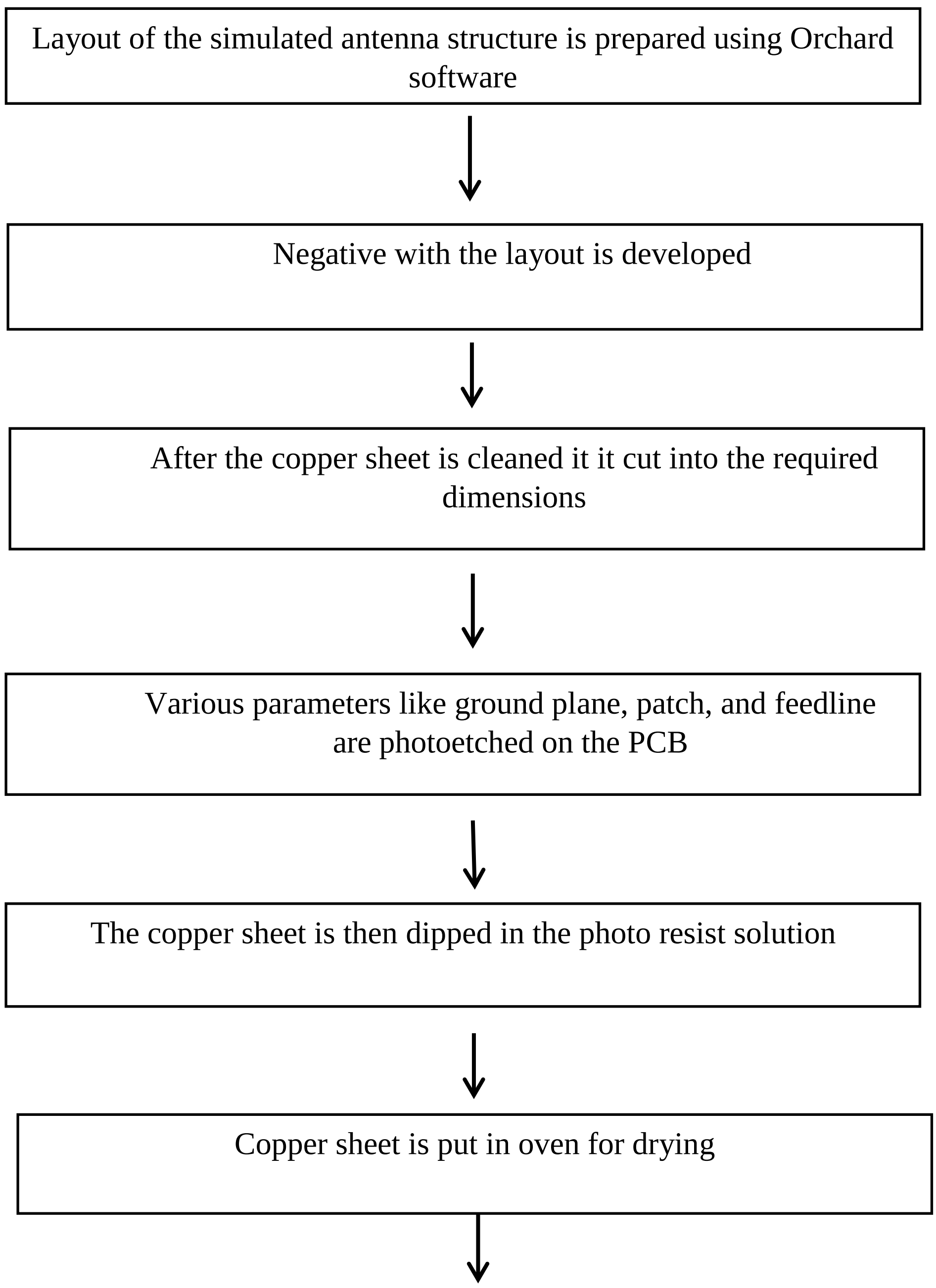
Chapter 7

Fabrication and Testing of Microstrip Antenna Arrays

In order to check the applicability of antennas, the fabrication and testing of antenna is carried out. This Chapter deals with the fabrication of the antenna arrays simulated in chapters 5 and 6. Firstly the fabrication process is explained and then the simulated and tested results are compared.

7.1. Fabrication Procedure:

The whole fabrication process is composed in the flow chart shown below.



Once the sheet is dried, it is put in UV exposure unit

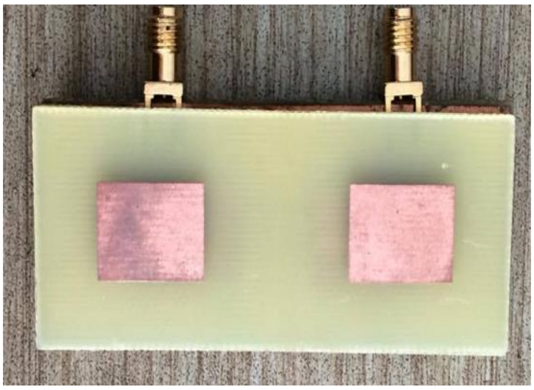
↓

Next the PCB is washed and is put in the etching solution containing ferric chloride solution. Then it is taken out and washed

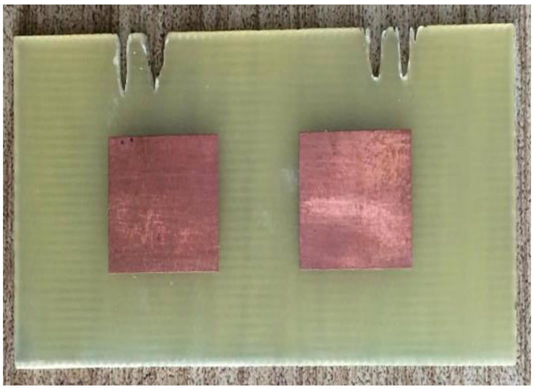
Figure 7.1 Flow Chart of Fabrication Procedure

7.2. Fabrication of Triple Band ACMPA Array Design:

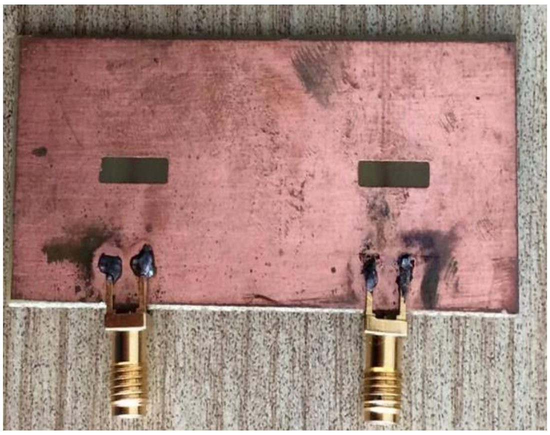
The layout is prepared using ORCAD software and the PCB of antenna is prepared using the procedure mentioned in flowchart. Figure 7.2 shows the snapshot of the fabricated antenna.



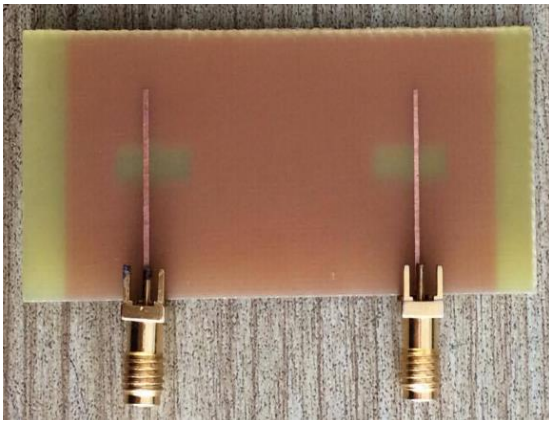
(a)



(b)



(c)



(d)

Figure 7.2 (a) Upper Patches (b) Lower Patches (c) Groundplane with Aperture (d) Feedline

7.2.1. Testing of Triple Band ACMPA Array:

The testing of the fabricated antenna has been done by using VNA model no E5071C of Agilent Technologies, whose frequency range is from 20 kHz to 8 GHz and it is shown in Figure 7.3 below:

Figure7.3 Network Analyser for Testing

7.2.2. Comparison of Simulated and Fabricated Antenna Array:

Figure 7.4 shows the simulated return loss of triple band ACMPA array. It shows three resonant frequencies covering the frequency bands from 4 to 4.18 GHz, 5.4 to 5.8 GHz, and 6.1 to 6.3 GHz with bandwidth 130 MHz, 404.7 MHz, and 108 MHz respective. Antenna shows S_{11} of -25dB, -22dB, and -19dB at respective resonances.

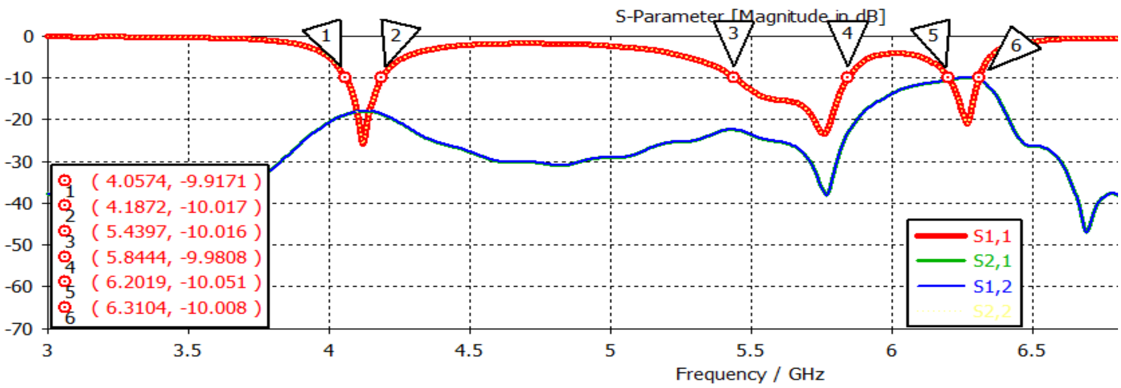


Figure7.4 Simulated Return loss S_{11} (dB) versus frequency plot of Triple Band ACSMPA Array

Figure 7.5 shows the return loss (S11) in versus frequency plot of the fabricated triple band ACMPA antenna array on VNA.

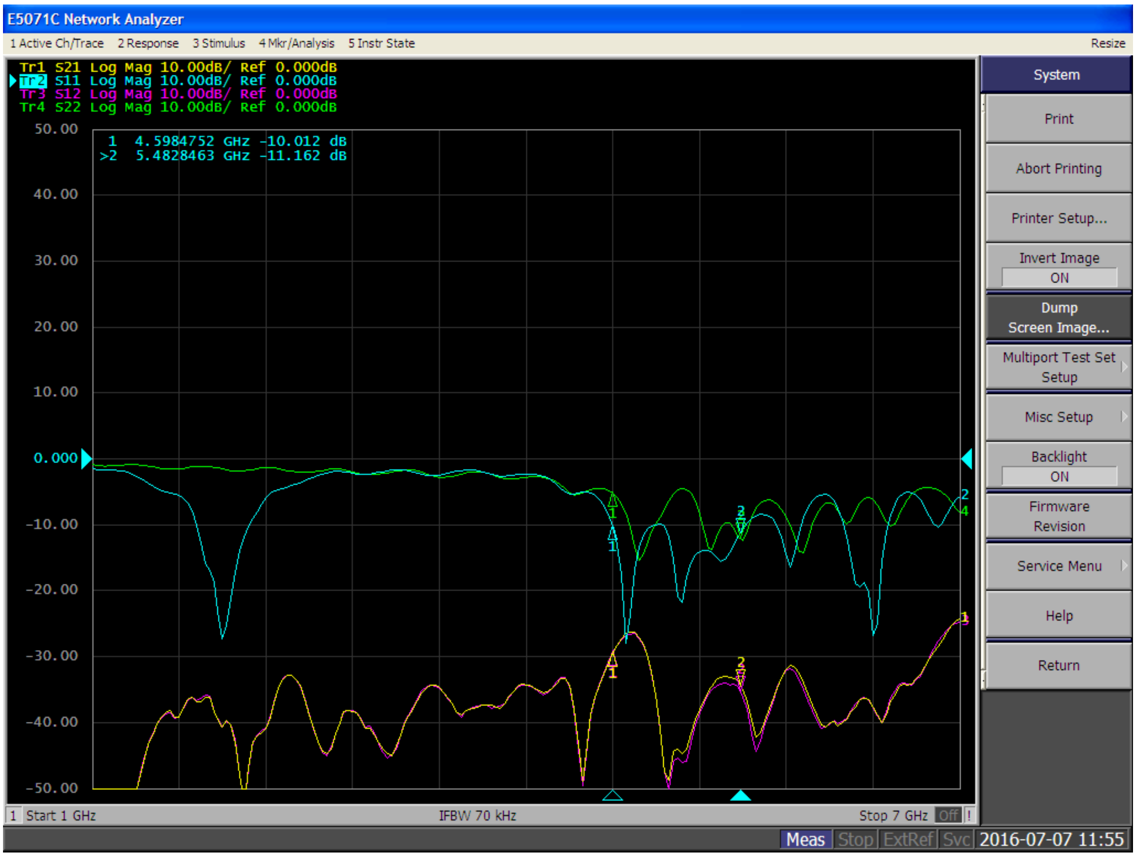


Figure 7.5 Tested Results

Table 7.1 shows the comparison of results and it is observed that simulated and measured results match quite closely.

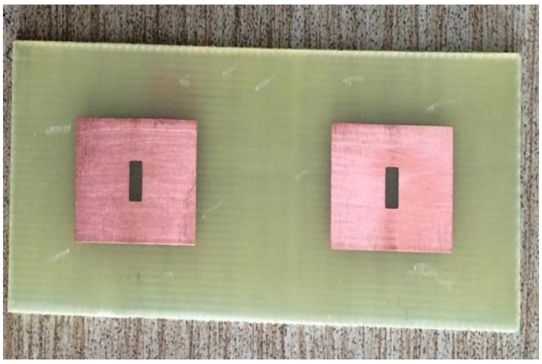
Table 7.1 Comparison of Simulated and Tested Results of Triple Band ACSMPA Array

Parameters	**Simulated Results**	**Tested Results**
Resonating Frequency	4GHz, 5.8GHz, 6.2GHz	5GHz, 5.7GHz, 6.3GHz
Bandwidth	130MHz,404.7MHz,108MHz	860MHz,300MHz,300MHz
Return Loss at Resonant Frequency	-25dB, -22dB, -19dB	-28dB, -21dB, -26dB
Transmission Loss	-19dB, -40dB, -10dB	-28dB, -35dB, -40dB
Application Covered	C-band, WiMAX, STM1	C-band, WiMAX, STM1

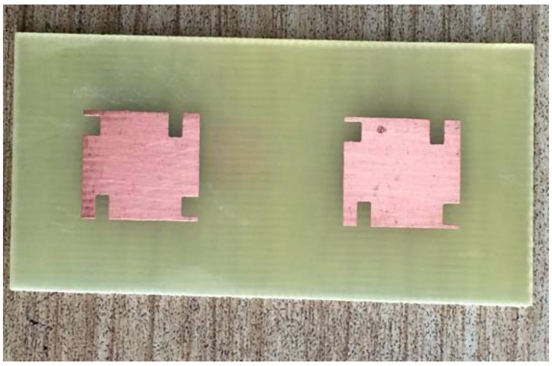
A little variation of the results is observed. The variations could be due to a material having variations along a length, width, and height, which causes resonance to shift; which during simulation it is assumed to be constant. There are others factors like chemical used, surface finish, and metal thickness which can cause a shift. In a stacked structure the antenna layers are stacked practically with the help of adhesive glue, the effective dielectric constant gets affected, which in simulations were not visible, but in a fabricated physical design it is much more visible.

7.3. Fabrication of Dual Band ACSMPA Array with Reduced Ground Plane:

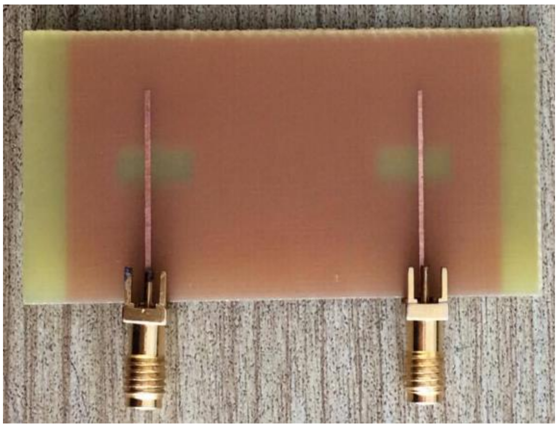
The dual band aperture coupled antenna array with stacking technique is fabricated using the procedure as explained above. As the structure involves three layers, each layer is fabricated individually using the same procedure.



(a)



(b)



(c)

(d)

Figure 7.6 (a) Upper Patch (b) Lower Patch (c) Feedline (d) Groundplane with Aperture

7.3.1. Comparison of Simulated and Fabricated Antenna Array:

Figure shows the simulated return loss of triple band ACMPA array. It shows three resonant frequencies covering the frequency bands from 4 to 4.18 GHz, 5.4 to 5.8 GHz, and 6.1 to 6.3 GHz with bandwidth 130 MHz, 404.7 MHz, and 108 MHz respective. Antenna shows S_{11} of -25dB, -22dB, and -19dB at respective resonances.

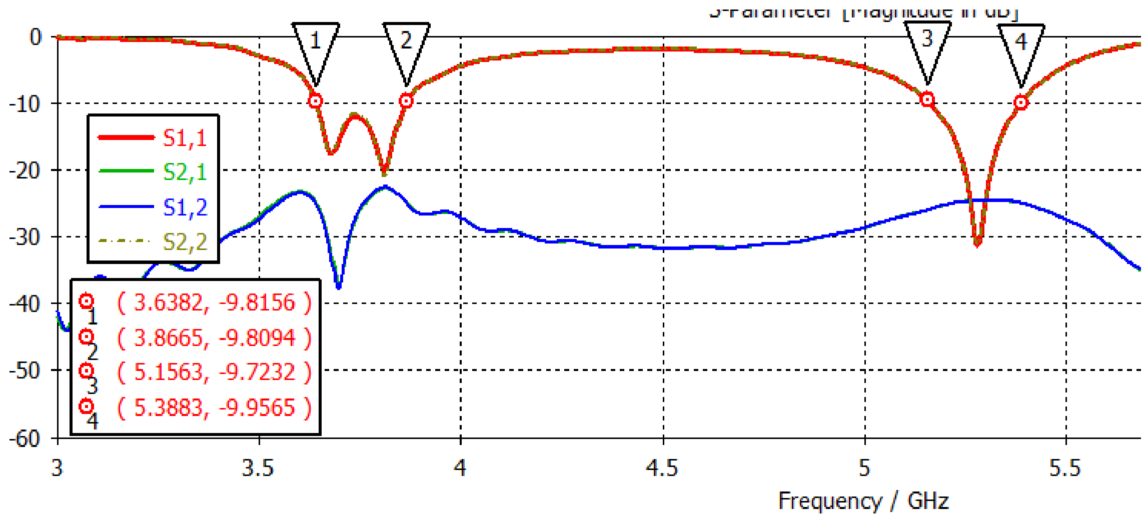
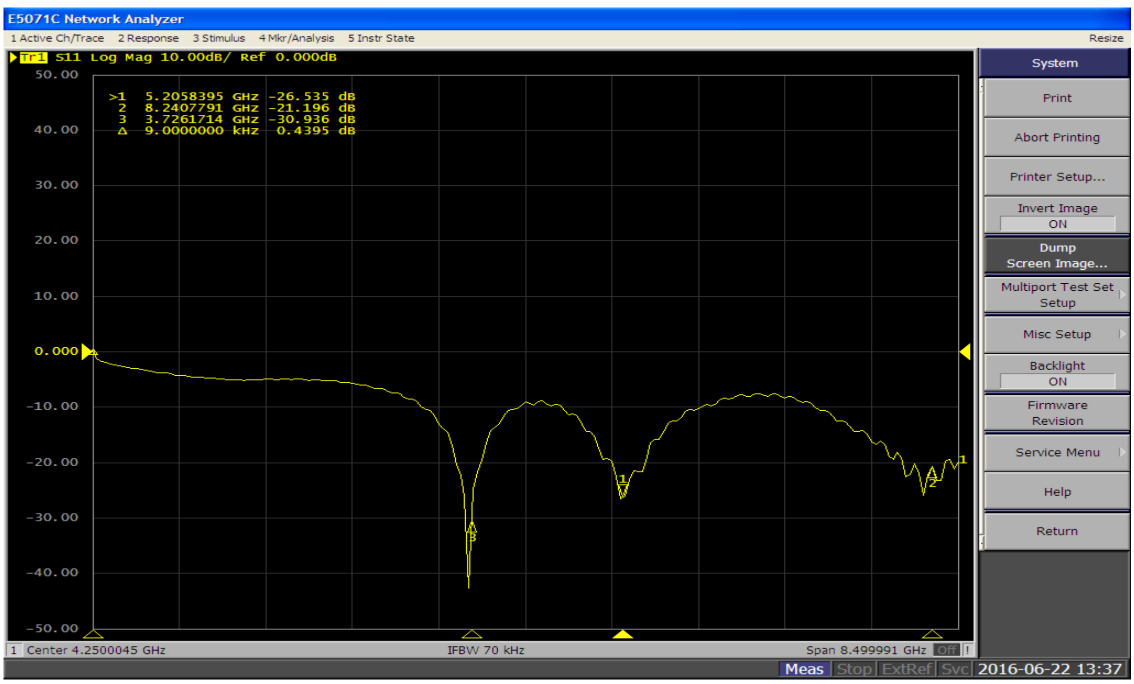
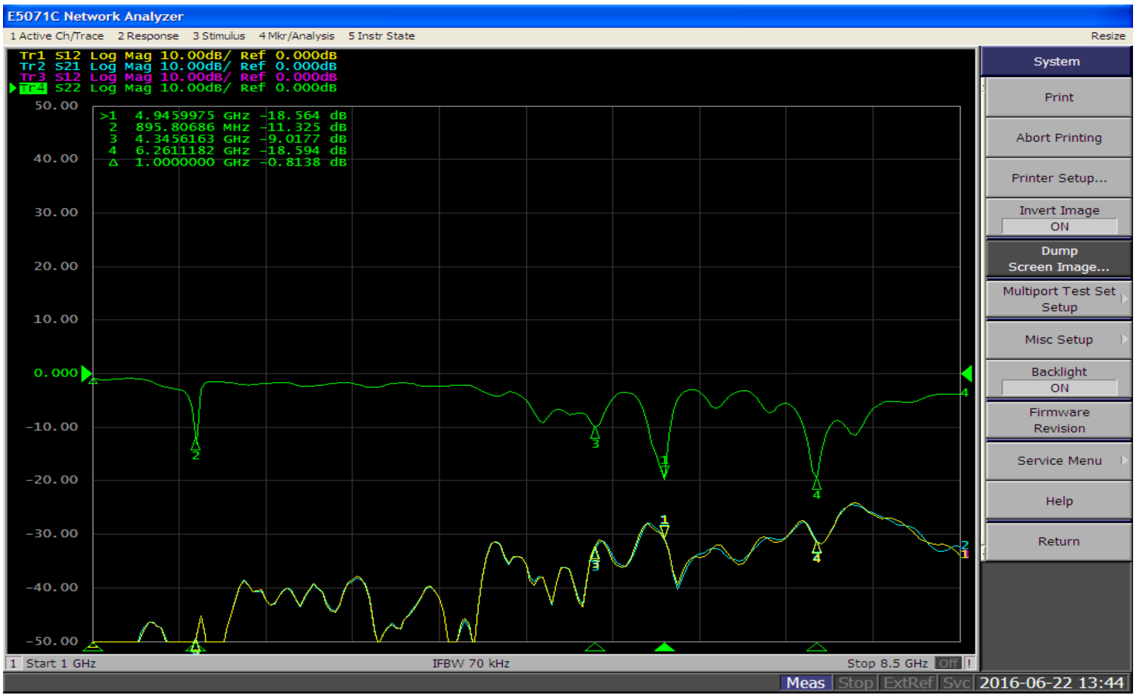


Figure 7.7 Simulated Return loss S_{11} (dB) versus frequency plot of Dual Band ACSMPA Array

Figure 7.8 shows the return loss (S11) in versus frequency plot of the fabricated dual band ACMPA antenna array on VNA.



(a)



(b)

Figure 7.8 (a), (b) Tested Results

Table 7.2 Comparison of Simulated and Tested Results of Dual Band ACSMPA Array

Parameters	**Simulated Results**	**Tested Results**
Resonating Frequency	3.6GHz, and 5.2GHz	3.7GHz, 5.2GHz
Bandwidth	228.3MHz, and 232MHz	940MHz, 1360MHz
Return Loss	-20dB, and -30dB	-40dB, -26dB
Transmission Loss	-23dB, and -25dB	-30dB, and -30dB
Application Covered	WLAN	WLAN

7.4. Conclusion:

In this chapter the stacked microstrip antenna arrays designed and simulated in chapter 5 and 6 are fabricated. The fabricated antenna is then tested with a VNA. A little variation in the tested results was observed. The shift in the result is due to the practical scenario.

Chapter 8

Conclusion and Future Work

8.1. Conclusions:

- The work starts with the study of MIMO wireless communication system, and the installation of microstrip patch antenna in multiple input and multiple output system. The main objective of the thesis was to design and fabricate an array for MIMO applications.
- In this report firstly a stacked microstrip antenna was theoretically analysed using equivalent circuit. Then a stacked microstrip antenna was designed which resonates at 6GHz with 656MHz bandwidth. Various parameters like feedline dimension, patches dimension were optimised for maximum coupling hence optimum results. The antenna characteristics like resonating frequency, bandwidth, directivity, gain, and return loss are simulated using CST MWSv'14 for the proposed design.
- In the next chapter dual band stacked antenna was designed and simulated. The two electromagnetically coupled layered patches are optimised such that the structure resonates at two frequencies hence making it a dual band. The antenna resonates at 3.2GHz and 4.5GHz with return loss of -16dB and -18dB respectively. The bandwidth obtained is 82.9MHz and 293.8MHz at respective resonances. The antenna finds application in C-band and WiMAX wireless communication.
- To overcome the ever increasing demands of the wireless communication, multiple antennas are required at the ends of the RF wireless link. In this context array is designed and simulated with stacked patches. The array structure was energised using aperture coupling feed. Aperture feed reduces the back radiations which further improves the performance. The array resonates at 4GHz, 5.8GHz, and 6.2GHz with 130MHz, 404.7MHz, and 108MHz respectively. The return loss offered by the system was found to be -25dB, -22dB, and -19dB at respective resonances. The simulated antenna array structure can be installed in C-band, WiMAX, and STM1 systems.

- In chapter 6, an aperture coupled stacked patch antenna array was designed. The structure consists of a reduced ground plane to reduce the back radiations. Slits were cut in the lower patches to improve the bandwidth. To further enhance the performance of the structure, slot is cut in the upper patches as well. Various parameters like return loss, directivity, gain, envelope correlation coefficient, and diversity gain are also discussed in this chapter. The antenna offers a return loss of -20dB, and -30dB at resonances of 3.6GHz, and 5.2GHz respectively. The bandwidth offered by the structure is 228.3MHz, and 232MHz. System can be fabricated for WLAN applications.
- In chapter 7, the antennas designed and simulated in chapter 5^{th} and 6^{th} are fabricated. The fabricated results were little different from the simulated ones. In the triple band ACSMA array, the resonance shifted from 4 GHz, 5.8 GHz, and 6.2 GHz to 5 GHz, 5.7 GHz, and 6.3 GHz also the bandwidth increased from 130 MHz, 404.7 MHz, and 108 MHz to 860 MHz, 300 MHz, and 300 MHz. Similarly in the dual antenna array the frequency range covered by the fabricated design changed from 3.63 to 3.86 GHz, and 5.15 to 5.38 GHz to 3.27 to 4.21 GHz, and 4.63 to 5.99 GHz. Both the fabricated and simulated antennas find application in C-band, WiMAX, WLAN, and STM1.

Table 8.1 Concluded Results of all the Designs

Design	**Resonant Frequency (GHz)**	**Return Loss (dB)**	**Bandwidth (MHz)**	**Gain (dB)**
Single Band Stacked Antenna	6.3	-23	658.9	6.100
Dual Band ACSMPA	3.2, 4.5	-16, -19	82.9, 293.5	6.086, 7.200
Triple Band ACSMPA Array	4, 5.8, 6.2	-25, -22, -19	130, 404.7, 108	5.900, 7.708, 6.005

Dual Band ACSMPA Array	3.6, 5.2	-20, -30	228, 232	5.176, 6.611

8.2. Future Work:

The research work carried out in the thesis can be further extended to:

- **Smart Antennas:** A reconfigurable smart antenna is an antenna capable of modifying dynamically its frequency and radiation properties. In order to provide a dynamical response, reconfigurable antennas employ SPDT switches. They are becoming quite popular now-a-days.
- **Split Ring Resonator Structure (SRS):** It has negative index. It consists of a pair of enclosed non-magnetic metal loops with splits at opposite ends. Non-magnetic metal may include metals like copper. The loop can be concentric or square as per the requirement. SRS is also known by the names left handed medium or double negative metamaterial. Apart from the metamaterial antennas they can also be used for acoustic and terahertz metamaterial.
- **Electromagnetic Band Gap Structure (EBG):** Electromagnetic Band Gap is a 3-D periodic structure used to reduce the effects of surface waves. They prevent the propagation of the electromagnetic (EM) waves in the specified frequency bands thus improving the performance of the structure by providing the broadband frequency. It helps reducing the surface waves as a function of frequency. In EBG only one ε_r or μ_r is negative at a time.
- **Patch Antennas with Switchable Slots:** Microstrip patch antennas with switchable slots have attractive features like simple structure, single feed, and single layer design; this makes them compatible for wireless communication systems. Dual frequency can be realised by employing patch antenna with one switchable slot while when conventional patch antenna with circular polarisation is utilised with two switchable slots can be used to achieve dual band with circular polarisation. It can also be employed in patch antennas to have switchable polarisation i.e. Right Hand Circular Polarisation (RHCP), and Left Hand Circular Polarisation (RHCP). For example PASS was employed in the antenna used for MARS rover mission.

- **Metamaterials:** It is a material in which the properties depend on the inter-atomic structure rather than on the composition of the atoms. It could be metallic or semi-conductor. Metamaterial has ε_r and μ_r both negative. There are many types of metamaterials for example some are able to bend visible and infrared light in the opposite sense from traditional refractive index. These types find applications in optical communication, medical diagnostic equipment, spectrometry, optical cloaking devices, and they can also be employed in trace grace detection monitoring system.

List of Publications

Published:

- A. Agarwal, A. Kaur: 'A Review Paper on Stacked Microstrip Antenna for MIMO Systems', *National Conference on Recent innovations in electronics, electrical & computer engineering,* Vol.2, pp. 232-235, 2015.
- A. Agarwal, S. Gupta, A. Kaur: 'Analysis of Multi-layered Stacked Patch Antenna', *Internaational Conference on Microwaves, Antenna, Propagation and Remote Sensing*, pp. 97-101, 2015.
- A. Agarwal, S. Gupta, A. Kaur: 'Stacked Patch MIMO Antenna Array for C-band Applications', *International Journal of Engineering Applied Sciences and Technology*, Vol.1, No.6, pp.1-5, 2016.

Communicated:

- A. Agarwal, A. Kaur: 'Aperture Coupled Stacked Microstrip Antenna Array', *International Journal of Advances in Microwave Techniques*, Vol.1, 2016.

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