DESIGN AND ANALYSIS OF MICROSTRIP ANTENNA USING METAMATERIAL & ACTIVE DEVICES

THESIS

submitted in fulfillment of the requirement of the degree of

DOCTOR OF PHILOSOPHY

to

YMCA UNIVERSITY OF SCIENCE & TECHNOLOGY

by

PREET KAUR

Registration No: YMCAUST/PH14/2012

Under the Supervision of

Dr. S.K. AGARWAL
Professor
Deptt. of Electronics Engineering
YMCA UST, Faridabad

Dr. ASOK DE
Director
National Institute of Technology
Patna, Bihar

DEPARTMENT OF ELECTRONICS ENGINEERING
Faculty of Engineering & Technology
YMCA University of Science & Technology
Sector-6, Mathura Road, Faridabad, Haryana, India

September 2016

DECLARATION

I hereby declare that this thesis entitled "**DESIGN AND ANALYSIS OF MICROSTRIP ANTENNA USING METAMATERIAL & ACTIVE DEVICES**" by **PREET KAUR**, being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in **ELECTRONICS ENGINEERING** under faculty of Engineering & Technology, YMCA University of Science & Technology Faridabad, during the academic year 2015-2016, is a bona fide record of my original work carried out under guidance and supervision of Dr. S. K. Agarwal, Department of Electronics Engineering, YMCA University of Science and Technology, Faridabad and Dr. Asok De, Director, National Institute of Technology (NIT), Patna and has not been presented elsewhere.

I further declare that the thesis does not contain part of any work which has been submitted for the award of any degree either in this university or in any other university.

(Preet Kaur)

Registration No: YMCAUST/PH14/2012

CERTIFICATE

This is to certify that this Thesis entitled **"DESIGN AND ANALYSIS OF MICROSTRIP ANTENNA USING METAMATERIAL & ACTIVE DEVICES"** by **PREET KAUR**, being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in **ELECTRONICS ENGINEERING** under faculty of Engineering & Technology YMCA University of Science & Technology Faridabad, during the academic year 2016- 2017, is a bona fide record of work carried out under my guidance and supervision.

I further declare to the best of my knowledge, that the thesis does not contain part of any work which has been submitted for the award of any degree either in this university or in any other university.

Professor S.K. Agarwal
Department of Electronics Engineering
YMCA University of Science & Tech.
Faridabad, INDIA

Professor Asok De
Director
National Institute of Technology
Patna, Bihar, INDIA

(Dr. Munish Vashishath)
Chairman, Department of Electronics Engineering
YMCA University of Science & Technology
Faridabad, INDIA

Date:

The Ph.D. viva-voce examination of Preet Kaur Research Scholar has been held on …….

(Signature of Supervisors) (Signature of Head) (Signature of External Examiner)

ACKNOWLEDGEMENT

I am deeply indebted to my supervisors Dr. S.K. Agarwal, Professor, Department of Electronics Engineering, YMCA University of Science & Technology and Dr. Asok De, Director, National Institute of Technology (NIT), Patna for their continuous encouragement, invaluable guidance, wholehearted cooperation, moral support, incessant encouragement and appreciation, which culminated in the successful completion of this research work. I consider myself extremely fortunate for having got the opportunity to work and learn under their able supervision over the entire period of my association with them. My supervisors with their sharp and inclusive intellect, maestro ability combined with astute research methodology and deep insight of the subject has unerringly steered the work on smooth and steady course. I wish to express my deepest gratitude to both of them.

I gratefully acknowledge for the best wishes and prayers of all my friends for their encouraging, caring words, constructive criticism and invaluable suggestions.

I also express my sincere thanks to Dr. Munish Vashishath, Head of Electronics Engineering department, YMCA university of Science and Technology for providing all necessary research facilities in the department. I am thankful to Mr. Lalit Mohan, Mr. A. K. Aggarwal for support and help during antennas fabrication and measurement work. I am also thankful to my colleague and friend, Dr. Sonia Bansal for her support and encouragement during this research work.

I also express my sincere thanks to Dr. Ashok Mittal, Director, AIT Delhi and Dr. Vibhakar Shirmali, Head of Electronics and Communication, GBPEC, Delhi, for providing all necessary research facilities in the department.

My sincere heartiest special thanks to my husband Mr. Vijay Pratap Singh for his constant encouragement and support. Without his support, completion of this thesis within the stipulated time would have been impossible. I am short of words, to express my loving gratitude to my sweet daughter, varnika and son, Pranav, for their love which inspired me during my entire work.

Lastly, my deepest gratitude is due to almighty God whose divine light and warmth provided me the perseverance, guidance, inspiration, strength to complete this work.

Preet Kaur

ABSTRACT

Wireless communication have significant role in today's technological advancements. In modern wireless systems, antenna is a crucial component. For designing an antenna for modern wireless system main factors which must be considered are low profile, performance and cost of an antenna. Microstrip antennas meet most of the desired characteristics of modern communication system due to their different advantages like small volume, low profile, light weight, easy integration with other microwave components, planar structure etc. But these antennas have some disadvantages like narrow bandwidth, low efficiency, low gain, low power handling abilities etc.

Conventional techniques are provided in literature to improve the performance of these antennas and to make them compact. To improve bandwidth techniques such as use of low dielectric substrate, aperture coupled patches, proximity coupling etc. can be used. To miniaturize the microstrip antenna high dielectric substrate, shorting pin, slots etc. can be used. But still there is need to design and improve the performance of microstrip antenna using novel technologies as conventional methods have their own limitations like impedance matching, cross-polarization etc..

Recently, researchers have proposed the use of metamaterial for designing and performance enhancement of microstrip antennas. Metamaterials are artificially designed materials that have the properties not found in naturally existing materials. Main advantage of these materials is that these can be engineered according to the need of antenna designer. Design of compact patch antenna is proposed in this research work using cylindrical rods artificial dielectric material. Permittivity of cylindrical rods is tailored according to reference patch antenna and incorporation of these designed rods in patch antenna results in a compact antenna. A general procedure to design a patch antenna at desired subwavelength frequency using rodded medium is also proposed. Gain and directivity of microstrip antenna can also be enhanced using the properly designed and optimized superstrate of rodded medium. Multiband patch antenna can also be designed using rodded medium by introducing the lower and higher order modes in cavity.

In many communication applications, there is a need of wide bandwidth microstrip antenna. Double folded I shaped, C shaped and split ring metamaterial are investigated to design a subwavelength and broadband patch antenna. Double folded I shape structure is an ENG type metamaterial and C shaped and split ring are MNG

type metamaterial. Analysis of results shows that for designing subwavelength and compact antenna, ENG metamaterial can be incorporated in microstrip antenna but at the cost of gain. MNG metamaterial provides the optimum solution for designing subwavelength and good performance microstrip antenna having good gain, directivity, efficiency and reduced return loss. Incorporation of split ring resonators in microstrip antenna results in a broad-bandwidth and subwavelength radiator. Simulation results of the proposed antenna are also verified experimentally and both results are in good agreement.

A simple technique for designing a compact patch antenna is presented by combining the conventional technique of slots with metamaterial embedding. The resulted compact antenna is very simple to fabricate. Double H shaped double negative (DNG) type metamaterial is used to design compact antenna using this technique. The prototype of this proposed compact antenna is fabricated and tested. Design of a high- performance microstrip antenna is also presented using double H shaped resonator without changing the resonant frequency of the reference antenna. The proposed antenna has better gain, directivity, efficiency, bandwidth and return loss as compared to reference patch antenna. This proposed high performance antenna is fabricated and results are verified experimentally.

In wireless communication, circular polarized (CP) antennas have achieved much attention due to their features which make them more reliable as compared to linearly polarized (LP) antennas. The waves radiated by circular polarized antenna have better mobility, penetration and less vulnerable to harsh weather conditions as compared to linear polarized waves. Circular Polarized antennas also have the advantages such as elimination of alignment issues, better connectivity, reduced multipath effects and better signal strength through obstacle. Conventional techniques used for designing these antennas use the complex feeding system. In this research work, circular polarized antenna design using chiral metamaterial is presented. Advantage of this proposed method is that it uses a simple feed and the antenna is very easy to fabricate. Chiral metamaterial structure lacks the mirror symmetry in any plane. Degeneracy between the two circularly polarized waves i.e. LCP and RCP is broken when it passes through chiral material. Circular dichroism and optical activity are the two effects of chiral metamaterial which are used to design circular polarized antenna. Bilayer twisted cross wires and gammadion chiral metamaterials are used to design circular polarized antennas.

The multitude of various standards in mobile phones and wireless communication demand for smart multifunctional antennas and compact multi-band antennas has increased drastically in recent years. With reconfiguration in antenna system compact multifunctional antennas can be designed. For achieving reconfiguration microwave active devices can be used. Reconfigurable antennas have advantages of small or compact size, effective use of electromagnetic spectrum, almost same radiation pattern and gain at all desired and operating frequency bands and frequency selectivity which is useful for reducing hostile effect of jamming and interference as compared to conventional antennas. Design of a multiband fractal antenna which can also be reconfigured is presented in this research work. Fractal antenna is selected for reconfiguration as it have multi-band characteristic and provides miniaturization. Fractal antennas are obtained by multiple iterations of a single elementary shape. These antennas are used to define a family of complex shapes that shows an inherent self-affinity and self-similarity in their geometrical arrangement. The proposed antenna works in four modes. The optimized reconfigurable fractal antenna is fabricated and tested. The fabricated and simulated results of the proposed antenna are in good agreement. This proposed antenna can be used for radar applications and wireless applications.

Frequency reconfigurable inverted circular patch antenna is presented for wireless applications. The Proposed antenna has very high gain and operates at two frequency bands which can be selected using pin diodes. Work had presented in literature that discussed the use of reconfiguration concept in design of dual band antennas. But the advantage of the present work over work presented in literature is that reconfigurable antenna has very high gain along with frequency selectivity. Both the simulation and measured results of gain return loss and radiation pattern are obtainable. Proposed antenna can be used for wireless application like PCS ,WLAN and Bluetooth applications.

A Novel high performance multifunctional antenna can be designed by using the concept of reconfiguration in metamaterials. Using this concept a polarization reconfigurable antenna is proposed. Chiral metamaterial bilayer split ring is used in the presented antenna to convert the polarization of rectangular patch antenna from linear to circular. By using pin diodes position of slots in lower layer of chiral metamaterial is changed which changes it characteristics. It works in two modes, in one mode chiral material allows the LCP wave to pass and stops the RCP

wave and in other reconfiguration state it passes the RCP wave and stops the LCP wave. Thus a polarization reconfigurable antenna is obtained by switching between the two states in chiral metamaterial.

The main goal of this research work is to design and analyze the microstrip antenna using metamaterial along with design of multifunctional antennas using microwave active devices. In this thesis, effect of embedding of metamaterial in microstrip antenna for improvement of performance parameters such as size of radiating element, impedance bandwidth, gain, directivity and efficiency etc. are demonstrated and discussed. Design and analyses of multifunctional antennas for wireless systems are also presented.

In nutshell during this research work, according to defined problem statement, the performance enhancement of microstrip antenna using different types of metamaterial is demonstrated and analyzed. A simple technique of design of circular polarized antenna using chiral metamaterial is proposed. Design and investigation of multifunctional antennas are also presented in this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND SYMBOLS

Symbol		Description
ε	:	Relative dielectric permittivity
μ	:	Relative magnetic permeability
c	:	Velocity of light
λ	:	wavelength
ω	:	Angular velocity
Γ	:	Reflection coefficient
G	:	Gain
D	:	Directivity
n	:	Refractive index
κ	:	Chirality parameter
U	:	Radiation intensity
ABW	:	Absolute bandwidth
FBW	:	Fractional bandwidth
P_R	:	Power reflected
P_T	:	Power transmitted
P_{rad}	:	Power radiated
E	:	Electric field
H	:	Magnetic field
k	:	Wave vector
RMPA	:	Rectangular microstrip patch antenna
MSA	:	Microstrip antenna
GSM	:	Global system for mobile communication
MM	:	Metamaterial
LP	:	Linear polarization
CP	:	Circular polarization
LCP	:	Left hand circular polarization
RCP	:	Right hand circular polarization
CM	:	Chiral metamaterial
SRR	:	Split ring resonator
ENG	:	Epsilon negative
MNG	:	Mu negative

SNG	:	Single negative
NIM	:	Negative index material
DNG	:	Double negative
LHM	:	Left handed medium
WLAN	:	Wireless local area network
LC	:	Inductive and capacitive circuit

CHAPTER 1

INTRODUCTION

An antenna is a device that radiates or receives electromagnetic waves. An antenna is defined by IEEE as a "transmitting or receiving system that is designed to radiate or receive electromagnetic waves." It is a transitional component between transmission line and free space. Antennas are crucial components in wireless communication. It may radiate equally in all the direction or concentrate the radiated energy in a particular direction. Various types of antennas like wire, aperture, parabolic, patch, assembly of elements, lens etc. are available. For selecting an antenna for a particular application or frequency range structural, electrical and mechanical aspects should be taken into account.

In modern wireless communication system antennas should be compact, directive, multifunctional, low profile, light weight, efficient, compatible with other electronic circuit and easy to fabricate. Patch antennas have characteristics of low profile, light weight, easy fabrication and are mechanically robust. These antennas can be designed to radiate dual and triple frequency and can be easily integrated with other electronic circuits. Due to above mentioned characteristics patch antennas have become popular in modern wireless industry.

1.1. INTRODUCTION OF MICROSTRIP ANTENNA

Microstrip antennas (MSA) are also called patch antennas. These antennas in their basic structure consist of radiating patch generally made of copper on one side of dielectric substrate and the ground plane on the other side as shown in Fig. 1.1. Radiating patch and feed line are photoetched on dielectric substrate. Radiating patch can be of any regular shape like rectangular, circular, square, elliptical, ring, triangular, disk or can be engineered to suit the designer's requirement. But square, circular and rectangular are most commonly used patches as these are easy to fabricate and can be analysed easily. Microstrip antenna can be designed as broadside and end fire radiator. Pattern will be maximum along the patch axis in case of end fire radiation and in broadside case maxima of pattern will be normal to radiator. For designing the patch antenna various substrate can be used and their relative dielectric constant usually vary from 2.2 to 12.

To design a microstrip antenna with good radiation efficiency, a thick substrate with low dielectric constant and low loss can be used, but it has narrow bandwidth due to high quality factor. Size of microstrip antenna also becomes large due to low dielectric substrate. Thus depending upon the application of microstrip antenna substrate should be chosen appropriately.

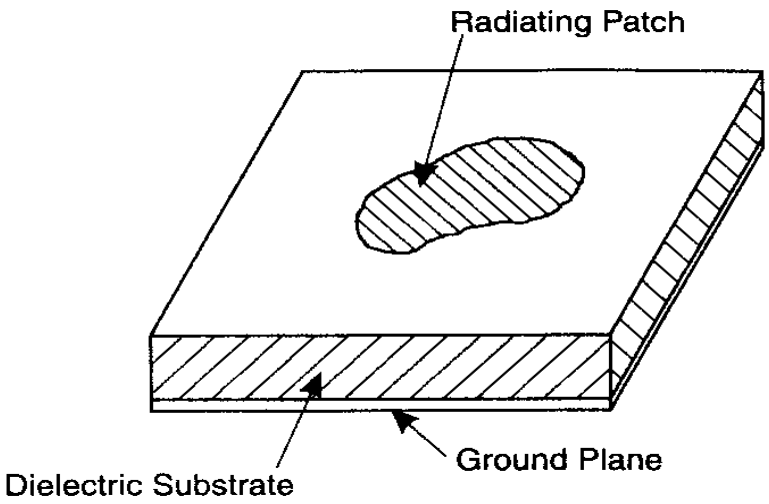


Fig. 1.1: Microstrip Patch antenna [179]

To feed microstrip antennas techniques like coaxial probe, microstrip line, proximity coupling and aperture coupling are most popular among the various feeding techniques available. Radiation from the microstrip antennas occurs from the fringing fields between the ground plane and the periphery of the patch. TM_{10} is the fundamental mode in the rectangular patch antenna and length of patch for this mode is approximately $\lambda/2$, where the wavelength λ pertains to dielectric medium.

Antenna Performance Parameters

Microstrip antenna performance is determined from various performance parameters. As some parameters are interrelated, hence all the performance parameters are not needed to be specified for complete understanding of performance of antenna. These are directivity, radiation power density, efficiency, gain, bandwidth, voltage standing wave ratio and input impedance etc.

- **Reflection Coefficient**

For transmission line reflection coefficient (Γ) is given as ratio of power reflected (P_r) from transmission line to power transmitted (P_t) in line.

Load impedance (Z_l) and characteristic impedance (Z_0) should be equal to attain perfectly matched system. In this case there is no reflection and hence the reflection coefficient is equal to zero.

$$\Gamma = \frac{P_r}{P_t} = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{1.1}$$

In antenna system, if there is mismatch of impedance then total input power will not be delivered to antenna and some of the power will be reflected. Reflected power is measured in terms of return loss (R) is given by

$$R = 20\log(\Gamma) \tag{1.2}$$

For maximum power to be delivered reflected power should be very small.

- **Radiation Pattern**

Radiation pattern is graphical or mathematical representation of radiation properties (power density, field strength, radiation intensity, directivity etc.) of antenna in free space as a function of space coordinates.

- **Directivity**

Directivity (D) is defined as a ratio of radiation intensity (U) of test antenna in given direction and average radiation intensity (U_{avg}).

$$D = \frac{U}{U_{avg}} = \frac{4\pi U}{P_{rad}} \tag{1.3}$$

P_{rad} is the radiated power of antenna.

- **Gain**

For describing the performance of antenna, gain is other useful parameter. Gain (G) of an antenna is given as

$$G = 4\pi \frac{Radiation\ intensity}{total\ input\ power} \tag{1.4}$$

Gain is very closely related to directivity and in term of directivity it can be written as

$$G = \eta D \tag{1.5}$$

Here η represents efficiency of the antenna.

- **Bandwidth**

Bandwidth is the range of frequency over which antenna meets some characteristics (gain, return loss, directivity, VSWR etc.) according to specific standard. Absolute bandwidth (ABW) is defined as difference between lower frequency and upper frequency is called absolute frequency and fractional bandwidth (FBW) is defined as percentage of difference of frequency divided by centre frequency.

$$ABW = f_H - f_L \quad (1.6)$$

$$FBW = \frac{f_H - f_L}{f_0} \times 100 \quad (1.7)$$

f_H is the upper frequency and f_L is the lower frequency of achieved frequency range and f_0 is the centre frequency.

The above are the parameters which determine the performance of an antenna. Reasons for popularity of microstrip antennas in modern communication systems as compared to other microwave antennas are due to following the advantages of these antennas:

- Low volume
- Light weight
- Thin profile and planar configuration
- Low fabrication cost
- Suitable for mass production using printed circuit technology
- Circular and linear polarizable
- Easy to integrate with other electronic circuits
- Easy to design for dual and triple frequency bands

The above advantages/characteristics of patch antennas make them suitable for modern communication system. However, these antennas have some limitations like lower gain, narrow bandwidth, low efficiency, spurious radiation from feed and junctions. Also the transverse dimension of patch antenna cannot be made arbitrarily small as resonant frequency depends on linear dimension.

To improve performance of microstrip antennas researchers have suggested several techniques. The bandwidth of patch can be increased by

- Using thick substrate with a low dielectric constant
- use of proximity coupled [43] or aperture-coupled patches [42]
- impedance-matching techniques[89]
- use of log periodic configurations[128]
- Multiple resonator techniques [61] and ferrite substrates [176].

To reduce the size of MSAs following techniques have been proposed.

- use of high dielectric constant material [44] [185]
- slots on the patch
- shorting walls [104][187] or shorting pin

To improve gain of patch antenna superstrate and arrays are used. But these conventional techniques have the problem of cross polarization, impedance matching, complex feeding etc.

To overcome these problems and to enhance the performance of patch antenna researchers recently proposed the use of metamaterial in antenna design.

1.2. INTRODUCTION OF METAMATERIAL

Metamaterials are artificially designed materials with basic properties like permittivity (ε) and permeability (μ) that define electromagnetic behavior of a material are different from the naturally occurring materials.

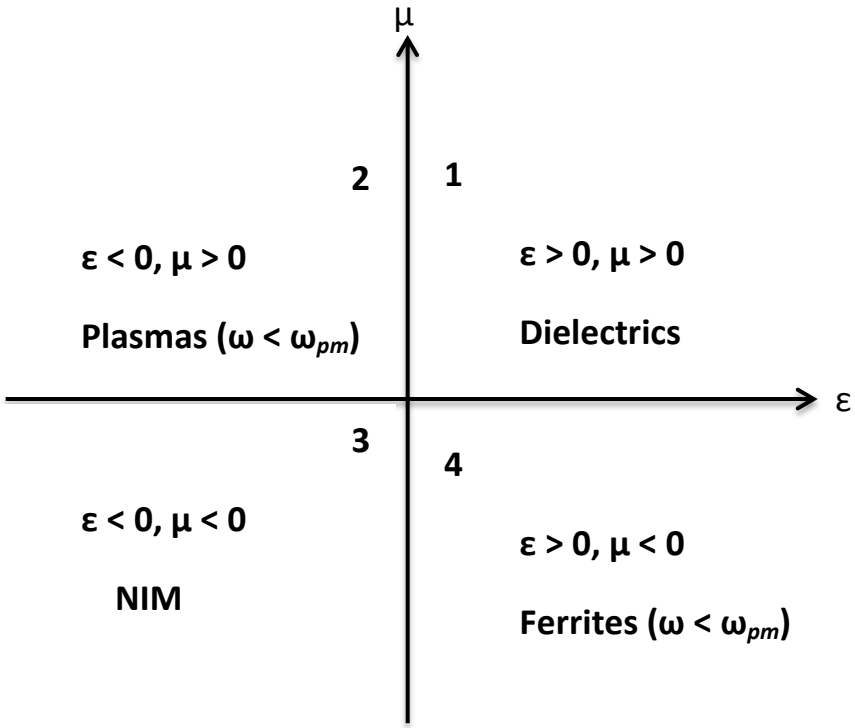


Fig. 1.2: Classification of materials

These materials can be synthesized by arranging the periodic structures of elemental or unit cells. The average dimension (a) of elemental or unit cell should be considerably smaller [14] [205] than the light wavelength (λ). i.e. $a \ll \lambda$. Based on the sign of permittivity and permeability, the materials can be divided into four categories as shown in Fig. 1.2.

- Quadrant 1: This region contains dielectric material not meta-materials that are naturally occurring. The region has positive permittivity and permeability.
- Quadrant 2: This region has negative permittivity and positive permeability value. These materials represent the class of meta-materials known as artificial

dielectrics. Due its highly negative dielectric value, these materials can be used for reducing the size of antennas.

- Quadrant 3: This region represents the material having both permittivity and permeability negative. These materials are called left handed materials due to backward wave propagation.
- Quadrant 4: This region represents the materials with positive permittivity value and negative permeability value below plasma frequency. This class of meta-materials is called artificial magnetic. These meta- materials can be used to reduce the size and to increase the gain of antenna.

Basic characteristics of Metamaterial

The electromagnetic properties of the materials, permittivity (ε) and permeability (μ) determine how the electromagnetic waves propagate through a material. To understand the propagation of electromagnetic waves through the metamaterial, let us start with the Maxwell's first order differential equations.

$$\nabla \times E = -j\omega\mu\, H \tag{1.8}$$

$$\nabla \times H = -j\omega\mu E \tag{1.9}$$

where ω represents the angular frequency of wave. For plane-wave magnetic and electric fields are

$$E = E_0 e^{(-jk \cdot r + j\omega t)} \tag{1.10}$$

$$H = H_0 e^{(-jk \cdot r + j\omega t)} \tag{1.11}$$

where k represents the wave vector, on combining the above equations (1.8-1.11) results

$$k \times E = \omega\mu H \tag{1.12}$$

$$k \times H = -\omega\varepsilon\, E \tag{1.13}$$

When permittivity and permeability are both positive then a right handed orthogonal system is made by vectors E, H and k [172] and wave propagates in forward wave direction in the medium. When permittivity and permeability are both negative, relationship between vectors E, H and k can be given as

$$k \times E = -\omega|\mu|H \tag{1.14}$$

$$k \times H = \omega|\varepsilon|\, E \tag{1.15}$$

In this case a left handed orthogonal system is made by vectors E, H and k [30]. Poynting vector S represents the flow of energy and is given as

$$S = \frac{1}{2} E \times H^* \tag{1.16}$$

From above equation it can be seen that direction of energy flow is not effected with simultaneous change in sign of permeability and permittivity. Thus group velocity is positive for both right handed and left handed system. Refractive index(n) can be given as

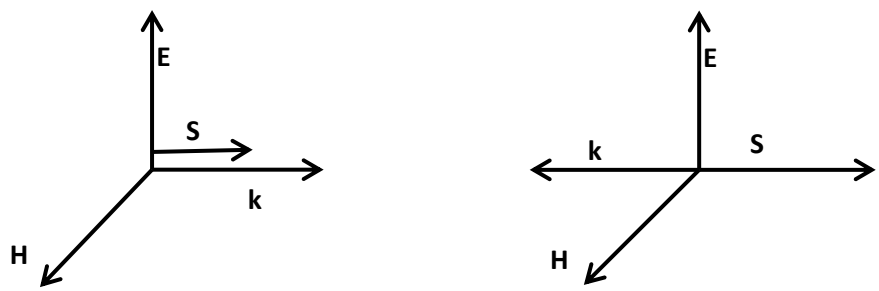
$$n = \pm\sqrt{\varepsilon\mu} \tag{1.17}$$

And phase velocity (v_p) is given as

$$v_p = \frac{c}{n} \tag{1.18}$$

where c represents the velocity of light in vacuum.

Refractive index is positive in right handed system and thus the phase velocity is positive. Hence propagation of electromagnetic wave and direction of energy flow will be in same direction, which results in forward wave propagation as shown in Fig 1.3 (a).



(a) (b)

Fig. 1.3 (a) Right handed system (b) Left handed system

Refractive index is negative in left handed system and thus the phase velocity will be negative. Therefore the propagation of electromagnetic wave and direction of energy flow will be in opposite direction, which results in backward wave propagation as shown in Fig 1.3(b). In non-uniform waveguide, backward waves commonly propagate [25, 26].

1.3. METAMATERIAL OVERVIEW

"A metamaterial is an engineered composite that exhibits superior properties not observed in nature or in the constituent materials." [28]. These materials can also be defined as "Metamaterials are typically man-made and have properties that are not found in nature" [28].

Kock was first to suggest an artificial dielectric material a type of metamaterial and used this material in lens antenna in 1946 [106]. In 1962 Rotman and in 1968 Smith has presented the work on artificial electric plasma produced using parallel plate and wire media respectively. In 1968, Victor Veselago [205] published the work about the electrodynamics of material with negative permeability and permittivity without practical realization and application of these materials. J.B. Pendry et.al. had shown firstly the realization of negative permittivity medium at microwave frequency using two dimensional matrix of thin wire medium [80] and in the subsequent paper[78], Pendry and his co-workers extended this idea to three dimensional wire net, by which the isotropic behavior was attained . In 1999, pendry et.al published[79] the most significant publication in metamaterial, in which they had proposed the split ring resonator (SRR) , a resonant practical, which is constituent of artificial negative permeability media. After this significant work research is going on in use of metamaterial in optical and microwave applications.

The extraordinary properties of a metamaterial are a consequence of their engineered constructs [145-146]. They are artificially engineered structures and have properties not possible with naturally occurring materials [28]. The key features of metamaterial are given below:

- These materials refract the light in a way contrary to right handed rule of electromagnetism and electric field, magnetic field and wave vector form a left handed triplet. But the energy flow is determined by real part of poynting vector and electric field, magnetic field and real part of poynting vector makes a right handed triplet in left handed media. So in such media wave front and the energy travel in opposite direction. This is unique property of these left handed media.
- In left handed media phase velocity and group velocity have opposite sign. This property shows that wavefronts and wavepackets travel in opposite directions and it also indicates the propagation of backward-wave in left-handed media.

- The greatest potential of metamaterials to create a structure with a negative refractive index [147]. This property is not found in natural occurring . Almost all the natural materials have positive values for both permittivity ε and permeability μ. Some metals like silver and gold have negative ε at visible wavelengths. The refraction of light in left handed metamaterial & conventional material is shown in Fig. 1.4.

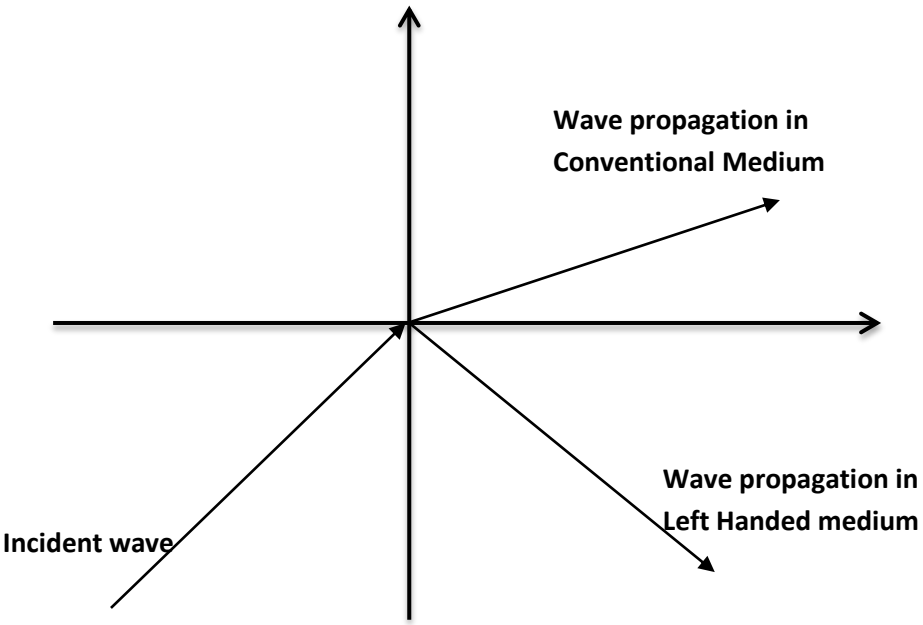


Fig. 1.4: Refraction in left handed media to normal media

The application and research area of metamaterial are given below:

1. Metamaterial can be used in antennas for enhancement of their radiation properties. Using these materials compact electrically small size antennas can also be designed. Chiral metamaterial can be used in standard antenna design for designing and performance enhancement of circularly polarized antenna. Researchers have proposed high performance antennas using these materials.
2. Metamaterials can be used to design absorber. First metamaterial based absorber was proposed by Landy et. al., which utilizes three layers, two metallic layers and one dielectric layer. This absorber shows 99% absorption at 11.48 GHz. Experimentally this absorber shows 88% absorptivity. Differences between simulated and experimental results are due to fabrication error. Thus metamaterial can be explored to design high quality absorber.

3. Metamaterial can be used to design compact microwave filters [37] and diplexer. Resonant type metamaterials are preferably used to design such devices as they need resonant elements. Split ring and complementary split ring resonators type resonators can be used to design narrow band and wide band filters.
4. Metamaterial can be used to design cloak. Cloaking means cancellation of magnetic and electric field generated by object and guiding of wave around the object. Object is made invisible by designing the refractive index of object such that all the rays of light incident upon it guided around it and on the other end ray recover the original path.
5. Metamaterial can be used for designing sensors. Using metamaterial sensitivity and resolution of sensor can be enhanced significantly. Sensors based on metamaterial can be used in biomedical, agriculture etc.
6. Metamaterial can be used as a phase compensator. A slab of double positive material provides positive phase shift while the double negative materials slab provides the opposite phase shift. This concept can be used to design phase compensator.
7. Metamaterial can be used to design super lens [93]. Metamaterials are used in super lenses to reach beyond the diffraction limit. Research showed that resolution capabilities go beyond the normal microscopes using metamaterials.
8. There are many trust areas where metamaterials can be used and explored.

1.4. METAMATERIAL TYPES

Depending upon the sign of permittivity and permeability, metamaterials are broadly classified into artificial dielectric, artificial magnetics and left handed materials. Chiral metamaterials are also the type of metamaterial which lacks mirror symmetry in its structure. All these types of metamaterial are discussed in detail below.

1. Artificial Dielectrics

In 1946, Kock [106] has given the concept of artificial dielectric material. These materials have negative permittivity and positive permeability (Quadrant II in Fig. 1.2) and these are also called epsilon negative material (ENG). Noble materials like gold or silver have a negative permittivity at very high frequencies but these materials also have an extremely large conductivity (or imaginary part of permittivity). There is a

substantial absence of materials with largely real and negative permittivity in the microwave regime.

The metamaterial with negative permittivity in microwave and other regions can be generated artificially by arranging thin rods or cylinders in cubic lattice structure such that lattice constant of the structure and diameter of rods are small as compared to operating wavelength [109] [154] as shown in Fig 1.5.

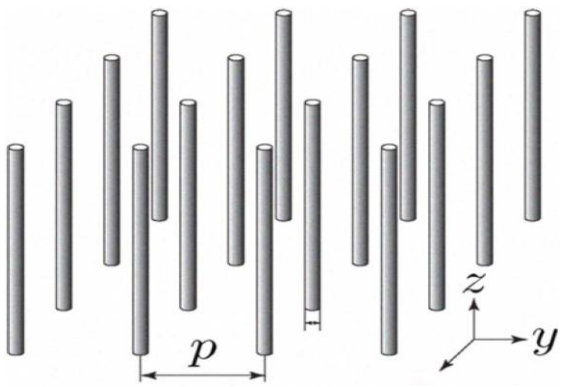


Fig. 1.5: Array of Cylindrical Rods [182]

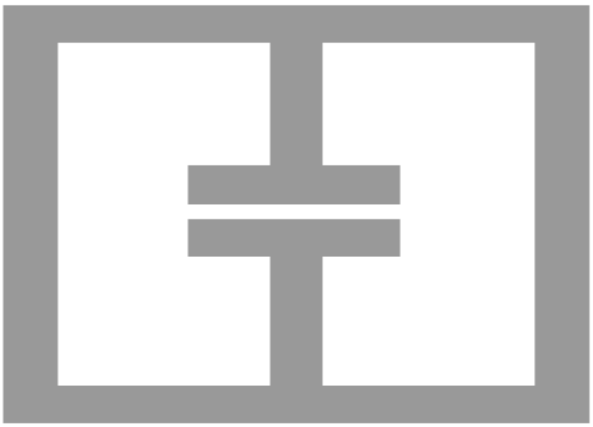


Fig. 1.6: Electric Coupled Field Resonator [182]

The modified structure of SRR [172] as shown in Fig. 1.6 also gives negative permittivity. The equivalent circuit of this proposed structure consist of two symmetric inductive loop connected to common capacitor. At resonance, magnetic moment associated with currents in both loop cancel each other and have a large electric polarizability.

2. Artificial Magnetics

These materials have negative permeability and positive permittivity (Quadrant IV in Fig. 1.2) and these are also called mu negative material (MNG). These materials show negative value of permeability below the plasma frequency. A stack of edge-coupled split rings (EC-SRR) displays negative permeability as shown in Fig. 1.7.

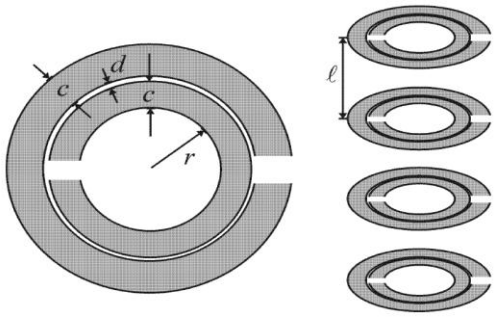


Fig. 1.7: Edge coupled split ring resonator [182]

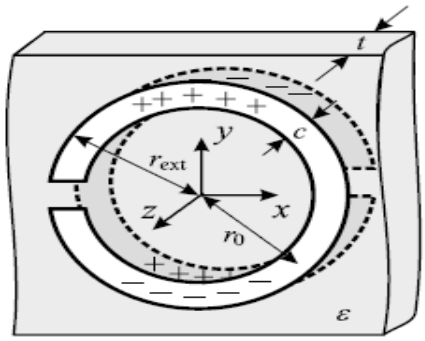


Fig. 1.8: Broadside coupled split ring resonator [182]

Broadside-coupled (BC-SRR) as shown in Fig. 1.8 also have negative permeability. It consists of metallic rings of copper that are printed on the both sides of dielectric substrate. Since a net electric dipole is not formed by charge distribution present in it, therefore, this structure is non bi-anisotropic structure. This structure also has smaller electrical size than EC-SRR.

3. Negative-Index Material (NIM)

Refractive index (n) mainly depends on the permittivity and permeability of the material and can be given as

$$n = \pm\sqrt{\varepsilon\mu} \tag{1.19}$$

Refractive index is purely imaginary when either permeability or permittivity is negative and it results in evanescent waves. When permittivity and permeability are both positive, then refractive index will be positive and it results in propagation of forward wave. When permittivity and permeability are both negative, the refractive index is negative and it results in propagation of backward wave. The materials with simultaneous value of negative permeability and permittivity (Quadrant III in Fig. 1) are called Negative-index materials. These materials are also called left handed materials. Omega shaped structure[20], S shaped structures[20], I shaped

structures[217], Double H shaped[138] structures and arrangement of alternating layers of circular split rings and thin metallic wires etc. exhibit negative index of refraction [45] [169] as shown in Fig 1.9.

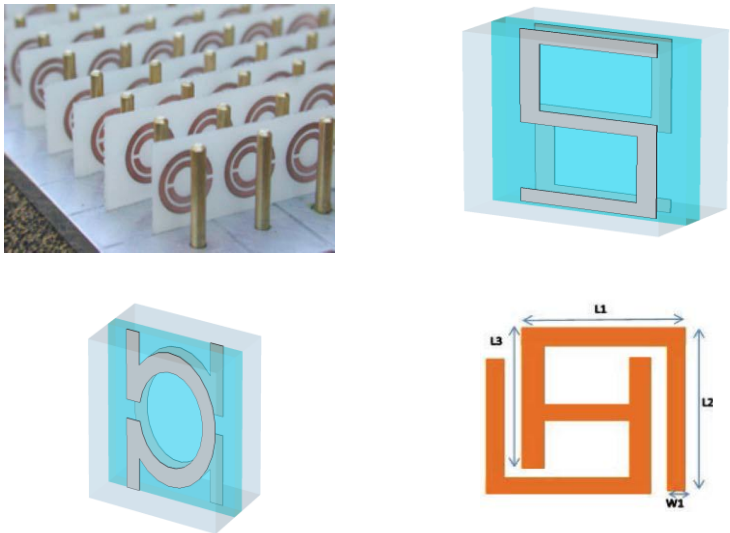


Fig. 1.9: Negative index metamaterial [45][20][138]

4. Chiral Materials

These materials consist of particles which cannot be superimposed on its mirror images as shown in Fig. 1.10. These materials are different from metamaterials in which permittivity and permeability are both required to be negative for attaining negative value of refractive index. But in chiral materials negative refractive index can be achieved due to strong chirality without having the negative value of either permittivity or permeability or both.

Refractive index n for chiral metamaterial is given as

$$n = \sqrt{\varepsilon\mu} \pm \kappa$$

Chirality parameter (κ) describes the cross coupling between magnetic field and electric field when wave propagates through chiral material.

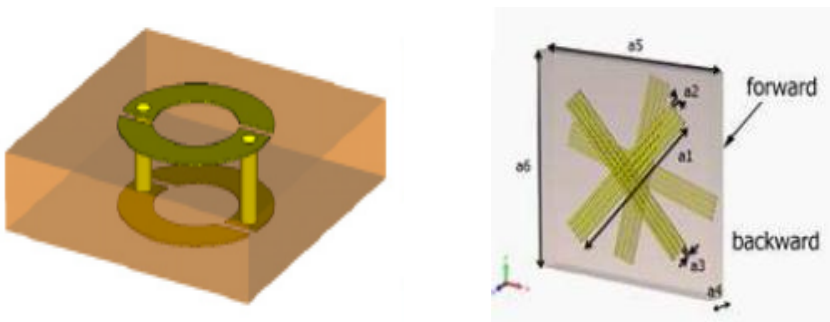


Fig. 1.10: Chiral Metamaterial [27]

These materials behave differently for left and right circularly polarized wave due to its chiral asymmetry property [27].

5. **Resonant Metamaterial**

These metamaterial are made of resonant elements e.g. split ring resonator. Permittivity and permeability of these metamaterial have large dynamic range close to the resonant frequency. Small change in frequency causes the large change in permittivity and permeability of these metamaterial. Using resonant element large dynamic range material parameters can be designed, which is main advantage of these metamaterial. But these materials have high loss and narrow bandwidth near resonant frequency.

6. **Non-Resonant Metamaterial**

Theses metamaterial are constituted by non-resonating particles or elements e.g. I shaped elements. Permittivity and permeability of these metamaterials vary slowly with respect to frequency. These metamaterials have small loss and broad bandwidth. These are main advantages of these metamaterials, but using them material parameters can be designed in small dynamic range.

1.5. MOTIVATION OF RESEARCH

In recent years, advancement in wireless communication has changed the expectation of antenna design and their performance [64]. Antennas that are compact, efficient, low cost, easy to fabricate, have significant bandwidth, directive and easy to integrate in complex system fulfil the need of modern wireless system. Also many systems (GPS, Bluetooth etc.) are integrated on single communication platform with advancement in electronics and wireless technology and hence there is a need of reconfigurable antenna which functions for all the systems. Needs of such antenna systems are the challenges for antenna designer. Patch antenna due to its low profile, easy fabrication, low cost and easy integration with other electronic component is popular in modern wireless communication. But these antennas also have the limitation of low gain, narrow bandwidth, spurious radiation, low efficiency, extraneous radiation from feeds and junctions etc. Moreover, as per the need of today's system there is need of compact patch antenna, but transverse dimension of patch antenna cannot be made arbitrarily short as resonant frequency directly depends on its linear dimension. To overcome these limitations conventional techniques have been suggested in literature. But these techniques have their own disadvantages of

impedance matching, cross polarization etc. and do not overcome all the limitations of patch antenna. This fact is the main motivating factor to think of techniques which improve the performance of the microstrip antennas using the metamaterial and to design reconfigurable antenna.

1.6. RESEARCH OBJECTIVE

In order to investigate the procedures of enhancing the performance of microstrip patch antennas using metamaterial and active devices, the following tasks are to be taken as a part of this research work:

1. To design metamaterial of different shape and size according to reference patch antenna frequency bands.
2. To design a compact patch antenna using metamaterial
3. To design subwavelength antenna and enhance the antenna parameters by incorporating different types of metamaterial structure in antenna design.
4. To analyze the designed metamaterial based antennas on the basis of results obtained.
5. To design a multiband antenna using active devices & analyze the antenna based on simulation and experimental results.
6. To design a polarization reconfigurable antenna using active device and metamaterial.

1.7. ORGANIZATION OF THESIS

This thesis contains eight chapters, including the present one.

In the first chapter the basic introduction of Microstrip antenna, introduction to metamaterial, their characteristics and types have been discussed.

Chapter two reviews the conventional as well recent methods that have already been used for the performance enhancement of microstrip antenna.

Chapter three presents the design and investigation of patch antenna using cylindrical rods artificial dielectric. Cylindrical rods have negative permittivity and it is used to make the patch antenna compact. A general procedure to design a compact subwavelength antenna using rods metamaterial is also presented in this chapter. Technique for gain enhancement and improvement of other performance parameter of patch antenna and design of multiband antenna using rods metamaterial is also presented in this chapter.

Double folded I shaped ENG metamaterial, C shaped and split ring MNG metamaterial are used in chapter four for design of subwavelength and broadband antenna.

Chapter 5 presents the design of compact and high performance patch antenna using double H shaped metamaterial.

Design of circularly polarized RMPA using chiral metamaterial is presented in chapter 6. In this chapter bilayer twisted cross rods and gammadion chiral metamaterial are used to design a circularly polarized antenna without using complex feeding mechanism.

Chapter 7 presents the design of reconfigurable multiband fractal antenna and inverted circular patch antenna for wireless application using pin diodes. In this chapter design of polarization reconfigurable antenna using chiral metamaterial and pin diodes is also presented. Bilayer split ring chiral metamaterial are used to change the polarization of RMPA from linear to circular. By using pin diode in chiral metamaterial the proposed antenna can be made to switch between LCP and RCP polarization modes.

Finally, concluding remarks and future scope of this research work are presented in chapter eight.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

With rapid advancement in wireless and communication technology, there is requirement for improvement in technology of antenna design. Microstrip patch antennas are widely used in modern wireless and communication system due to their inherent advantages to meet the demands of modern communication systems. But still there is need to improve its performance using novel technologies, as conventional techniques of patch antenna design and performance enhancement has its own limitations. In the recent techniques to improve the performance of patch antenna, metamaterials have attracted significant consideration of antenna designers. In designing of an antenna substrate material plays an important role and a simple technique to modify performance parameters of antenna is to make changes in substrate material by modifying its permittivity and permeability. By using metamaterial, antenna substrate can be artificially engineered according to the needs of antenna designer. Patch antennas designed using this artificial engineered substrate provides better performance as compared to the conventional patch antennas and these high performance patch antenna have variety of applications in modern wireless communication system and defense.

This chapter presents a detailed literature review of conventional techniques used for performance enhancement and miniaturization of patch antenna along with advantages and limitations of microstrip patch antenna. Recent trends for designing and performance enhancement of patch antenna using artificial material are discussed besides various techniques for designing of reconfigurable antenna using active devices.

The technical contents of this literature review are categorised into four sections. In the section 2.1 advantages and limitation of patch antenna are discussed and section 2.2 touches up on conventional techniques to miniaturize and to enhance directivity, bandwidth, and efficiency of patch antenna. Section 2.3 presents the recent techniques for enhancement of the performance of patch antenna using metamaterial is highlighted. Followed by this, section 2.4, provides the development in reconfigurable antenna using active devices.

2.2 ADVANTAGES AND LIMITATIONS OF MICROSTRIP ANTENNS

Microstrip patch antenna has following advantages [1.1] due to which these are very popular in wireless industry.

1. Lightweight and low volume
2. Low-profile
3. Low fabrication cost
4. Planar configuration hence can be made conformal to host surface.
5. Support both linear and circular polarization
6. Able to radiate dual and triple frequency
7. Mechanically very robust.

Microstrip patch antenna has following limitations [179].

1. Main limitation of MSA is that its size cannot be made arbitrarily small. Its resonant frequency depends on the linear dimension and it should be half wavelength long. So its size gets fixed according to frequency and in today's system where size of communication systems are shrinking it is need to find out the methods to make antenna compact and it can be designed such that resonant frequency don't have dependency on size.
2. Narrow bandwidth is the other limitation of microstrip antenna. Typically it has bandwidth of 1-5% and this factor limits its application. So this is also the main trust area of investigation for antenna designers.
3. MSA has lower gain and reduced efficiency these are also the major limitations of these antennas which affect its widespread application.
4. Lower power handling capability
5. Extraneous radiation from feeds and junctions

The above limitations need to be overcome so that it can fit in modern communication systems.

2.3 CONVENTIONAL TECHNIQUE TO MINIATURIZE AND PERFORMANCE IMPROVEMENT OF MSA

To improve the performance of patch antenna techniques has been suggested in literature. Narrow bandwidth is the major limitation of patch antenna. Following are conventional techniques used to increase the bandwidth of patch antenna.

The shapes of basic patch antennas such as rectangular and circular were modified by cutting slots in rectangular ring and circular ring to increase the

bandwidth [34] [160]. Bandwidth of patch antenna was increased due to reduction in its quality factor Q. Luk et.al and Wong et.al. [122][211] used the same technique by cutting U slots in rectangular and triangular patch antenna to improve antenna bandwidth.

Bandwidth could be improved using the multi resonator structure [212] [106] [108]. In this technique parasitic patch antennas were gap coupled to central fed patch antenna. Various configuration could be used to couple the antennas like coupling along the radiating edge, non-radiating edge etc. Antennas could also be coupled electromagnetically to increase the bandwidth [162] [164] [180]. One of patch antenna was fed by coaxial cable and other antennas were electromagnetically coupled to it. Dimensions of patch antenna area adjusted such that their resonance frequencies were close to each other and overall a broadband width is yielded.

Using aperture coupling bandwidth of patch antenna could be increased. In aperture coupled patch antenna electromagnetic field from the microstrip feed line placed on the other side of the ground plane was coupled to radiating patch through a small aperture or slot in the ground plane. To optimize the performance different substrate could be chosen for the radiating patch and feed line. Electromagnetic coupling between the aperture and patch could be optimized by choosing best shape of aperture [24] [53] [123].

Bandwidth could also be increased using impedance matching network. For impedance matching quarter wave transformer and tuning stubs could be used. Matching network was placed close to the radiating element to improve the bandwidth and efficiency. Capelle et.al. had obtained the 10% improvement in bandwidth using matching network [168].

Using the concept of Log-periodic antenna bandwidth could be increased. This concept was applied to patch antennas to attain multi-octave band-width. In this technique dimension of patch antenna were increased logarithmically and the succeeding patches were fed 180° out of phase with respect to the previous patch antenna [68] [103] [161] [65]. But in this technique radiation pattern varies over the impedance bandwidth. It was the main disadvantage of this technique.

Impedance bandwidth of patch antenna could be improved by adding losses in the antenna, but this reduces the gain of antenna. Losses could be introduced in the form of discrete chip resistor and lossy substrate mateial etc. Lin and Wong improved

the impedance bandwidth of rectangualr patch antenna by resistor loading 4.9 times that of unloded antenna but it causes the reduction of 2 dB gain [209-210]. Fayyaz et.al. had proposed a different impedance matching network technique. In this matching network was designed such that reactance behaviour could be opposite to that of patch at resonance. Below the resonance load was capacitive and above the resoannce it was inductive. Now the patch antenna had two resonance which gave rise to broadbandwidth. It increased form 20 MHz to 75 MHz in loaded patch antenna [57].

Zaid et.al. had proposed a dual frequency and broadband stacked patch antenna using stacked patch technique [224]. In this two quarter wave antenna were stacked oppositely to obtain the dual frequency and for getting broadbandwidth shortcircuits were done along the same plane.

Using the ferrite substrate for patch antenna broader bandwidth could be obtained. By changing the magnetic field bandwidth of about three octaves could be obtained. As the ferrite had high dielectic constant so size of patch antenna was also reduced using this technique. But main disadvantage of this technique was poor efficency due to lossy substrate and requirement of external magnetic field which makes the size of antenna bulky [140] [163] [47].

Microstrip patch antenna in its regular shapes could not produce multi-octave bandwidth. By modifiying the shape of patch antenna octave bandwidth could be achieved. A rectangular patch antenna was designed without the substrate and ground plane and it was fed at the edge by a coaxial feed with a perpendicular ground plane. Effective dielectric constant of patch antenna could be equal to 1 with large h. Both of these factors could produce broad bandwidth. This modified structure was called as planar rectangular monopole antenna [181]. Other structures like hexagonal, triangular, elliptical and circular monopoles also produce broadbandwidth. An elliptical monopole [73] [70] [8] attained bandwidth of 1:11 for VSWR $\leq$ 2 with ellpticity of 1.1.

A broad band dual polarized with decoupled input ports and high isolation at centre frequency of 1800 MHz is designed [204]. Cross polarization levels were very less in this designed antenna. impedance bandwidth in both dual linear polarization states was greater than 14% and high decoupling was attained between input ports.

Wide bandwidth was obtained in microstip patch antenna using parasttic elements[131] . This patch antenna was designed using L-shaped probe feeding. The antenna was designed at centre frequency of 2.6 GHz. L-probe feed along with parastic elements helped to attain the wide bandwidth in patch antenna. Antenna had 11.04% of impedance bandwidth in frequency band of 2.44 GHz to 2.729 GHz .

To reduce the size of patch antenna and to increase its gain following conventional techniques were used. Size reduction of patch antenna could be done using high dielectric substrate but this technique lead to narrow bandwidth [197] [98] [88]. To reduce the size of patch antenna short circuit technique could be used. Short circuited patch antenna attained the same resonant frequency at approximately half the size of conventional patch antenna [127]. For short circuiting, shorting wall, shorting plate and shorting pin could be used to reduce the size of patch antenna [189] [174] [96].

With loading of patch antenna with shorting post, size of patch antenna could be reduced as well as change of polarization and multi-frequency operation could also be achieved [201] [200] [6]. Shorting pin could be applied at the centre or at the edge of the patch. Addition of shorting post in patch antenna added LC resonator circuit in parallel with equivalent circuit of unloaded antenna and hence the resonance frequency of patch antenna changed. Larger inductance of shorting post resulted in smaller resonance frequency of patch antenna. Wong et.al. presented a rectangular patch antenna with shorting post [96]. Loading of shorting post in this antenna produced two lowest resonant modes and size reduction of about 2.6% was attained.

A dual frequency square patch antenna with shorted pins attained the size reduction of 5 in area at lower band. This antenna could receive both linear polarization and circular polarization. It had circular polarization at upper frequency band and linear polarization at lower frequency band [52].

A compact rectangular patch antenna with shorted pin was designed for mobile communication [156]. The desired resonant frequency was achieved using shorting pin. Gap coupled patch antenna was minimized using shorting post [157] and produced triple frequency bands. By changing the radius of shorting post input impedance and mutual coupling of gap coupled circular patch antenna could be controlled [158] [155].

A design of compact elliptical patch antenna for Ku application was designed by Sharma et.al. on RO3003 substrate followed by thin foam and a ground plane [129]. A square slot was cut in ground plane below the elliptical patch to obtain compactness. The proposed antenna had overall dimensions of 50 mm x 50 mm x 3.162 mm at resonant frequency of 14.65 GHz.

Using slots and slits in design of patch antenna its size could be reduced. A compact patch antenna for S-band had designed using slots in its design. This antenna was made to resonate at dual frequency of 3.55 GHz and 4.99 GHz. Antenna had compactness of 18.2% and had 270 MHz impedance bandwidth. A miniaturized broadband patch antenna for wireless and space application was designed using U shaped patch antenna and W shaped ground plane [202]. To improve the bandwidth effective thickness of substrate was increased. For size reduction of patch antenna its effective electrical length was increased.

Gain of patch antenna was very low. Conventional techniques reported in literature for gain enhancement was use of superstrate structure, change of dielectric material, use of array and partial removal of substrate etc. Using the technique of partial substrate removal a patch antenna with good gain and broad-bandwidth was presented [152]. In this antenna bandwidth was increased using multiple layer dielectric substrates of silicon layer and glass layer. This antenna had size of 12 × 8 mm^2 and resonate at 6.479 GHz. Gain of the antenna was 4.035 dB with 314 MHz impedance bandwidth.

Gain of patch antenna designed for military system was increased using reflector layer [15]. This antenna was designed at 2.45 GHz and gain of antenna increased using a FR_4 substrate layer coated with copper on both sides and placed at an air gap of $0.04\lambda_0$ from patch. The antenna had impedance bandwidth of 2% and gain of 5.4 dB.

Proximity coupling was used to increase the gain of rectangular patch antenna presented for radar application [203]. Wide bandwidth and high gain was needed for radar application. Gain of this antenna was 4.22 dBi and work in frequency band of 2.8-3.1 GHz. A high gain patch antenna for wireless application was designed using C shaped slot cut in it. The antenna had a bandwidth of 50% in frequency range of 1-3 GHz. Gain of antenna was 7.3 dBi at 2.31 GHz [12].

2.4 RECENT TRENDS TO DESIGN AND IMPROVE PERFORMANCE OF MSA USING METAMATERIAL

Metamaterials can be used to overcome the problem of conventional techniques and can be used to improve the performance of conventional patch antennas. In the following section, technique used by various researchers for improving the performance parameters like gain, directivity, bandwidth, suppression of side lobe & back lobe, efficiency etc. and compactness of patch antenna using metamaterial is discussed and explained.

Microstrip patch antenna size can be reduced considerably by loading it with metamaterial. Patch antenna produces subwavelength resonance due to modification of resonant modes under loading condition. A compact triple band antenna was presented using metamaterial loading for all WiMAX applications [133]. This antenna was designed using monopole rectangular microstrip antenna with two left handed transmission line cell and CPW feed. The metamaterial unit cells of left handed transmission line were loaded on monopole microstrip antenna. Unit cell of these metamaterial were formed of interdigital capacitor and inductive slot. In order to introduce the two different frequency bands in antenna system each unit cell of metamaterial was designed separately. The third band was introduced by monopole microstrip antenna. The proposed antenna showed 66% reduction in size at a frequency band of 2.4 GHz as compared to conventional antenna. It showed miniaturization of 25% at frequency band of 5.5 GHz and 50% at the frequency band of 3.5 GHz.

A compact metamaterial-inspired circular monopole antenna [223] based on the design in [86] covers the bandwidth of 220 MHz at frequency of 2.3 GHz. To make antenna compact a T-shaped slot was cut out in circular patch [83].

A compact rectangular patch antenna [173] was designed by embedding square shaped multi split ring resonator in it. The proposed metamaterial had four rings and it showed negative permeability. Rectangular patch had the size of 0.5mm×5mm×1.6mm and Multi split ring resonator was placed close to the reference antenna. According Faraday's law of electromagnetic induction, when microstrip antenna was excited, emf was induced in metamaterial rings and triggered flow of current in rings. This resulted in shift of resonant frequency to lower side. The unloaded antenna had resonant frequency of 17.89 which shifted to 8.51 when the

metamaterial rings were placed at distance of 0.25mm from reference microstrip antenna.

Rods and split ring resonator which made a left handed medium were used to reduce the size of microstrip antenna [199]. Using this metamaterial 36.7% of size reduction and 12.43% of bandwidth enhancement was achieved. Due to chopped and slotted patch antenna multiband operation was attained.

A compact and wideband patch antenna [91] was designed using metamaterial having planar structure. In order to attain CRLH property, metamaterial unit cell is formed with complementary split ring resonator and interdigital capacitor. Shunt admittance was provided by SRR slot that was etched on ground plane and shunt capacitance was provided by interdigital capacitor that was inserted in microstrip antenna. Increase in interdigital finger length caused increase in series capacitance. Thus resonant frequency shifted to lower side and size of antenna reduced by 55%. In proposed antenna, TM_{10} mode was introduced due to increased interdigital finger length. Thus TM_{11} mode combined with TM_{10} mode and a wideband could be achieved.

A compact antenna designed by loading CSRR on ground for beam steering by Wenquan et.al. [95]. Researcher used the mu negative metamaterial [192] [59] [4] [120] for size reduction size of microstrip patch antenna.

Metamaterials have the interesting feature of controlling the direction and power of emission of patch antenna in small solid angle. The copper grids layers separated by foam were used to make metamaterial [188] to change the emission of an embedded source. This metamaterial had the plasma frequency of 14.5 GHz. According to Snell's law, rays refracted from the metamaterial would be near to normal and best directivity was obtained at 14.65 GHz. A higher directivity using rods and ring as superstrate [76] was obtained using same technique as presented in [188].

Directivity of electromagnetic emission could be improved by embedding the radiator in metamaterial that was anisotropic and had effective permeability and permittivity close to zero [218]. Based on this concept, an anisotropic metamaterial with effective permittivity close to zero was used and it was found that anisotropic behavior caused the high directivity [81].

S coupled and Double split rings two types of metamaterial superstrates [171] were used to enhance the gain, directivity and bandwidth. Directivity was enhanced

using the concept of zero refractive index. Patch antenna was designed such that all of its radiated energy concentrated close to zero refractive index. A 5×7 array of S shaped metamaterial was used and refractive index was close to zero in 13.5 GHz-17.5 GHz frequency range. Thus all the radiated energy of antenna concentrated in this frequency band and maximum directivity was attained. For achieving zero refractive index an array of double split ring were also used. To obtain enhanced gain superstrate of metamaterial was placed at a distance of $\lambda/3$ from ground plane. By incorporating two superstrate layers of metamaterial bandwidth was also enhanced. The distance between two superstrates layers was from $\lambda/3$ to $\lambda/2$.

Pentagonal Rings shaped metamaterial cover [26] was used to increase directivity and directivity of microstrip antenna. The optimized metamaterial had both negative permeability and permittivity in frequency range of antenna. Superstrate of metamaterial was positioned at distance of 3.2 mm from ground. Directivity of this antenna was enhanced by 2.019 dB due to focusing of radiated energy of antenna by metamaterial superstrate [40] [149].

To enhance the gain of microstrip antenna array use of superstrates of magneto-dielectric were also presented in literature. Using this method gain was enhanced without any significant increase in size of antenna. It was found that enhancement in gain depend upon the distance between superstrate and antenna. Advantage of this method over EBG based technique [18] [113] was that it resulted in an antenna which was low profile. A high gain and ultra-wideband patch antenna was designed using planar metamaterial [71]. Crossed gaps and isolated gaps of triangle were used etched on ground and patch to achieve better impedance matching characteristics. Due to metamaterial gain of reference antenna increased from 1.4 dB to 5.42 dB and its size was also reduced.

An absolutely different approach to enhance the gain and bandwidth of a traditional patch antenna was presented by using metamaterial that had planer patterned structures etched on ground plane and the upper patch [116]. Cross strip gaps were distributed periodically on ground plane. Similarly triangular gaps were distributed periodically on upper patch. Due to coupling between ground plane and upper patch an inductive-capacitive circuit was formed. In this antenna system, a backward wave travelled along the plane of microstrip patch. Thus gain and bandwidth were enhanced due to increase in radiation along direction of patch.

To improve the gain of monopole antenna two different methods were proposed. In first method, below a monopole antenna ground plane was suspended [153]. It was found that by controlling the ground plane dimensions gain could be enhanced. Ground plane dimensions could be optimized to work as a reflector and it resulted in broadside unidirectional radiation pattern. As compared to traditional antenna using this technique a gain enhancement of 3 dB was achieved. Antenna also became compact due to shift of resonant frequency towards lower side. In second technique, superstrate made of printed metallic strips were used to enhance the directivity and gain. This superstrate of metamaterial was placed at a height of about 11 mm from ground plane and it caused the 3 dB enhancement of gain.

To improve directivity and gain of microstrip antenna a cover of left handed metamaterial was formed with microstrip line and two triangular SRR printed on substrate [229]. Two gaps were cut on ground plane which work as defected ground structure. The designed metamaterial had permeability and permittivity negative in different frequency bands. Directivity and gain of antenna get enhanced by positioning the cover of left handed material above it. It also shifted the resonant frequency of antenna to lower side.

Broadband patch could also be designed using metamaterial loading. A broadband printed monopole antenna loaded with metamaterial [134] designed at 4.06 GHz. Transmission line that had negative refractive index was used as metamaterial. Loading of metamaterial was adjusted such that it introduced even mode current at a frequency of 5.5 GHz and antenna transformed into folded monopole. Because of in phase current at the top edges, ground plane was made to radiate at 3.55 GHz. A wideband antenna was resulted due to radiation of ground plane in dipole mode which was orthogonal to folded monopole mode.

A microstrip antenna [111] loaded with left handed metamaterial and dipole to make it compact and broadband. The proposed antenna had array of unit cell of metamaterial that had negative refractive index and were placed in 2×3 array. Using stepped impedance transformer impedance of proposed antenna was matched. This was also matched by cutting a slot of rectangular shaped in ground plane. Due to the properties of coupled left handed resonance and phase compensation a broad-bandwidth of 63% was attained over the frequency band of 1.3 – 2.5 GHz.

Gain and bandwidth of rectangular microstrip antenna was enhanced using an array of metamaterial patches [135]. The feedline which was used to connect the metamaterial patches positioned off-centered. An array with shunt feeding [117-119] could also be used for achieving wide bandwidth but it had disadvantage of large dimensions. Efficiency of patch antenna could be improved using metamaterials. Bimal Garg et. al. had improved the efficiency of patch antenna by embedding meta material in it [26]. Using metamaterial a high efficiency monopole antenna with improved bandwidth was presented [134]. This antenna had efficiency of 90%.

Radiation pattern and gain of conformal patch antenna was improved using metamaterial [92]. Uniform flat lens used as a metamaterial was placed in front of the patch antenna. This antenna was designed at 3.5 GHz. Using metamaterial lens gain of antenna get improved by 75.38%, directivity by 53.56% and bandwidth by 0.71%. It also enhanced the power radiation and radiation of main lobe level. Results showed that antenna efficiency had improved by 11.86%.

Effect on performance of patch antenna by incorporating different metamaterial surface as ground plane was studied and compared [29]. Patch antenna was designed on Duroid substrate having relative dielectric constant of 2.2 and heights of substrate was 1.6 mm. Antenna was fed using microstrip line and resonate at the frequency of 2.4 GHz. When the antenna was backed with conventional ground plane its gain was 7.21 dBi. The proposed antenna was also backed by frequency selective surface, artificial magnetic surface and electromagnetic surface. Among these materials artificial magnetic material based patch antenna gave highest gain of 9.0 dBi.

Patch antenna was miniaturized using thin wire and split ring metamaterial [14]. These metamaterial were embedded under the patch antenna. Without these metamaterial antenna was made to resonate at 6 GHz with a gain of 6 dB and had impedance bandwidth of 700 MHz. Embedding of metamaterial enhanced the permeability of antenna substrate and thus it reduced the operating frequency. Resonant frequency of patch antenna reduced from 6 GHz to 1.84 GHz for same patch size. Gain of metamaterial embedded patch antenna was 6 dB with impedance bandwidth of 600 MHz. Simulated and measured results showed good agreement. The proposed antenna was miniaturized by approximately 65%. This antenna drawback of this antenna was its narrow frequency band.

To improve the performance of patch antenna a rectangular slot was cut in square patch antenna and in its ground plane a complementary split ring resonator (CSRR) metamaterial structure was etched [195]. This metamaterial structure reduced the resonant frequency of antenna and size was reduced by 13.5%. The combination of metamaterial structure and slot improved the performance of patch antenna. Gain of proposed antenna improved by 2 dB, return loss by 8 dB with size reduction.

Mutual coupling in microstrip patch array was suppressed using metamaterial superstrate. Between the closely packed elements of phased array superstrate of metamaterial was placed [225]. Modified structure of CSRR was printed on superstrate which reduced space and surface wave effect. Analysis of proposed scheme was carried out on both high and low permittivity substrate. Experimental results showed that 27 and 11 dB of coupling suppression were obtained using low and high permittivity substrate. The proposed design could be realized easily and compact. Design of multiband microstrip patch antenna was presented by etching complementary metamaterial structure in ground plane of patch antenna [141]. Simulation was performed using CST microwave studio. Results were presented for both complement metamaterial loaded and unloaded antenna. The proposed antenna made to resonate at frequency of 1.88 GHz, 2.02 GHz and 2.43 GHz. Resonant frequency of unloaded antenna was 2.4 GHz. Using proposed techniques antenna size was also reduced.

Effect of incorporation of epsilon near zero metamaterial on microstrip patch antenna was studied [10]. For realization of ENG metamaterial wire medium was used. Both simulated and measured results were obtained and results were in good agreement.

Using metamaterial surface, broadband, low profile and circularly polarized microstrip patch antenna was proposed [196]. Patch was of the truncated square shape and it was placed between the ground plane and periodic metal plates. This technique produced an extra resonance and minimum axial points. Thus impedance matching improved and axial ratio bandwidth enhanced. The proposed antenna was fabricated and tested. Measurement results showed that antenna worked in frequency band of 4.70 GHz – 4.78 GHz and had 23% of axial ratio bandwidth. The proposed antenna also had good LCP broadside radiation pattern. Radiation efficiency of antenna was more than 90% in operating range.

A conformal antenna operating in frequency range of 2.36 GHz-2.4 GHz was proposed for band of medical body area network [227]. A metamaterial surface consisted of two array of I shape elements and it was placed underneath the planar monopole antenna. The proposed antenna was compact and had impedance bandwidth of 5.5% gain of 6.2 dBi and 23 dB front to back ratio. The proposed antenna structure was very robust to structural deformation and superior to conventional patch antenna and planar monopole antennas.

Circular polarized antenna was designed to achieve 70% optical transparency [38]. It was achieved by using wire mesh patch. Antenna was fabricated using ceramic substrate. It reduced the cost and simplified the construction. Phase difference was added orthogonal modes of patch and which resulted dual band circular polarization radiation. The proposed antenna designed to operate at frequency of 2.35 GHz and 2.73 GHz with radiation efficiency of 70% and 78% respectively.

A novel patch antenna was designed for multiband applications using metamaterial [63]. Incorporation of metamaterials helped to obtain high gain and miniaturization of patch antenna. Square, star and hexagonal patches designed over CSRR loaded reactive impedance surface. Unit cell of this metamaterial was studied and its parameters obtained using CST were presented. Among the patch antennas studied in this work, star patch antenna array provided highest gain of 10.6 dBi. This antenna could be used for synthetic aperture radar system. Design of efficient dual band antenna using metamaterial was presented by Arycan et.al. [19].

Rectangular patch antenna was designed for RFID application [178].Using automatic identification (AUID) technology objects can be tracked and radio frequency identification (RFID) came under AUID system. Tag antenna and reader antenna these were two antennas in RFID system. Performance of designed rectangular patch antenna was enhanced using O shaped metamaterial. This metamaterial had positive permittivity and negative permeability. Bandwidth of the rectangular patch antenna increased manifolds by incorporation of metamaterial in reference antenna.

Chiral metamaterial provides an alternate route for negative refraction. Circular dichroism and optical activity are their two important properties beside the negative refraction. These metamaterial can be used for performance enhancement and design

of patch antenna. Many chiral metamaterial designs have been reported in literature, but their use in patch antenna is yet to be explored in microwave applications.

Chiral metamaterial composed of bilayer cross-wire strip was presented for polarization rotation [60]. This chiral metamaterial showed the asymmetric transmission of linearly polarized wave. Using transmission matrix, relation between the incident polarization and polarization rotation was presented. Asymmetric transmission of linear polarized wave was verified both using simulation and experimentation. This chiral metamaterial could be used to design the polarization control devices in microwave region.

Uniaxial Chiral metamaterial constructed using double layered four U shaped split ring resonators was presented for frequency range of 3.5 GHz-7.5 GHz [226]. Split ring resonators were mutually twisted by 90^0. This chiral metamaterial showed the circular dichroism and optical activity. Due to large chirality this metamaterial showed negative refraction for circular polarized wave. Thus refractive index for LCP or RCP was negative near resonance. This structure was planar and easy to fabricate. The proposed artificial structure could be used for microwave applications.

Flattened spiral segments metamaterial were presented for polarization rotation effect [151]. The presented multilayered helix structure could be easily fabricated. A transmission coefficient of this chiral metamaterial was studied and it was found that it rotated the direction of linear polarized wave. It was also found that this metamaterial offered different electromagnetic properties for LCP and RCP wave.

Chiral metamaterial created using two dimensional lattices of eight cranks was investigated [66]. The study showed that this chiral metamaterial had circular dichroism, negative refraction and had enormous electromagnetic activity. Transmission and reflection coefficient of this metamaterial was obtained using free wave experimental setup and numerical simulations. The values of effective permittivity, permeability and chirality parameters were calculated. The results obtained from simulation for this chiral metamaterial were also verified experimentally and results were found to be in good agreement.

Bilayer cross wire chiral metamaterial had giant circular dichroism and optical activity [94]. Geometry of this chiral metamaterial was very simple and could be easily fabricated. Numerical simulations showed that this chiral metamaterial had negative refractive index. For calculating the various performance parameters of

chiral metamaterial a retrieval procedure was also presented in this work. The presented chiral metamaterial could be used for optical and microwave applications.

Using the two layered periodic arc structured chiral metamaterial a dual circularly polarized horn antenna for Ku band was presented [216]. The complete antenna system worked as band pass filter and polarization transformer. In the frequency range of 12.4 GHz to 12.5 GHz antenna realized LCP wave and produced RCP wave in frequency range of 14.2 GHz to 14.4 GHz. Value of axial ratio was 0.95 dB at frequency of 14.35 GHz and 1.05 dB at 12.45 GHz. As compared to conventional horn antenna gain of the presented antenna system degraded only by 0.6 dB. The circular dichroism property of CM structure assisted the horn antenna to radiate right hand circular polarized wave at 14.35 GHz and left hand circular polarized wave at 12.45 GHz. This antenna could be used in satellite communication system and had simple structure.

Chiral metamaterials worked as polarizers and using them undesired polarized wave could be filtered it out. Using this concept a microstrip patch antenna with chiral metamaterial polarizer was presented [130]. In this work, a circular polarized microstrip patch antenna was firstly designed and after that chiral metamaterial cover was used to filter out the unwanted radiated wave of an antenna. Radiation pattern and axial ratio of resultant antenna designed using CM also improved.

A technique to enhance the performance of circularly polarized antennas was presented by using CM cover [50]. The antenna structure had a log-spiral radiator, a superstrate of chiral metamaterial and a reflector under the radiator. The proposed structure was analyzed by finite difference time domain method. Analysis showed the merits of proposed structure. Unit cell of CM had four S shaped elements on upper surface and four mirrored elements on bottom surface. But the performance of antenna needs further improvements.

Miniaturize structure of unit cells of chiral metamaterial was presented by Zarifi et.al. For miniaturization fractal geometry, meandered structure and wideband antenna design ideas were proposed. Using these techniques miniaturized chiral metamaterial structures showed the giant optical activity and negative refraction were presented [49]. The proposed structure could be used as ultra-thin microwave polarizer and could be scaled for other frequencies. They had planar structure and thus

very easy to fabricate. These structures could be used for improving the performance of CP antennas.

A dual band chiral metamaterial structure was presented [48]. Due to strong chirality of chiral metamaterial it showed giant optical activity and negative refractive index for left and right hand circular polarized wave. Using the design curves its frequency bands could be adjusted and it could also be generalized for multiband. At 5.1 GHz and 6.8 GHz rotation angle was 47^0 and 33.5^0 respectively. In this work, design of triple band chiral metamaterial structure was also presented. This CM structure could be used for microwave and optical applications.

Using metamaterial subwavelength antenna could also be deigned. Design and analysis of subwavelength resonant patch antenna was presented by Andrea Alu et. al. analysis showed that by loading the conventional radiators with double negative and/or single negative metamaterial they exhibited low resonant frequency but might not radiate efficiently for such small electrical size. If the proper mode was selected in some complex geometries then these radiator might radiate efficiently even for small electrical size. Taking into consideration material losses, dispersion and presence of antenna feed in numerical simulation a practical implementation was foreseeable. This analysis opened new venues for designing small size radiators with high performance. These small size radiators could be used in practical applications [13].

Beam steering low cost miniaturized patch antenna was presented for wireless communication [207]. This antenna used complementary split ring resonators loaded ground plane. The proposed ground structure allowed the wide band beam steering range. Effect on the radiation pattern of antenna was also analyzed by investigating the various parameters of CSRR metamaterial. Beam direction was affected by the refractive index of loaded part. The proposed CSRR loaded antenna was fabricated and results were verified experimentally. Experimental results showed that beam of proposed antenna scan from -51^0 to 48^0 by changing the parameters of metamaterial structure. The proposed antenna had simple structure, low cost and has low profile. This antenna was very valuable for wireless communication. Varactor diodes could be used in ground plane to obtain the tune-ability for beam steering.

Circular patch antenna size could be reduced significantly by loading it with μ negative metamaterial. Loading of circular patch substrate partially with inhomogeneous substrate excited a subwavelength resonant mode in circular cavity.

MNG metamaterial were assumed to be isotropic and continuous in theoretical analyses. Proper and careful loading of circular patch with MNG metamaterial made antenna compact. With current technology fabrication of isotropic MNG sample was difficult. It was shown that proposed antenna radiate desired subwavelength frequency even though the fabricated MNG metamaterial was not fully isotropic. For this design full wave numerical simulation was presented [58].

Loading of MNG metamaterial could reduce the size of circular patch antenna. Considering this idea numerical and theoretical analysis of subwavelength elliptical patch antenna loaded partially with magnetic material was presented [159]. A general theory presented for inhomogeneous loaded elliptical patch antenna gave a closed form solution for modes supported by proposed antenna. The size of resonator could be reduced to arbitrary small dimensions by loading the antenna with properly designed metamaterial. In subwavelength elliptical patch antenna two orthogonal modes were excited. The proposed antenna was found to be more flexible compared to circular geometry. Simulation results showed that the proposed elliptical geometry had great potential and could be used to design electrically small and low profile antenna.

Analysis of effect of metamaterial on a superstrate loaded cylindrical rectangular patch antenna was presented [184]. Between the substrate and superstrate a metamaterial layer was inserted. Electric surface current method was used for analysis. Radiation patterns were also presented in far field for different negative values of permittivity and permeability. Investigation of effect of air gap on performance of presented antenna was also done.

Metamaterials have become the focus of research during the recent years. A model for designing efficiently small antenna was reported [177]. The proposed antenna had good bandwidth characteristics. These characteristics were obtained by embedding using negative permeability metamaterial into the conventional antenna.

A compact patch antenna was designed by loading the antenna with new metamaterial [77]. The metamaterial consisted of spiral and three wires which were made of copper and these are printed on opposite side of substrate. At 3 GHz permeability of metamaterial element was negative. By incorporating the metamaterial in antenna system design its size reduced by 40%.

Impedance bandwidth and return loss of patch antenna were improved by using a metamaterial structure of array of rectangular rings with rectangular strips

[25]. This metamaterial was attained by using rectangular waveguide having perfect magnetic wall and perfect electric walls. For extraction of permittivity and permeability of above said metamaterial was obtained using Nicolson-Ross-Weir (NRW) method. The designed patch antenna was made to resonate at frequency of 1.47 GHz. Return loss of metamaterial loaded antenna reduced by 15.33 dB and impedance bandwidth improved by 22.3 MHz as compared to unloaded antenna.

An electrically small and very efficient antenna was designed using metamaterial structure [16-17]. The metamaterial structure was planar two dimensional and volumetric three dimensional. Numerically it was proved that proposed antenna had good radiation efficiency. Impedance matching between the source and the proposed antenna system was very good. Thus overall efficiencies of antenna system were very high.

Subwavelength patch antenna was designed using metamaterial which consisting of 8× 2 loop arrays of periodic resonant circuits [84]. Resonant circuits had inductance and a series capacitance to create artificial magnetic element. Periodic structure of these metamaterial elements behaved like a medium having negative value of permeability and permittivity in desired frequency band. Analysis was done using transmission line model. Patch antenna had six substrate layers of above resonant metamaterial. Experimentally it was found that wavelength of resultant antenna is 1/18 of the wavelength of standard patch antenna. Thus using LC loop arrays subwavelength antenna was designed.

Due to surface wave in patch antenna gain deteriorate. Metamaterial can be used for surface wave suppression. One such design was presented using magnetic metamaterial [22]. In antenna, between the ports on ground a strong transverse magnetic coupling exists which causes surface wave and it could be reduced using magnetic material. In this work, characterization of above said metamaterial was presented and it was proved that this metamaterial behaved as anisotropic plasma thus suppressing the surface wave.

To improve the gain and efficiency of patch antenna metamaterial superstrate could be used [67]. For design of superstrate BC-SRR (broadside coupled split ring resonators) were used. The antenna array obtained by arranging the four patch antennas in a row worked at frequency of 2.18 GHz as shown by simulations. The superstrate increased the gain of antenna array by approximately 3.5 dB without any

significant increase in size of proposed antenna system. It also showed the improvement in efficiency by 10%.

Metamaterial embedded patch antenna with polyester substrate designed for WLAN applications [87]. This proposed antenna was a wearable antenna and it made to resonate at a frequency of 5.10 GHz. Bending of antenna effects the performance of this wearable antenna, using slots in structure this effects could be reduced. But it caused impedance mismatch. To solve this problem, split ring resonators were embedded in the antenna system and the resultant antenna had good impedance matching at desired frequency. The reason for impedance matching by embedding SRR metamaterial was due to introduction of additional inductance, mutual inductance and capacitance by SRR.

I-shaped metamaterial was a left-handed material. Using this metamaterial design and investigation of patch antenna was presented [217]. I shaped metamaterial was designed such that its permittivity and permeability was negative at 6.24 GHz. The electromagnetic wave resonance was enhanced at this frequency and this causes the improvement in antenna gain and bandwidth. Return loss reduced due to metamaterial inclusion in reference patch antenna. Thus antenna with improved performance was obtained by embedding I shaped metamaterial in patch antenna. The proposed antenna could be used for mobile and satellite communication. For MIMO communication system [165] antenna array based on metamaterial substrate was presented.

Non resonant metamaterial could also be used to improve the bandwidth of patch antenna. Lei et.al. used non-resonant metamaterial structure to broaden the bandwidth of antenna [115]. To improve the bandwidth of antenna inhomogeneous substrate technique was very effective. Using natural occurring material it was difficult to design a inhomogeneous substrate, but by controlling the geometric parameters of unit cell of non-resonant metamaterial it could be easily realized. Permittivity and permeability of metamaterial was tailored in frequency range of interest to improve the bandwidth. Bandwidth of proposed antenna improved from 0.5% to 20.6% as compared to reference antenna. By combining the present technique with other bandwidth broadening techniques, bandwidth of antenna could be improved further.

2.5 DEVELOPMENT IN DESIGN OF RECONFIGURABLE ANTENNAS USING ACTIVE DEVICES

The multitude of different standards in cell phones and wireless communication miniaturized multi-band antennas and smart multifunctional antennas. Using pin diodes, varactor diodes, FET and transistors compact multifunctional antennas having reconfiguration properties can be designed. A lot of research has been done on designing of such type of antennas during the last few years.

Wideband and multiband reconfigurable antenna were proposed and studied [72]. Antenna system had two patch elements with C-slots and work from 5 GHz – 7 GHz in wideband mode. Slots on patch elements were employed to change the patch of surface current so that wide band and dual band modes could be excited in antennas. PIN diodes were used as switches and placed between the feed network and patch elements. Wide band mode was excited by switching ON both the microstrip patch element with the help of PIN diodes. In this mode impedance bandwidth of antenna system was found to be 33.52%. Dual band mode could be obtained by switching ON the either of the patch antenna element. By changing the dimension and position of C-shaped slots frequencies of proposed antenna system in dual band mode could be controlled. Frequency control of dual band mode did not affect the frequency and bandwidth wide band mode. Thus using the same dimensions in the proposed antenna system one wide band mode and two dual band operation could be excited which was major advantage of the antenna system. This had also overcome the need of large surface area needed by wideband patch antenna.

Rectangular ring slot antenna which was frequency reconfigurable fed by CPW line [99]. By switching the slot line lengths in proposed antenna reconfiguration was achieved. This antenna was designed to resonate at two frequencies. The outer layer of slot line determined the lower frequency band of operation and the inner layer of slot line govern the high frequency band. By adding more slot line this concept could be extended to multiple frequency bands. Antenna designed using this concept resonates at 3.0 GHz and 8.0 GHz with -17 dB and -22 dB reflection coefficient respectively.

Reconfigurable stacked patch antenna was designed using PIN diodes for terrestrial applications [206]. The proposed antenna worked at 2 GHz and 600 GHz and had 20.7% of impedance bandwidth. In one mode, proposed antenna made to resonate at 2 GHz and had circular polarization at 2 GHz with broadside radiation

pattern. In other mode, it resonated at 600 MHz and operated as PIFA with pattern directed toward azimuth. In this mode polarization of antenna was linear and could be used for terrestrial applications. Design of antenna consisted of two patches, the smaller patch was designed on thick substrate RO4003 with relative dielectric constant of 3.38 and larger microstrip patch was on air. Three diodes were used for switching. In one mode, smaller patchworks as driven patch and upper patch were electromagnetically coupled to it. The resultant antenna system provided bandwidth of 20.7%. In other mode, smaller patch was switched off and upper patch was switched on. Due to shorting pin connected to upper patch this antenna system worked as PIFA and resonated at 600 MHz.

Bandwidth enhancement and frequency agility could be obtained using reconfigurable antennas [132]. Varactor could be used for tuning of antenna for such applications. A slot antenna fed with microstrip line was tuned using varactor over a wide range. Length of slot in this antenna was 79.06 mm and width was 0.40 mm. At the end of feed line varactor diode was attached for tuning. By increasing the reverse voltage of varactor, this antenna could be tuned over the range of 40 MHz from 4.74 GHz to 4.78 GHz. In this range reflection coefficient is below -10 dB. Capacitance varies as the reverse voltage of varactor diode changes and this was equivalent to change in electrical length of antenna. This antenna could also be tuned over the frequency range of 180 MHz from 4.96 GHz to 4.87 GHz by varying DC voltage across the varactor diode from 0 V to 10 V.

Using shorted patch antenna good radiation efficiency could be obtained. Design of reconfigurable antenna was proposed using shorted patch and varactor diode. At the resonate frequency shorted patch was quarter wavelength long. If capacitor was attached at radiating edge its physical length could be changed and antenna had become reconfigurable. Using this concept reconfigurable shorted patch was designed at 800 MHz/900 MHz. This antenna was designed for GSM applications.

A reconfigurable aperture antenna with the array of metallic patches and connected by switches was proposed [110]. By changing the switch position antenna could be reconfigured to achieve different goals. Genetic algorithm was used to find the position of various switches for particular goal. Electrically small dielectric patches were supported by thin dielectric substrate. The antenna system had 120 patches and 208 switches. It worked in the frequency range of 0.85 GHz to 1.45 GHz. By

optimizing switch position this aperture antenna radiated a broadside and bidirectional radiation pattern in the frequency range of 0.85 GHz to 1.25 GHz. This antenna had wide bandwidth of 38%. It also had left right symmetry in radiation pattern in this mode. In other switch configuration the antenna worked in frequency range of 1 GHz to 1.1 GHz and it had unidirectional, end fire radiation pattern. Bandwidth was narrow in this case. In the second configuration antenna did not have left-right symmetry and radiation characteristics were different from previous mode. For switching of proposed antenna pin diodes were used.

A single turn square spiral patch antenna was reconfigured for frequency and pattern. Length of spiral was 80 mm and it was approximately one wavelength at desired resonant frequency [62]. Coaxial probe was used for feeding this antenna. It was placed at the edge of innermost end of spiral. There was gap of 1 mm between the first and last spiral section. This antenna operated at 3.7 GHz and had linear polarization. Two switchable configurations were possible in this antenna. In one configuration impedance bandwidth was same while the radiation pattern could be redirected using switches. In second configuration frequency changed, antenna operated at 3.7 GHz and 6 GHz with broadside radiation pattern.

Patch antenna with switchable slots (PASS) was proposed for dual band circular polarization, multiple frequency operation and circular polarization diversity [55-56]. A slot was cut in standard microstrip antenna. A switch was connected at the center of slot to control its position. Pin diodes was used as switch. When the switch was off, current on the patch had to go around the slot and the resultant patch of current was longer. Thus it made to resonate at low frequency. When the switch was on, current flow directly through the switch and resultant current path was shorter. Thus in this mode antenna resonated at higher frequency. Using this concept an antenna was designed on duroid substrate. The proposed antenna resonated at 4.82 when switch was on and at 4.38 GHz when switch was off.

For achieving dual band circular polarization concept of PASS could be used. Pair of tuning stubs could be used in probe fed patch antenna for achieving circular polarization. The designed antenna had axial ratio of 2.9 dB at resonant frequency of 4 GHz in one mode. In other mode it had axial ratio of 1.6 dB at frequency of 4.37 GHz.

PASS design could also be utilized for achieving circular polarization diversity. For this two orthogonal slots were cut in probe fed microstrip patch antenna. Using the

different positions of two switches LCP or RCP could be attained while using the same positon of feed along the diagonal line of microstrip patch. When diode 1 was on and diode 2 was off, RCP radiation pattern was obtained and when diode 1 was off and diode 2 was on LCP radiation pattern was obtained. At frequency of 4.64 best value of axial ratio was obtained with CP bandwidth of 3% for both LCP and RCP radiation pattern.

Reconfigurable microstrip parasitic array based on yagi-uda concept was presented [190]. This antenna consisted of three printed strips parallel to each other on dielectric substrate. Spacing between the strips was kept approximately quarter wavelength. At the resonant frequency length of central strip was one half of guide wavelength and a probe of 0.65 mm was used to feed it. Other two strips on the either side of center strip were parasitic elements. For achieving reconfiguration length of parasitic strips could be increased or decreased with respect to center element. This antenna worked in three modes. With respect to broadside direction antenna radiation pattern could be shifted between -35^0, 0^0 and $+ 35^0$.

Reconfigurable and tunable antenna could be designed using metamaterials [137]. Nageswara et. al. had proposed the reconfigurable antenna based on metamaterial surface [136]. Metamaterial surface was located above the patch antenna and rotated. It caused the change in relative permittivity and thus the resonant frequency of patch antenna changed. Metamaterial was of double negative type. The proposed antenna worked in frequency band of 5.2 GHz to 5.9 GHz. It covered the WLAN and ISM band of wireless system. This antenna was designed and analyzed using HFSS.

Mohammed et.al. presented a antenna having polarization reconfigurability [150]. This antenna consisted of metamaterial surface and a source antenna. Unit cell of metamaterial was truncated square patch and 16 such units of metamaterial were used on a substrate. Source antenna was a microstrip line fed slot antenna. Metamaterial surface converted the linear polarized wave of source antenna to circular polarized. Simulated results were verified by experimental results. The proposed antenna worked at a frequency of 2.4 GHz and could be used for WLAN applications.

2.5 CONCLUDING REMARKS

In this chapter, advantages and limitations of microstrip antennas are discussed. Issues related to narrow bandwidth, low gain, low radiation efficiency, large size of the radiating patch etc. have been addressed. For enhancement of bandwidth conventional

techniques such as parasitic patches, thick substrate with low dielectric constant, optimization of patch shape, capacitive loading etc. can be used. For reducing the size of patch antenna conventional techniques such as high dielectric constant material, shorting walls, slots or shorting pin can be used. Traditional techniques like addition of superstrate etc. can be used for enhancement of gain, but conventional techniques used for performance enhancement of patch antennas have their own limitations. There is a need of novel methods to design and enhance the performance of microstrip antennas. A literature survey on performance enhancement of patch antenna using novel techniques of metamaterial is presented. It is evident that there is an ample scope to enhance the performance of patch antenna using different metamaterials as proposed in literature. In this research work, cylindrical rods, double folded I shaped, C shape, split ring resonators and double H shaped metamaterial are investigated. Using these metamaterials performance of patch antenna is enhanced and reduction in size is attained. Design and investigation of patch antenna using chiral metamaterial is also presented. Design of multifunctional antenna using pin diodes and metamaterial is also demonstrated.

CHAPTER 3

DESIGN OF SUB-WAVELENGTH, DIRECTIVE & MULTIBAND RMPA USING CYLINDRICAL RODS

In modern wireless system need for compact, broadband, multiband and directive patch antenna has increased dramatically. In this chapter, cylindrical rods which are artificial dielectric are used to miniaturize and improve the performance of patch antenna.

3.1. INTRODUCTION

During the last few decades, the demand for compact, directive, low cost, light weight and efficient antenna has grown. Microstrip patch antenna due to their inherent capabilities of light weight, low profile, cost and easy to fabricate provides the solution to the same. Although, these antennas are very thin as compared to operating wavelength in their cross-section, still, their transverse dimension cannot be made arbitrarily short as linear dimensions should be of order of the half wavelength for antenna to resonate [23]. Therefore to achieve further miniaturization of these antenna high dielectric constant material [23] [7], shorting walls [5] or shorting pin [175] can be used, as reported in literature. But these techniques have the problem of impedance matching and cross polarization.

Recently, there has been growing interest to design patch antenna using artificial material for simultaneously achieving miniaturization and performance enhancement. According to Collin [170] “An artificial material is special class of metamaterial obtained by arranging a large number of conducting obstacles in a regular three dimensional pattern”. Dielectric constant of cylindrical rods artificial material is negative so it is a single negative (SNG) metamaterial. Applications of single negative (SNG) metamaterials have been studied in miniaturization of sub-wavelength cavities [144], waveguide [1] and antennas [13] [2] [54]. The bandwidth enhancement and weight reduction using cylindrical pin structure has been attempted by for Global Navigation Satellite System (GNSS) antenna application in [41].

Though, these researchers provided the solution for compactness but none has provided an in depth study about the rodded medium artificial dielectric and how the parameters of rods affect the resonant frequency and performance parameters of the patch antenna.

In this chapter, a design of patch antenna using cylindrical rods is presented and analyzed. A general procedure for designing a subwavelength, compact antenna is also presented in this chapter.

3.2. THEORY OF RODDED MEDIUM

Rodded medium behaves like isotropic plasma [100] when the rods form a cubical lattice structure provided that the lattice constant of the structure and diameter of rods are small as compared to operating wavelength. As the wavelength approaches the spacing between the rods diffraction effect becomes dominant and rodded medium no longer behaves like an artificial material. Rodded medium also exhibits the property of anisotropic plasma when rods are placed in one or two direction and characterized by permittivity tensor as given below:

$$\varepsilon = \varepsilon_o \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \tag{3.1}$$

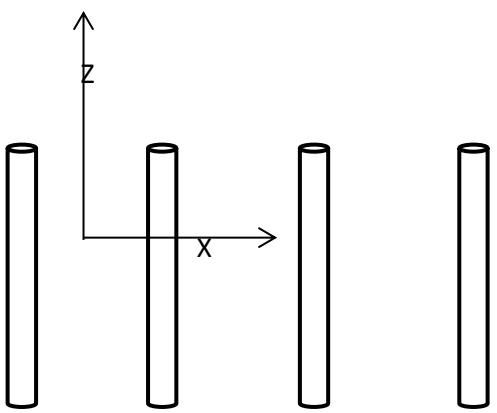


Fig. 3.1: Cylindrical Rods Placed along z axis

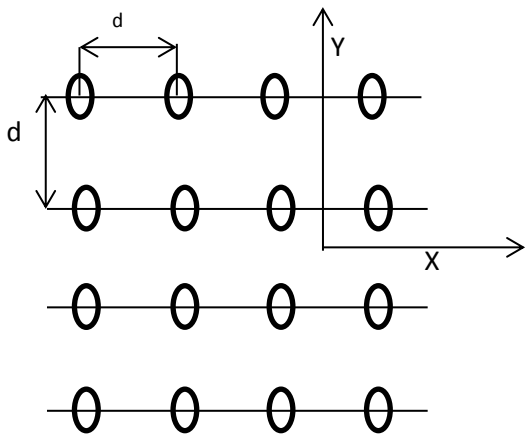


Fig. 3.2: Equivalent Grating Structure or view in x-y plane

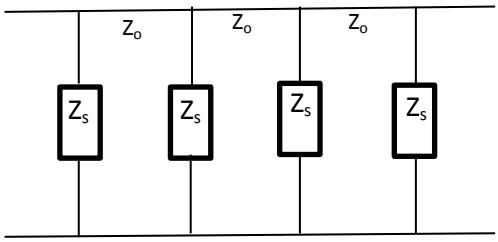


Fig. 3.3: Equivalent transmission line structure

If the rods are placed along the z direction as shown in Fig. 3.1 and Fig. 3.2 and electric field is also applied in z direction i.e. parallel to the axis of rods, then rods can be represented by inductance (L). Thus impedance Zs = jωL shunted across the transmission line having characteristic impedance Z_o as shown in Fig 3.3. Using the transmission line model, dielectric constant ε_z can be calculated as

$$\varepsilon_z = 1 - \frac{{\lambda_o}^2}{2\pi d^2 \ln\left(\frac{d}{r}\right)} = 1 - \frac{{\lambda_o}^2}{{\lambda_p}^2} \tag{3.2}$$

$${\lambda_p}^2 = 2\pi d^2 \, ln\left(\frac{d}{r}\right) \tag{3.3}$$

$${\omega_p}^2 = \frac{2\pi c^2}{d^2 \ln\left(\frac{d}{r}\right)} \tag{3.4}$$

λ_0 is the free space wavelength, λ_p of rodded medium is analogue to cut-off wavelength in plasma, d is the distance between the rods, r is the radius of rods, c is velocity of light and ω_p is the plasma frequency of the rodded medium.

Now if the electric field is applied perpendicular to the axis of the rods i.e in x direction. Then rods in Fig. 3.3 can be represented by capacitor (Zs = 1//jωC) shunted across the transmission line having characteristic impedance Z_o . Using transmission line model dielectric constant in x direction can be calculated and it is given as $\varepsilon_x = 1$ and similarly $\varepsilon_y = 1$. So the resulting dielectric tensor for the artificial dielectric with rods in z direction is

$$\varepsilon = \varepsilon_o \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 - \frac{{\lambda_o}^2}{{\lambda_p}^2} \end{bmatrix} \tag{3.5}$$

If the rods are also applied in x and y direction then dielectric constant is given as

$$\varepsilon = \varepsilon_o \begin{bmatrix} 1 - \frac{{\lambda_o}^2}{{\lambda_p}^2} & 0 & 0 \\ 0 & 1 - \frac{{\lambda_o}^2}{{\lambda_p}^2} & 0 \\ 0 & 0 & 1 - \frac{{\lambda_o}^2}{{\lambda_p}^2} \end{bmatrix} \tag{3.6}$$

Since all the diagonal terms are equal, the medium is isotropic and dielectric constant is given as

$$\varepsilon = \varepsilon_o \left(1 - \frac{{\lambda_o}^2}{{\lambda_p}^2}\right) \tag{3.7}$$

$$\varepsilon = \varepsilon_o \left(1 - \frac{{\omega_p}^2}{{\omega_o}^2}\right) \tag{3.8}$$

Using the equation (3.7) & (3.8) dielectric constant of rodded medium can be calculated for different values of d and r.

3.3. DESIGN OF REFERENCE ANTENNA

Rectangular patch antenna is taken as reference antenna. Microstrip line inset fed reference patch is designed using the FR_4 substrate. The substrate has following parameters:

- Dielectric constant ε_r= 4.4
- Loss tangent δ= .0025
- Height h=1.6mm.

Reference antenna is designed at resonant frequency of 5.2 GHz using equation (3.9-3.11). Length of the patch antenna is calculated as

$$l = \frac{c}{2\, f_o \sqrt{\varepsilon_{reff}}} \tag{3.9}$$

Where l is the length of the rectangular shaped patch, f_o is resonant frequency, c is velocity of light, ε_r is the relative permittivity of the substrate and ε_{reff} is effective dielectric constant of substrate which is calculated using (3.10) .

$$\varepsilon_{reff} = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2}\left(1+\frac{12h}{W}\right)^{-1/2} \tag{3.10}$$

W is the width of patch antenna and is calculated using equation (3.11)

$$W = \frac{c}{2\, f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{3.11}$$

The designed reference rectangular patch antenna is simulated and optimized using HFSS as shown in Fig 3.4.

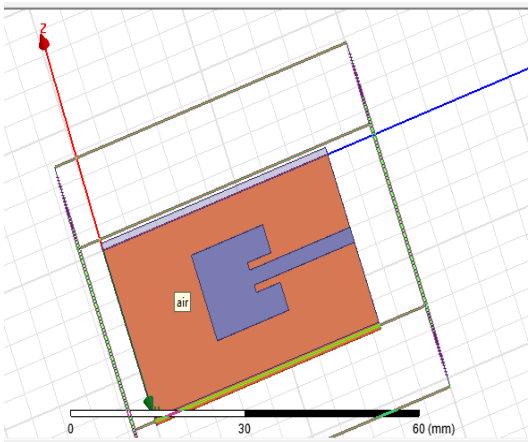


Fig.3.4: Reference RMPA Antenna with Inset Microstrip Feed

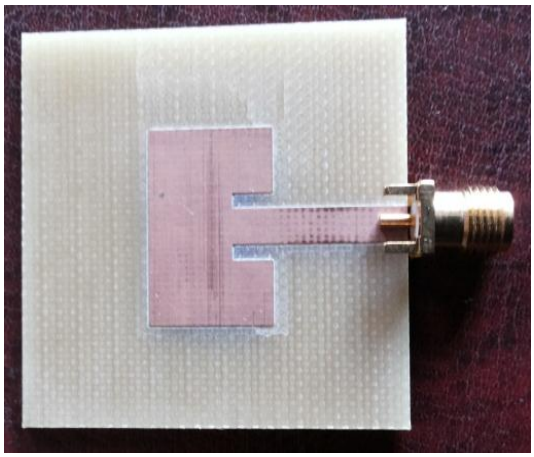


Fig. 3.5: Top view of Fabricated Reference Antenna

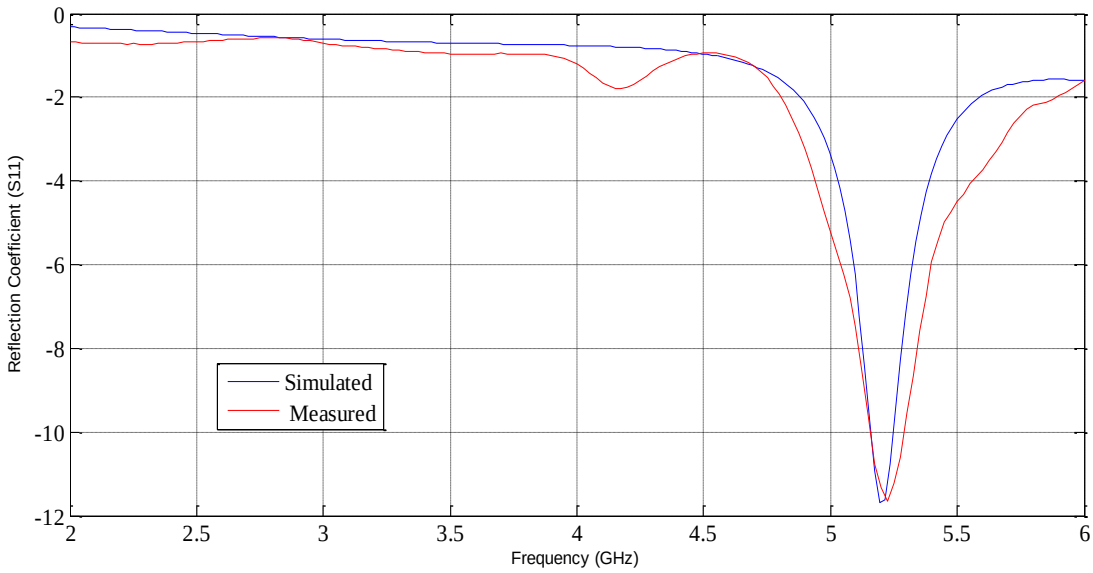


Fig .3.6: Simulated and Measured Reflection Coefficient (S11) of Reference Antenna

The length and width of patch antenna is 17.6 mm × 13.2mm respectively. The ground size dimensions are 41.59 mm × 35.9 mm and antenna is fed with inset microstrip line. Top view of fabricated reference antenna is shown in Fig 3.5.

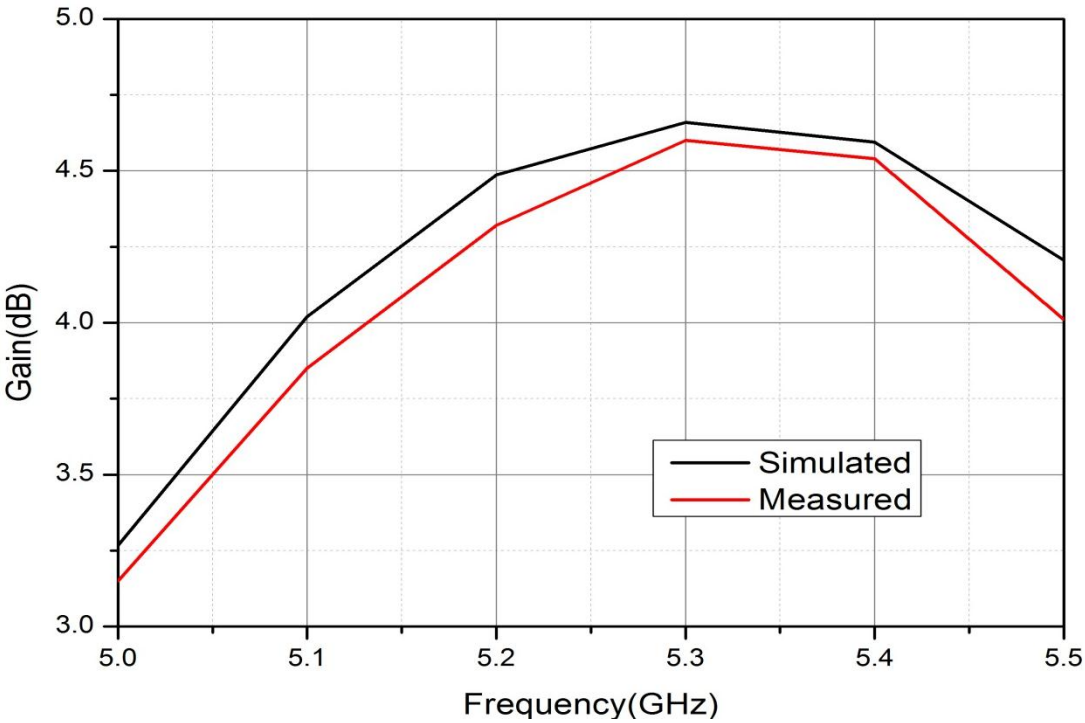
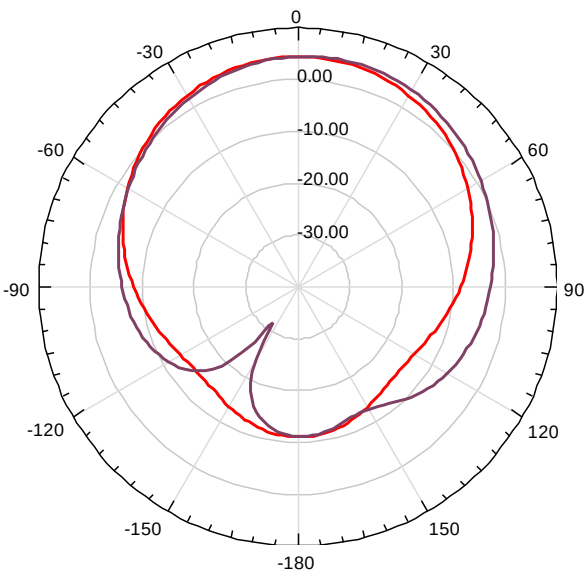


Fig. 3.7: Simulated and Measured Gain of Reference Antenna

Fig. 3.6 shows the simulated and measured reflection coefficient of reference antenna. Reference antenna resonates at frequency of 5.2 GHz with 11.68dB return loss and has 70 MHz bandwidth.



Curve Info	max	xdb10Beamwidth(3)
dB(GainTotal) Setup1 : LastAdaptive Freq='5.2GHz' Phi='0deg'	4.4888	78.6385
dB(GainTotal) Setup1 : LastAdaptive Freq='5.2GHz' Phi='90deg'	4.6354	85.6900

Fig.3.8: Radiation Pattern of Reference Antenna

Gain of antenna at resonating frequency is 4.48 dB as shown in Fig 3.7. The 3 dB beamwidth of reference antenna is 78.63^0 and 85.69^0 at $\varphi=0^0$ and $\varphi=90^0$ respectively as shown radiation pattern graph in Fig. 3.8.

3.4. DESIGN OF RODDED MEDIUM

Rodded medium is designed in frequency range of reference antenna. Dielectric constant of rodded is calculated using the Matlab program using equation (3.7- 3.8) and plotted.

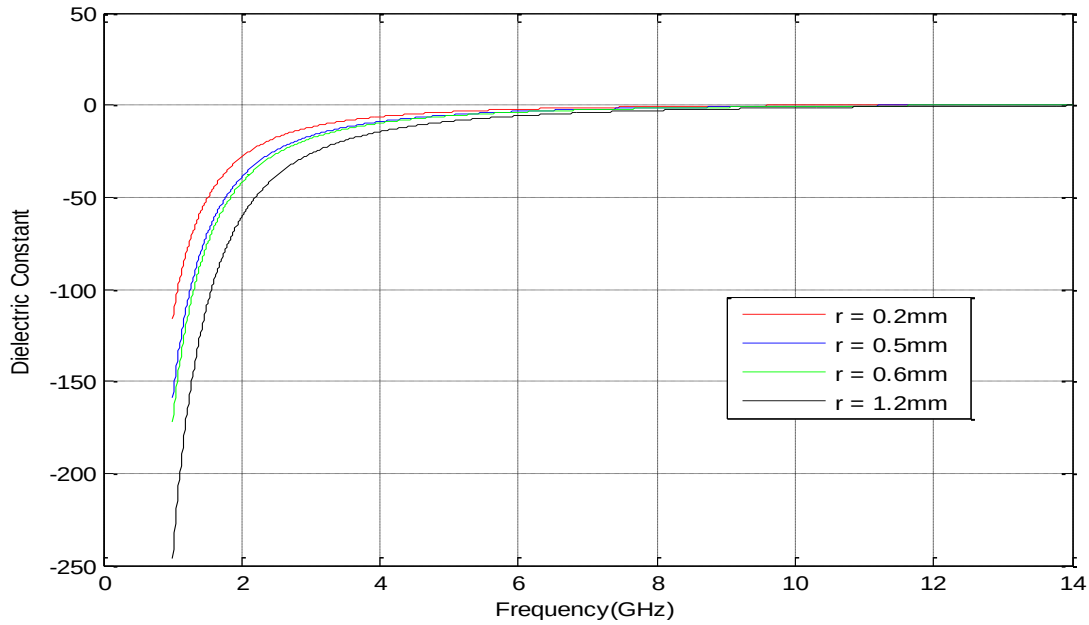


Fig. 3.9: Dielectric constant of Rodded Medium having Spacing d=6mm and Variable Radius

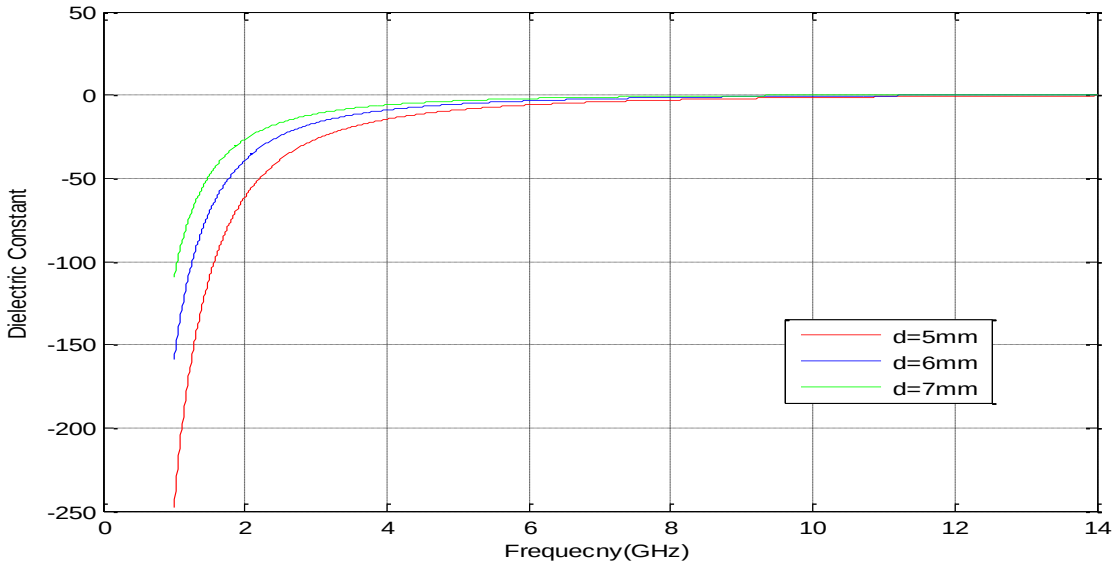


Fig. 3.10: Dielectric Constant of Rodded Medium with r =0.5 mm and Variable d

Fig 3.9 and Fig. 3.10 shows the dielectric constant of rodded medium for different values of radius and spacing between the rods. From Fig.3.9 and 3.10, it is clear that rodded medium has negative value of ε_r in desired frequency range (5.2 GHz), so it behaves like artificial dielectric in this range.

In Fig. 3.9 distance d between the rods is kept constant (d=6 mm) and radius is changed. As the radius of rods increases value of dielectric constant becomes more and more negative for a particular frequency. Similarly, when the radius r is kept constant (r =0.5 mm) and the distance between the rods is varied, value of dielectric constant becomes more and more negative at a particular frequency as shown in Fig. 3.10.

3.5. DESIGN OF COMPACT RMPA USING RODDED MEDIUM

For designing compact antenna, designed rodded medium is embedded in substrate of reference antenna beneath the radiating patch as shown in Fig. 3.11. By embedding the rods in substrate of patch antenna its dielectric constant gets changed and hence the resonant frequency of antenna is changed depending upon the parameters of rods.

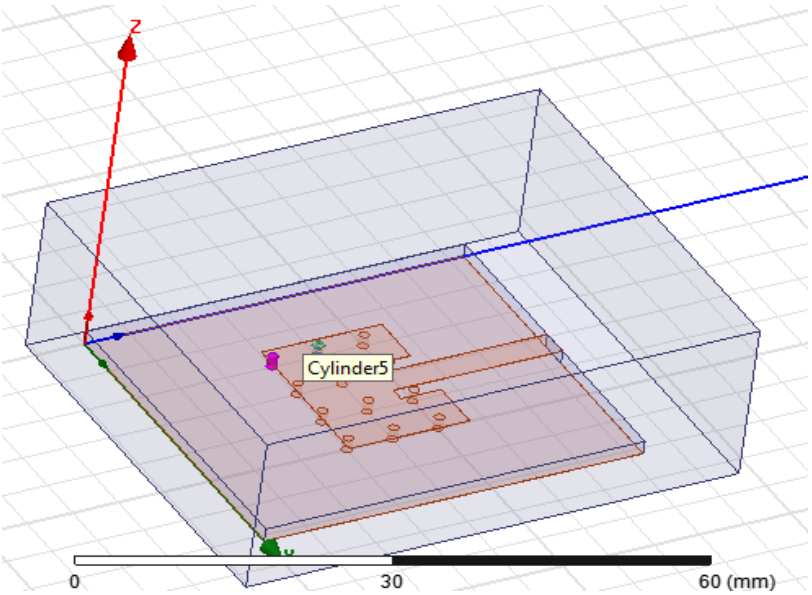


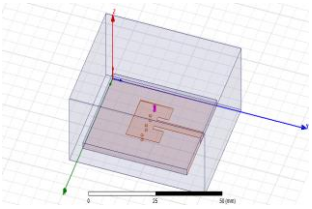
Fig. 3.11: Cylindrical Rods Embedded RMPA

Effect of height, radius of rods, addition of different layers and spacing between the rods on the resonant frequency and other performance parameters of RMPA is studied and analysed.

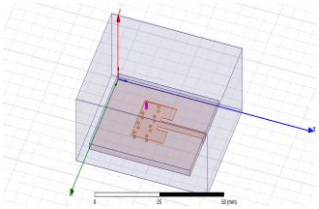
Parametric Study:

- **Effect of Addition of Different Layers of Rods in Substrate of RMPA on Antenna Performance**

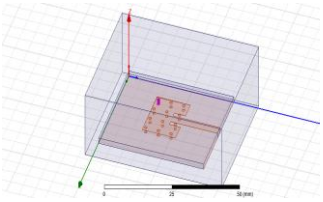
Addition of different layers of rods in substrate also affects its resonant frequency. Different cases of addition of rods layers in substrate of RMPA are shown in Fig. 3.12. As observed from Fig. 3.13, rods affect the antenna performance and resonant frequency utmost when they are applied only beneath the patch while embedding it all over the substrate does not further changes its performance.



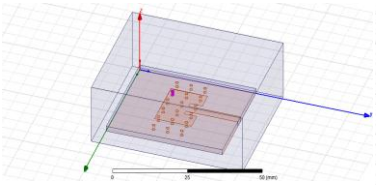
Case1: Addition of one row of rods in substrate of RMPA



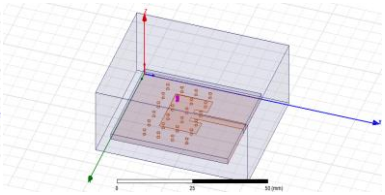
Case 2 : Addition of two rows of rods in substrate of RMPA



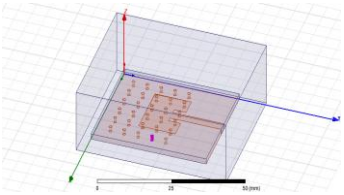
Case 3: Addition of three rows of rods in substrate of RMPA



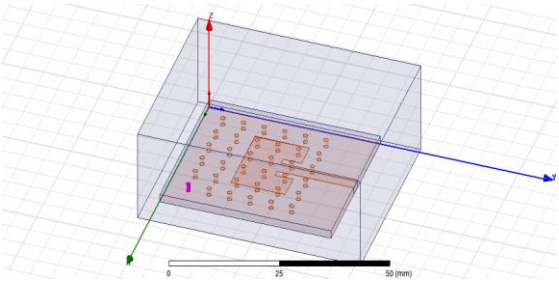
Case 4: Addition of three rows and two columns (outside the patch) of rods in substrate of RMPA



Case 5: Addition of four rows and two columns (outside the patch) rods in substrate of RMPA



Case 6: Addition of five rows and two columns (outside the patch) rods in substrate of RMPA



Case 7: Addition of six rows and two columns (outside the patch) rods in substrate of RMPA

Fig: 3.12: Addition of Different Number of Layers of Cylindrical Rods in RMPA

- **Effect of Height of Rods on Antenna Performance**

As height of the rods is increased resonant frequency shift to the lower side and antenna becomes more and more compact as shown in Fig 3.14. But the gain and radiation efficiency reduces as height of the rods is increased due to increase in conductive loss with height.

- **Effect of Radius of Rods on Antenna Performance**

Resonant frequency of antenna reduces as radius of rods is increased as shown in Fig 3.15. So by increasing the radius compactness of antenna can be increased. Gain and radiation efficiency reduces as radius of the rods is increased because rods are made of copper and losses increases with increased radius.

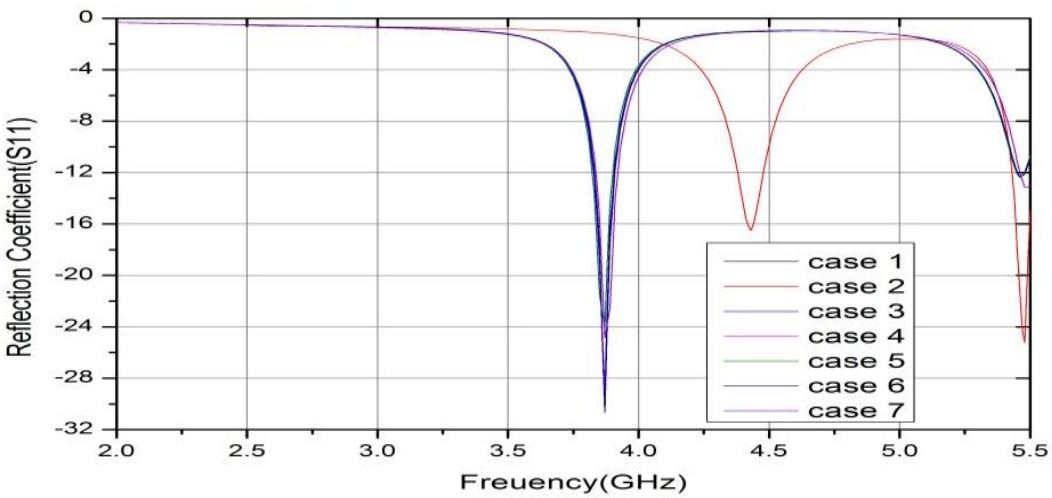


Fig. 3.13: Simulated Reflection Cofficient of RMPA with Different Layers Rods in Substrate

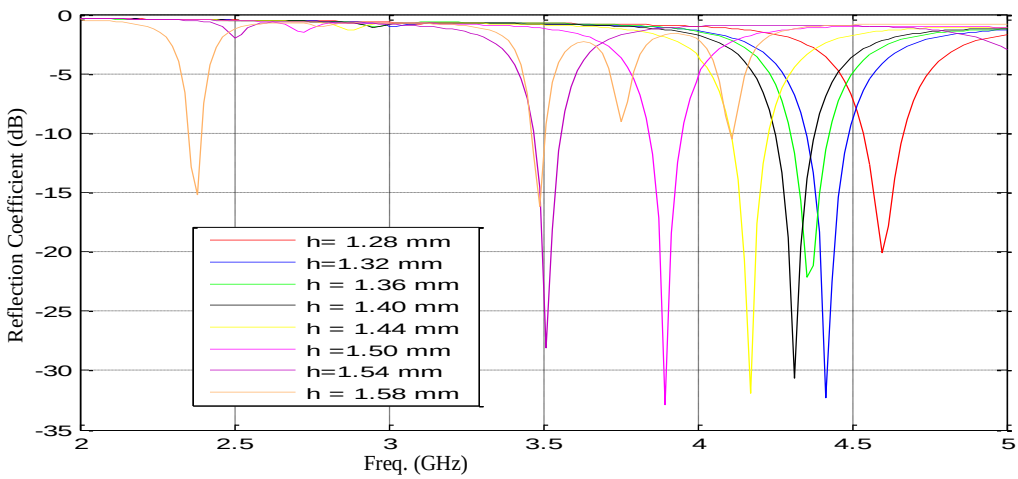


Fig.3.14: Reflection Coefficient of Cylindrical Rods Embedded Antenna with h vary (d=6 mm, r=.5 mm)

- **Effect of Spacing Between The Rods on Antenna Performance**

Resonant frequency depends on the spacing between the rods. Fig. 3.16 shows the variation in resonant frequency of rodded medium loaded antenna when the distance between the rods is 5mm, 6mm and 7mm. Antenna becomes more compact as distance between rods is decreased

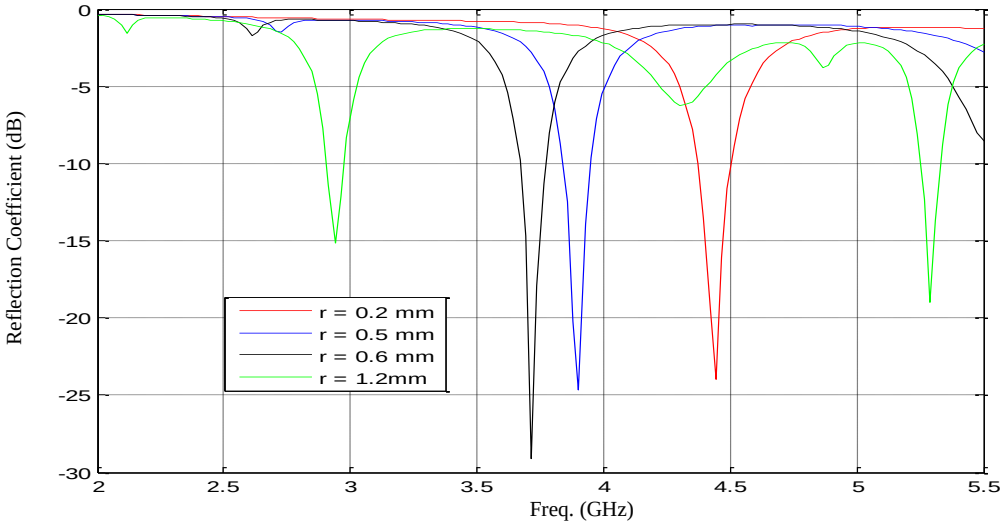


Fig. 3.15: Reflection Coefficient of Cylindrical Rods Embedded Antenna with r vary (d=6 mm, h= 1.5 mm)

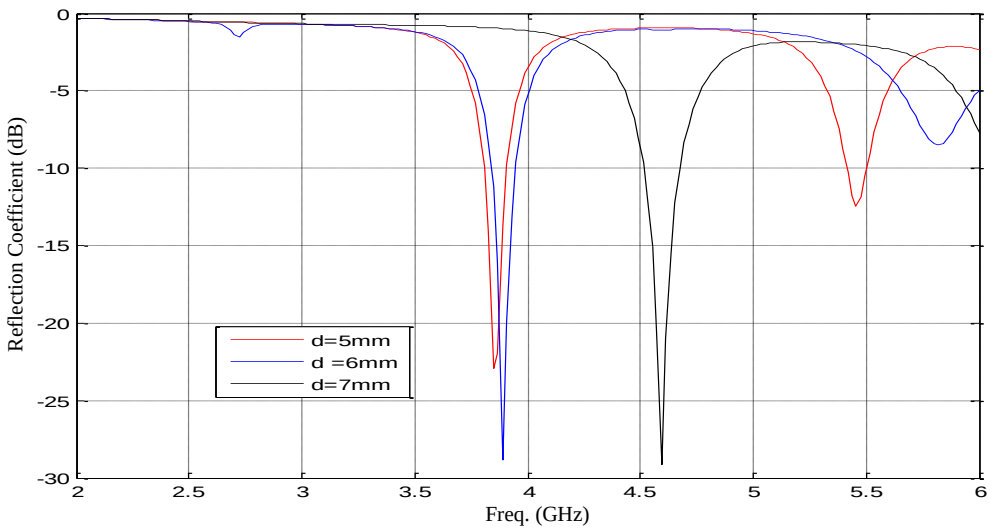


Fig. 3.16: Reflection Coefficient of Cylindrical Rods Embedded Antenna with d vary (r= .5 mm, h= 1.5 mm)

Gain and radiation efficiency also depends on distance between rods, so distance between rods should be chosen according to desired gain and radiation efficiency.

Rods radius (mm)	Rods height (mm)	Distance b/w rods (mm)	Resonant freq. (GHz)	Gain (dB)	Reflection coefficient (dB)	Bandwidth (MHz)	Efficiency (%)	Reduction in size%
.5	1.28	6	4.59	3.42	-20.073	150	51.90	22.6
.5	1.32	6	4.4	3.02	-31.85	120	50.38	29.04
.5	1.36	6	4.34	2.86	-21.95	130	50.35	31.05
.5	1.40	6	4.31	1.96	-30.63	140	50.2	32.03
.5	1.44	6	4.17	1.81	-31.76	120	48.67	36.47
.5	**1.50**	**6**	**3.88**	**1.5**	**-32.83**	**120**	**44.78**	**47.2**
.5	1.54	6	3.5	1.16	-27.85	100	40.23	55.56
.5	1.58	6	2.37	0.43	-14.77	60	29.96	79.83
Rods radius	**RODS height**	**Distance b/w rods**	**Resonant frequency**	**Gain**	**Reflection Coefficient**	**bandwidth**	**efficiency**	**Reduction in size%**
0.2	1.5	6	4.56	2.29	-17.93	130	53.7	23.7
0.5	1.5	6	3.88	1.5	-32.83	120	44.78	47.2
0.6	1.5	6	3.38	1.25	-18.19	90	30.18	58.71
1.2	1.5	6	2.95	0.05	-13.73	70	5	68.59
Rods radius	**Rod height**	**distance**	**Resonant frequency**	**Gain**	**Reflection Coefficient**	**bandwidth**	**efficiency**	**Reduction in size%**
0.5	1.5	7	4.58	0.5	-28.86	160	18	22.9
0.5	1.5	6	3.88	1.5	-32.83	120	44.78	47.2
0.5	1.5	5	3.84	1.4	-22.88	110	42.18	46.32

Table 1: Antenna Performance Parameter as the Height, Radius and Spacing between the Rods is Varied

Table 3.1 shows the antenna performance parameter as the height, radius and spacing between the rods is varied. As observed from Table 3.1, the best results are obtained when radius r=0.5mm, distance between rods d=6mm and height of rods is 1.5 mm.

At the optimized parameters (d=6mm, r=.5mm and h=1.5mm) antenna resonates at 3.88 GHz with reflection coefficient -32.83dB and have the impedance bandwidth of 120MHz as shown in Fig 3.17.

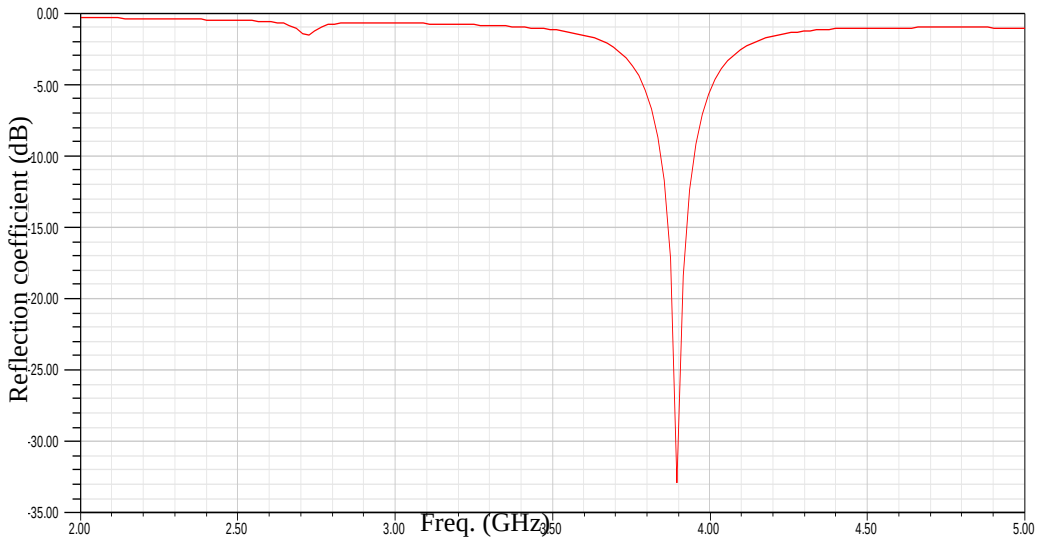


Fig. 3.17: Reflection Coefficient of Cylindrical Rods embedded antenna (d=6mm, r=.5mm and h=1.5mm)

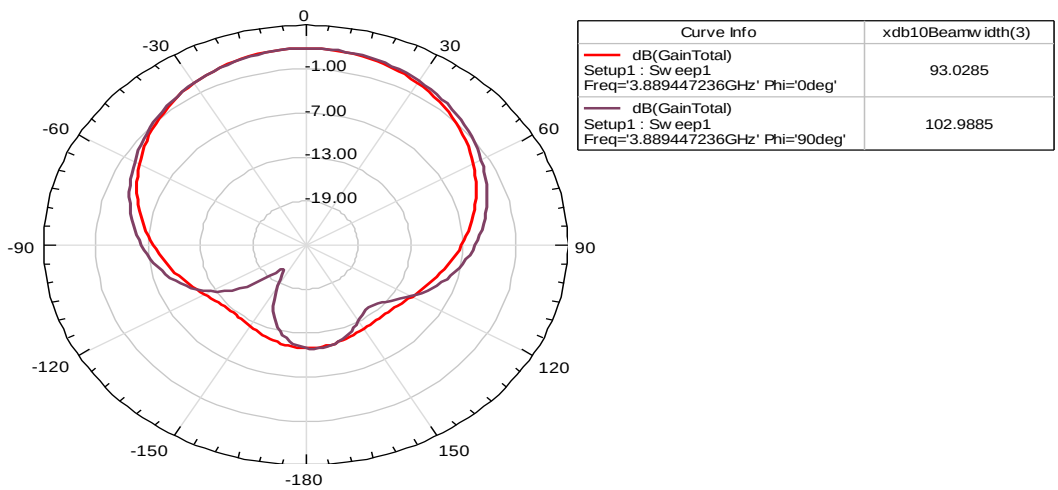


Fig. 3.18: Simulated Radiation Pattern of Antenna at 3.88 GHz

Fig. 3.18 shows the simulated radiation pattern of antenna. From radiation pattern graph it can be seen that 3dB bandwidth of antenna is 93.02^0 and 102.98^0 at $\varphi=0^0$ and $\varphi=90^0$ respectively.

3.6. MATHEMATICAL ANALYSIS

Theoretically, resonant frequency of rectangular patch antenna with the inhomogeneous substrate, filled with two isotropic and homogenous materials with permittivity and permeability ε_1, μ_1 and $\varepsilon 2$, μ_2 can be evaluated by applying standard cavity model. ε_1, μ_1 is permittivity and permeability of DPS and ε_2, μ_2 is permittivity and permeability of rodded medium. When the substrate is embedded with rodded medium, TM_{0mo} modes are introduced in the rectangular cavity and resonant frequency of these modes can be obtained by applying all the boundary conditions and solution of the following dispersive equation.

$$\sqrt{\frac{\varepsilon 1}{\mu 1}}\tan(k_1 \eta W) = -\sqrt{\left|\frac{\varepsilon 2}{\mu 2}\right|}\tan(k_2(1-\eta)W) \tag{3.12}$$

$$k_1 = \omega\sqrt{\varepsilon 1 \mu 1} \tag{3.13}$$

$$k_2 = \omega\sqrt{|\varepsilon 2||\mu 2|} \tag{3.14}$$

η is filling ratio of DPS. If in equation ω and η are so chosen that small argument approximation can be applied for tangent components, the above equation can be simplified as

$$\frac{\eta}{(1-\eta)} \cong -\frac{\varepsilon 2}{\varepsilon 1} \tag{3.15}$$

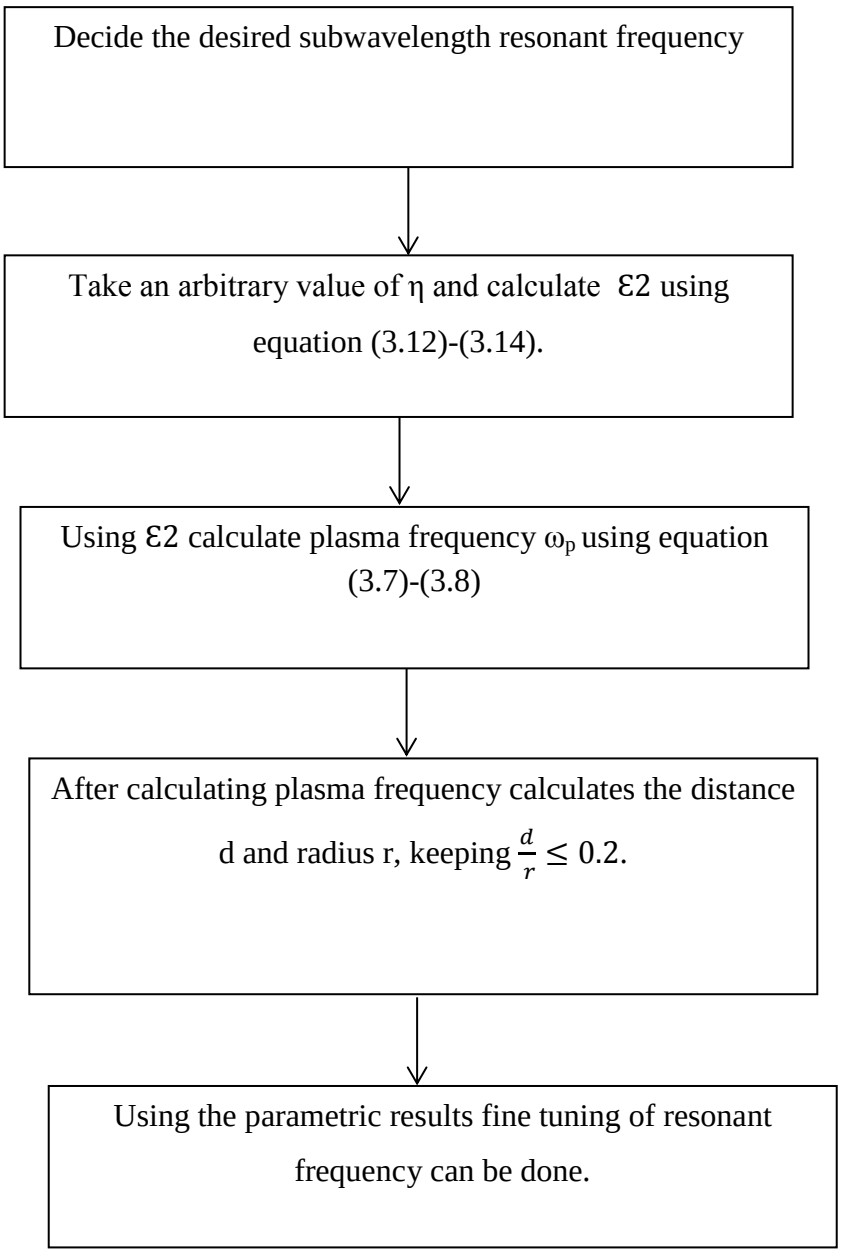
This characteristic relationship implies that at certain frequency there is no need to choose the size of rectangular patch constrained at resonance by length and width. Instead if the sign of two permittivity are oppositely signed and above equation is satisfied a sub wavelength patch antenna can be designed. Hence using ENG material such as rodded medium sub wavelength antenna can be designed.

The optimized cylindrical rods embedded RMPA simulated using HFSS software resonates at 3.88 GHz. In this optimized structure filling ratio of DPS material $\eta = 0.7$ and theoretical calculated value using the equations (3.12)-(3.14) is 3.82 GHz which is good approximation with simulated value. The antenna designed above using rods embedded substrate is 47.2% compact, and its return loss improves from -11.68 dB to -32.83 dB and impedance bandwidth increases from 70 MHz to 120 MHz as compared to reference antenna, but the drawback of this designed antenna is that its gain reduces from 4.38 dB to 1.5 dB.

This problem can be solved by using cylindrical rods embedded superstrate as discussed in next section. Here a general procedure for designing an antenna at desired sub wavelength frequency using rodded substrate is given.

3.7. GENERAL PROCEDURE TO DESIGN A SUBWAVELENGTH ANTENNA USING RODDED MEDIUM

By using cylindrical rods embedded substrate TM_{0m0} modes are introduced in rectangular patch antenna, if 0<m<1 it results in compact patch antenna. To design a rectangular patch antenna at desired sub wavelength frequency following steps should be carried out.



3.8. DESIGN OF PROPOSED SUBWAVELENGTH AND DIRECTIVE ANTENNA

To overcome the problem of reduced gain in above designed antenna cylindrical rods embedded superstrate can be used. By using this superstrate directivity, gain, radiation efficiency of antenna will improve and 3 dB beam width will reduce. The reason for improved performance is discussed below. Effective permittivity of rodded medium is given as

$$\varepsilon_{eff} = \left(1 - \frac{{\omega_p}^2}{{\omega_o}^2}\right) \tag{3.16}$$

When the frequency is below the plasma frequency effective permittivity is negative. At plasma frequency ε_{eff} is zero and the index of refraction ($n = \sqrt{\mu_r \epsilon_r}$) is zero. The effective permittivity of rodded medium just above the plasma frequency is positive, but still less than one & close to zero and corresponding index of refraction will be less than one and close to zero. Therefore when the operating frequency is close to the plasma frequency any incident rays exiting from inside the rodded medium superstrate to free space will be normal to surface and the directivity of antenna will improve.

To improve the directivity of the above designed antenna, rodded medium is designed such that its plasma frequency is equal to the resonance frequency of compact antenna i.e. 3.88 GHz.

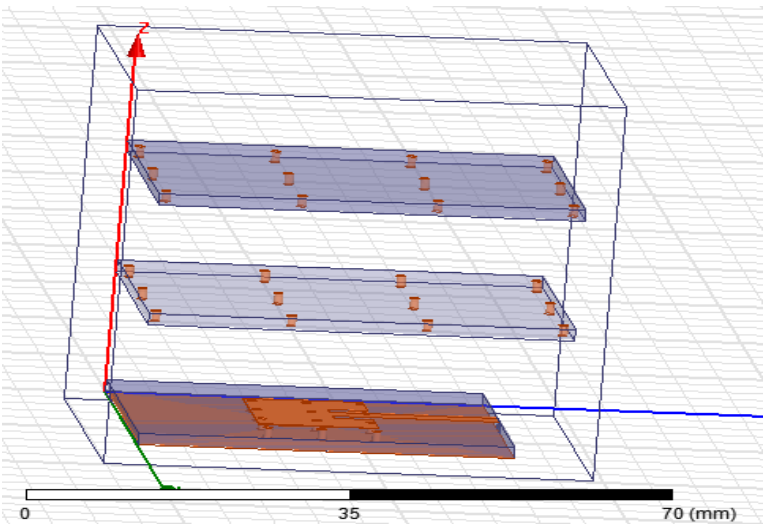


Fig. 3.19: Cylindrical Rods Embedded RMPA with Rods Embedded Superstrate

From the equation (3.1)-(3.2) distance d and radius of rods is calculated by putting $\omega_p = 3.88\ GHz$. The calculated value of distance between the rods d= 14.43mm and radius of rods r=0.15mm. After calculating the d and r, the proposed antenna is modelled and simulated in HFSS using two cylindrical rods embedded superstrate as shown in Fig. 3.19 and results of this proposed antenna is shown in Fig.3.20-3.22. By applying superstrate over the compact antenna there is small shift in resonant frequency from 3.88 GHz to 4.01 GHz as shown in Fig. 3.20. Gain of the antenna increases from 1.5 dB to 5.27 dB as shown in Fig 3.21.

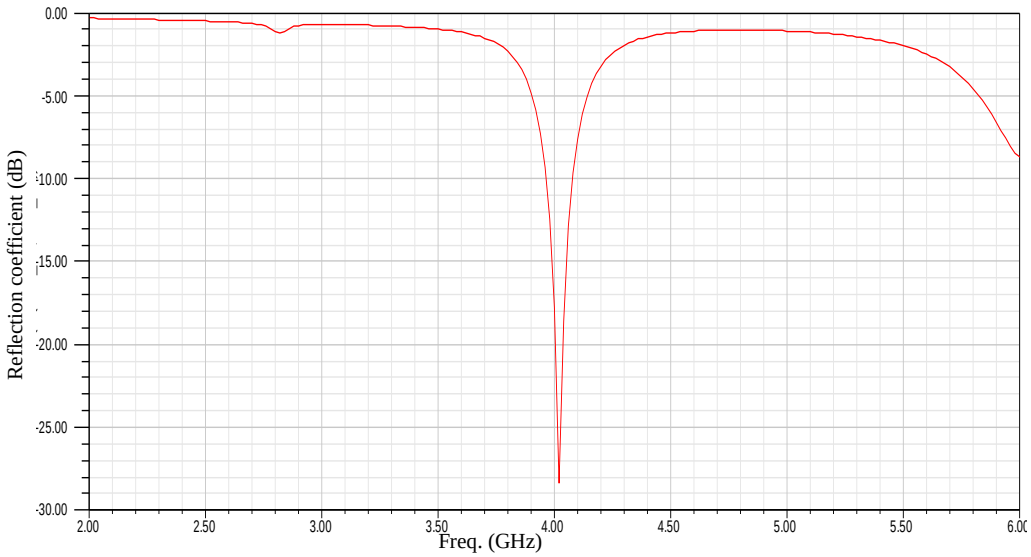


Fig. 3.20: Reflection Coefficient of Cylindrical Rods Embedded RMPA with Rods Embedded Superstrate

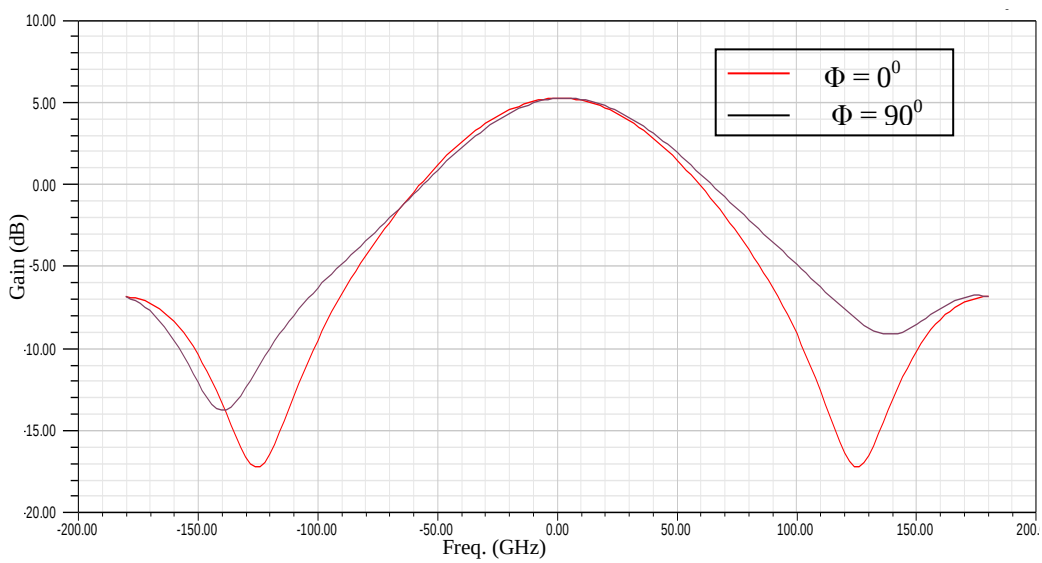


Fig.3.21: Gain of cylindrical rods embedded RMPA with rods embedded superstrate

In radiation pattern graph of antenna at 4.01 GHz is shown in Fig. 3.22. From radiation pattern graph it can be seen that the 3 dB beamwidth of proposed antenna is 78.01^0 and 80.67^0 at $\varphi=0^0$ and $\varphi=90^0$ respectively.

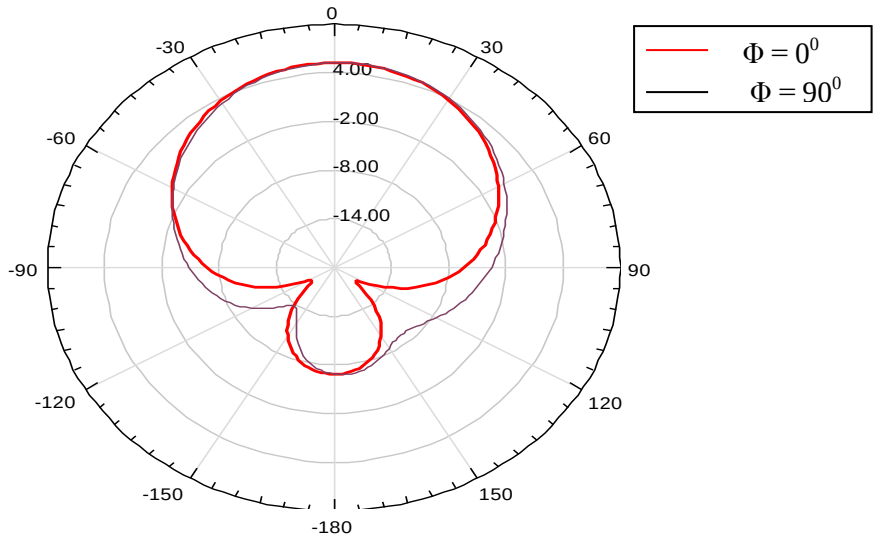


Fig. 3.22: Radiation Pattern of Cylindrical Rods Embedded RMPA with Rods Embedded Superstrate

Table 3.2 shows the comparison of performance parameters of reference patch antenna, RMPA with rodded substrate and RMPA with rodded substrate and superstrate. From this table, it can be observed that by proposed optimized antenna becomes 41.2% compact by embedding rods in substrate of reference patch antenna and return loss improves from 11.68dB to 28.83 dB. Impedance bandwidth of the patch antenna improves from 70 MHz to 120 MHz. Gain of the proposed antenna improves from 4.48 dB to 5.27 dB as compared to reference antenna. Directivity of antenna also improves by use of rodded medium. For reference rectangular patch antenna, 3 dB beamwidth is 78.63^0 at $\varphi = 0^0$ and 85.69^0 at $\varphi = 90^0$. In proposed antenna, it is 78.01^0 for $\varphi = 0^0$ and 80.67^0 for $\varphi = 90^0$. Reduction in 3 dB beam width shows that the directivity of proposed antenna has improved as compared to the reference antenna.

Multiband antenna can also be designed using rodded medium. Design of a multiband antenna using rodded medium is presented is presented in the next section.

	Reference antenna	RMPA with rodded substrate	RMPA with rodded substrate & superstrate (proposed antenna)
Resonant frequency	5.2 GHz	3.88 GHz	4.01GHz
Compactness	-----	47.2%	41.2%
Reflection Coefficient	-11.68 dB	-32.83 dB	-28.83dB
Impedance Bandwidth	70 MHz	120 MHz	120 MHz
Gain	4.48 dB	1.5 dB	5.27 dB
3dB Beamwidth	78.63^0 at $\varphi = 0^0$ 85.69^0 at $\varphi = 90^0$	92.02^0 at $\varphi = 0^0$ 102.98^0 at $\varphi = 90^0$	78.01^0 at $\varphi = 0^0$ 80.67^0 at $\varphi = 90^0$

Table 3.2: Comparison of performance parameters of Reference antenna, rodded substrate antenna and proposed antenna

3.9. DESIGN OF MULTIBAND ANTENNA

Multiband antenna can also be designed by embedding the properly designed cylindrical rods. By embedding cylindrical rods in substrate of patch antenna T_{0m0} modes are introduced in patch antenna. By introducing higher order (m>1) and lower order (0<m<1) modes in patch cavity which satisfy the dispersive equation (3.12)-(3.14) in RMPA, a multiband antenna can be designed.

The rectangular microstrip Patch antenna without rodded medium is designed using the substrate FR_4 epoxy (dielectric constant ε_r= 4.4, loss tangent δ= .0025 and height h=1.6mm) such that it resonates at 2.43GHz with reflection coefficient of -13.79dB and at 1.78 GHz with reflection coefficient of -10.18dB as shown in Fig.3.23.

By introducing cylindrical rods having radius r = 0.5mm, height h = 1.48mm and distance between rods d=5mm in the substrate of this designed RMPA antenna as shown in Fig. 3.24, it resonates at four resonant frequencies 1.25 GHz, 1.77GHz, 2.43 GHz and 5.35 GHz as shown in Fig. 3.25. One lower order mode and one higher order mode is introduced in RMPA, while keeping the dominant mode intact. Fig. 3.26 shows the radiation pattern of designed multiband antenna for different resonant frequencies for $\varphi = 0^0$.

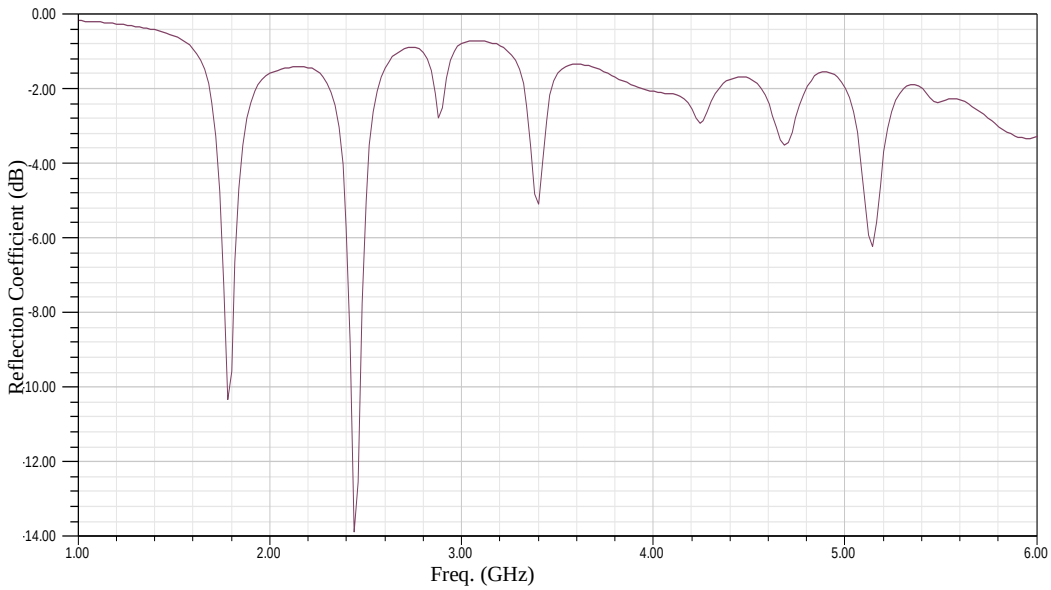


Fig. 3.23: Reflection coefficient of RMPA

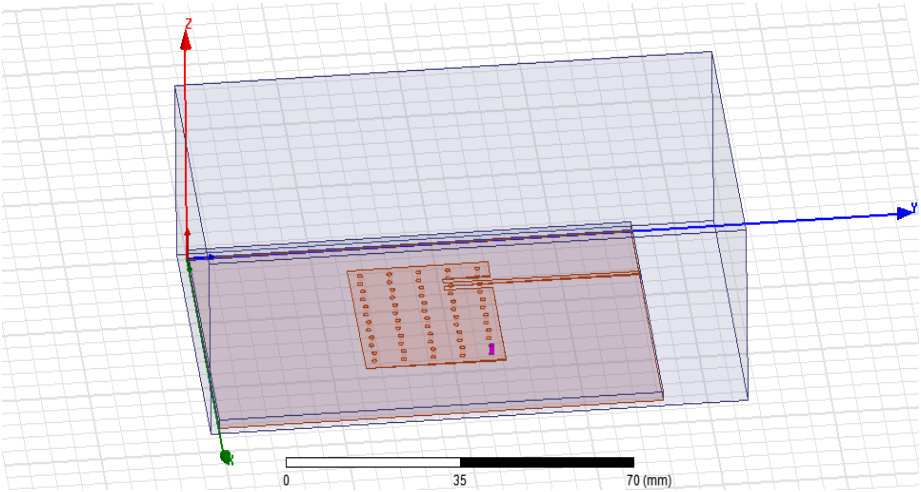


Fig. 3.24: Simulation Model of Rodded Medium Embedded RMPA

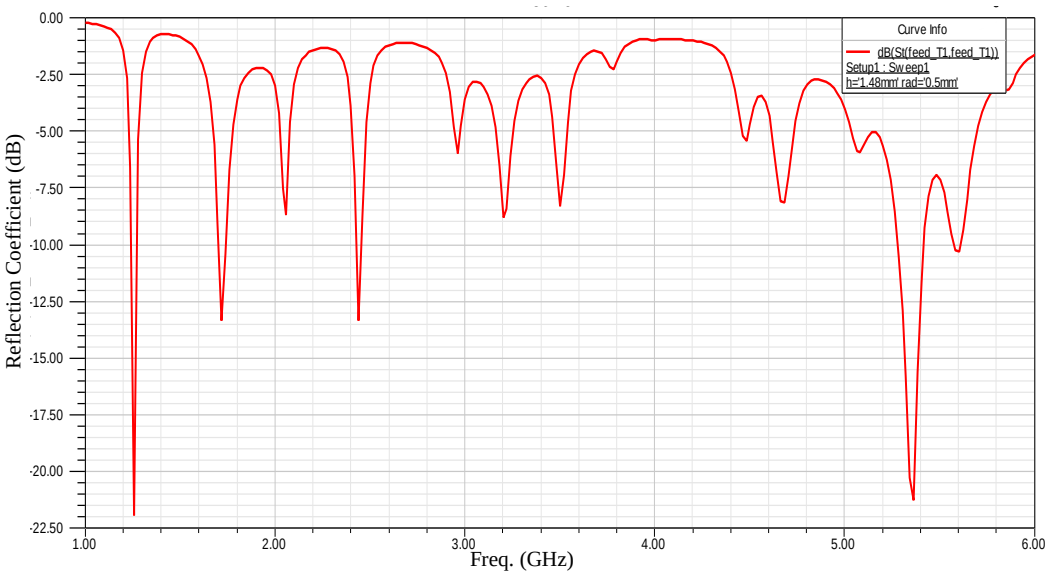


Fig. 3.25: Reflection Coefficient of Cylindrical Rods Embedded Tetra-band RMPA

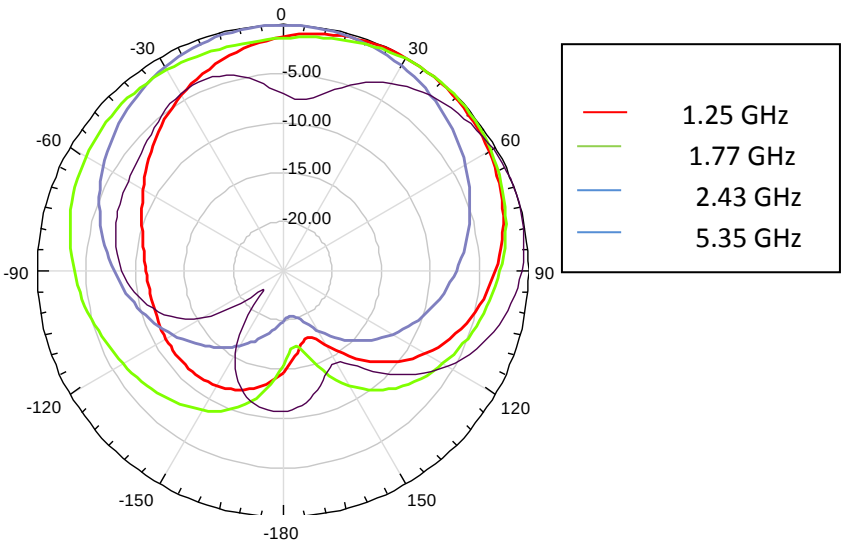


Fig. 3.26: Normalized Radiation Pattern of Cylindrical Rods Embedded Tetra-band RMPA at $\varphi=0^0$

3.10. CONCLUDING REMARKS

In this research work, comprehensive investigation of rodded medium artificial dielectric and its impact on the performance of patch antenna is done. The study reveals that epsilon negative (ENG) rodded medium can be applied to patch antenna in different manner for various purposes. In order to design a compact antenna with improved return loss, bandwidth at desired sub-wavelength frequency, rods embedded substrate can be used. This approach significantly enhances all the performance parameters except the gain which can be improved by using properly designed rodded medium embedded superstrate. In addition, this research work also provides a technique to design a multiband antenna by introducing lower and higher order modes while keeping the dominant modes intact in rods embedded patch antenna. A general procedure to design a patch antenna at desired subwavelength frequency using rodded medium is also proposed in this work.

Using the above approach, a sub-wavelength RMPA with improved return loss, enhanced bandwidth and gain is designed at 4 GHz. In addition, the technique proposed for designing multiband antenna a tetra band antenna resonating at 1.25 GHz, 1.77GHz, 2.43 GHz and 5.35 GHz is also presented. In short, based on the requirement of the particular application patch antenna can be tailored using cylindrical rods artificial material.

CHAPTER 4

DESIGN OF SUB-WAVELENGTH AND BROADBAND PATCH ANTENNA USING ENG AND MNG METAMATERIAL

The aim of this chapter is to design subwavelength and broadband rectangular microstrip antenna. Double folded I shaped, ENG metamaterial and C shaped and split ring, MNG metamaterials are used to design such antenna.

4.1. INTRODUCTION

The need of antenna with wide bandwidth is of importance in radar, electronic warfare and communication applications. Microstrip patch antenna has many attractive characteristics, but has disadvantage of narrow bandwidth. To design a broad band patch antenna different techniques like parasitic patches [112], thick substrate with low dielectric constant [33], optimization of patch shape [35], capacitive loading [69] etc. have been provided in literature. For designing the subwavelength and broad bandwidth patch antenna, inhomogeneous substrate technique has proven to be very efficient [32]. It is very difficult to design an inhomogeneous substrate using ordinary material. But using metamaterial element it can be realized easily.

Recently, Metamaterial has been extensively explored by antenna designer to improve the performance of patch antenna. By controlling geometric parameters of unit cell of metamaterial, material properties like permittivity and permeability can be controlled and good performing antenna and other microwave components can be designed. Metamaterials can be synthesized by arranging the periodic structures of unit cells. The performance parameters of patch antenna like gain, efficiency, and bandwidth can be improved by loading the patch antenna with properly designed metamaterial [228] [191]. Using metamaterials the significant reduction in size of microstrip patch antenna can also be accomplished [3].

In the present work, double folded I shaped, C shaped and split ring metamaterial elements are designed to control the permittivity and permeability of patch antenna substrate. These metamaterial elements are optimized to obtain a subwavelength broad band antenna. Double folded I shaped metamaterial has negative permittivity and is called epsilon negative (ENG) metamaterial. The split-ring resonator and C shaped metamaterial element have negative permeability and are

called Mu negative (MNG) metamaterial. The above mentioned metamaterials have either ε negative or μ negative, so they are called single negative (SNG) metamaterial. In this chapter, effect of adding different layers of these metamaterial on the performance of patch antenna is investigated and finally, a subwavelength broadband rectangular patch antenna is presented.

4.2. DESIGN AND RESULTS OF DOUBLE FOLDED I SHAPED ENG METAMATERIAL

Doubly folded I shaped metamaterial is designed according to reference patch antenna (as described in chapter 3) and it resonates at 5.2 GHz as shown in Fig. 3.6. Unit cell of double folded I shaped metamaterial is modelled in HFSS as shown in Fig. 4.1. Optimum Geometric parameters of this designed metamaterial is shown in Fig 4.2.

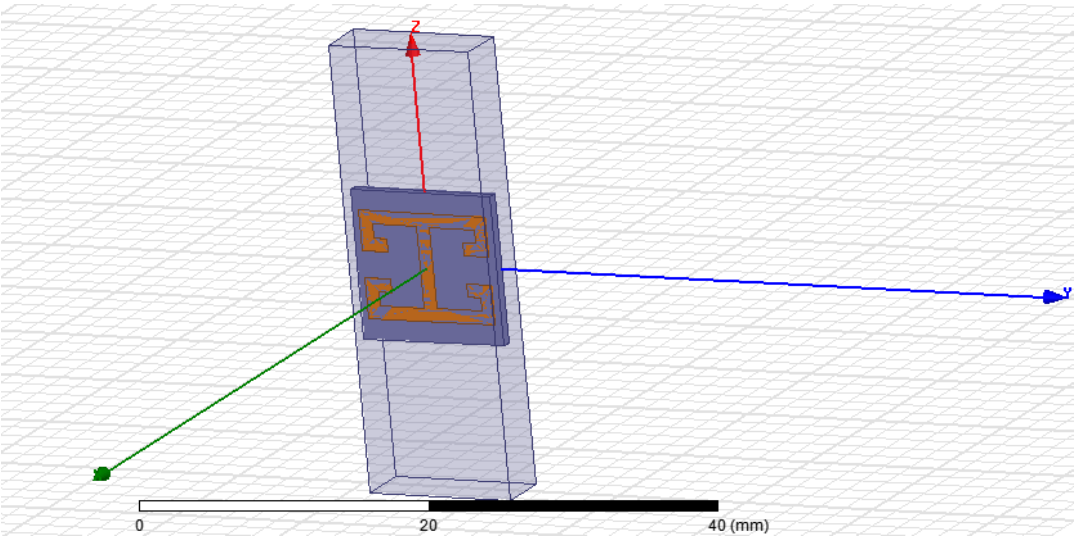


Fig 4.1: Simulation Model of Double Folded I Shaped ENG Metamaterial

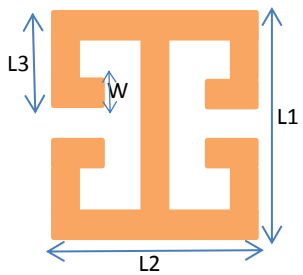


Fig 4.2: Geometric structure of Double Folded I Shaped ENG Metamaterial
(L1= 8mm, L2= 10 mm, L3= 3 mm, W=1 mm)

For simulation, unit cell boundary conditions are applied on this metamaterial and S parameters are obtained. Effective Permittivity (ε_r) and permeability (μ_r) of this metamaterial are extracted from S parameters by using well-known relation (4.1-4.3) for S parameters and the material parameters for the plane wave excitation [46].

$$n = \frac{1}{kd}\cos^{-1}\left[\frac{1}{2S_{21}}\left(1 - {S_{11}}^2 + {S_{21}}^2\right)\right] \tag{4.1}$$

$$z = \sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \tag{4.2}$$

$$\varepsilon = \frac{n}{z}, \quad \mu = nz \tag{4.3}$$

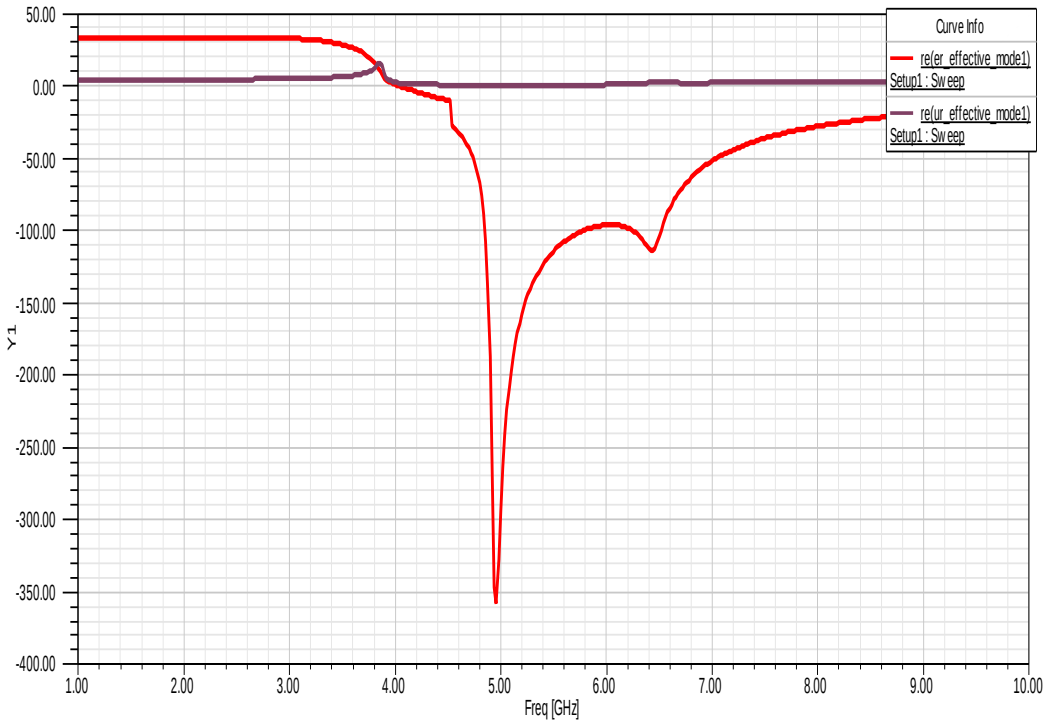


Fig. 4.3: Real Permittivity and Permeability of Double Folded I shaped ENG Metamaterial

Where d is unit cell dimension, S_{11}, S_{21} are S parameters and z is impedance. Fig 4.3 shows the permittivity and permeability of designed double folded I shaped metamaterial and it can be seen from this graph that permittivity is negative in frequency range of 5.2 GHz and permeability is positive. So this is Epsilon Negative (ENG) metamaterial. Fig. 4.4 shows the real and imaginary part of permittivity of this designed metamaterial.

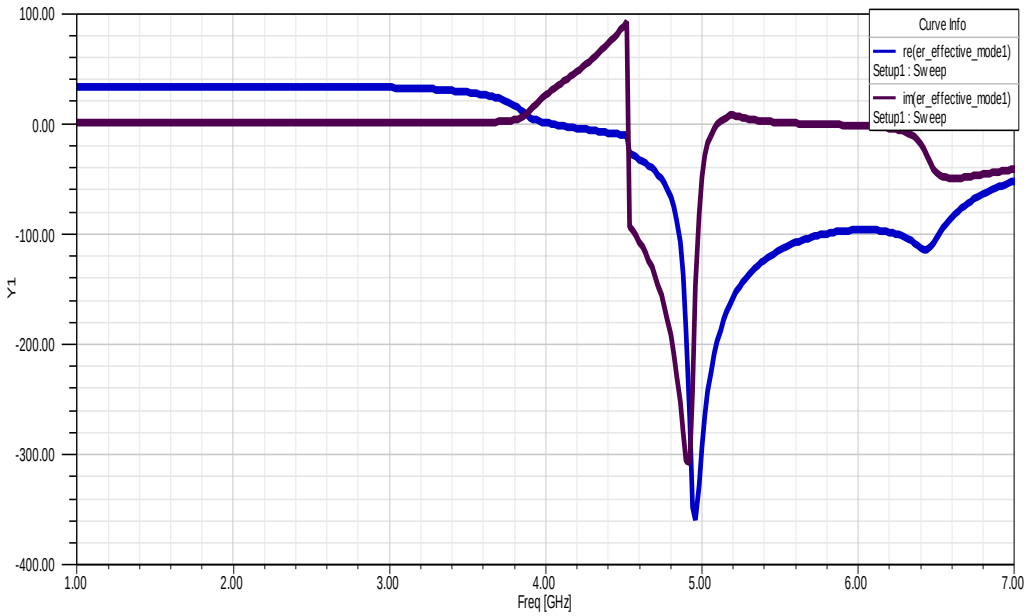


Fig.4.4: Real and Imaginary Permittivity of Double Folded I Shaped ENG Metamaterial

4.3. DESIGN AND RESULTS OF PATCH ANTENNA WITH DOUBLE FOLDED I SHAPED ENG

The optimized double folded I shaped ENG metamaterial is placed beneath the reference RMPA and effects of addition of different layers of this metamaterial on the performance parameters of antenna is studied and analyzed.

- **Effect Of Adding One Layer Of Metamaterial Beneath RMPA**

One layer of this designed metamaterial is applied under the patch antenna as shown in Fig. 4.5. When this layer is added beneath the center of patch antenna, it causes the subwavelength mode to resonate in patch antenna. The antenna now resonates at subwavelength frequency of 3.53 GHz as shown in Fig. 4.6.

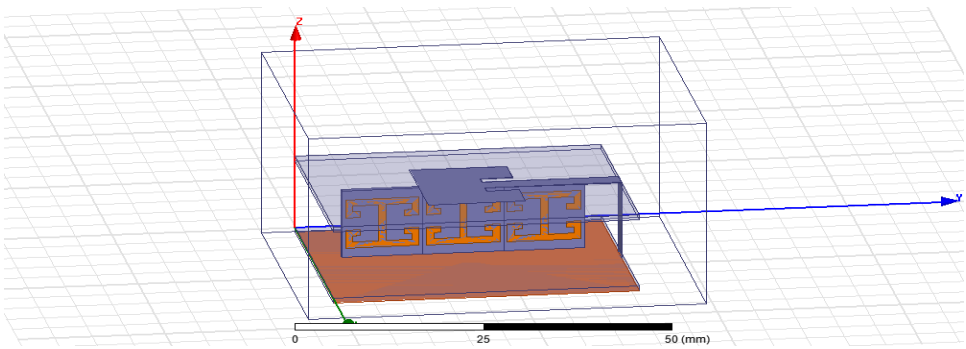


Fig 4.5: Simulation Model of Double Folded I Shaped Metamaterial (1layer) Embedded RMPA

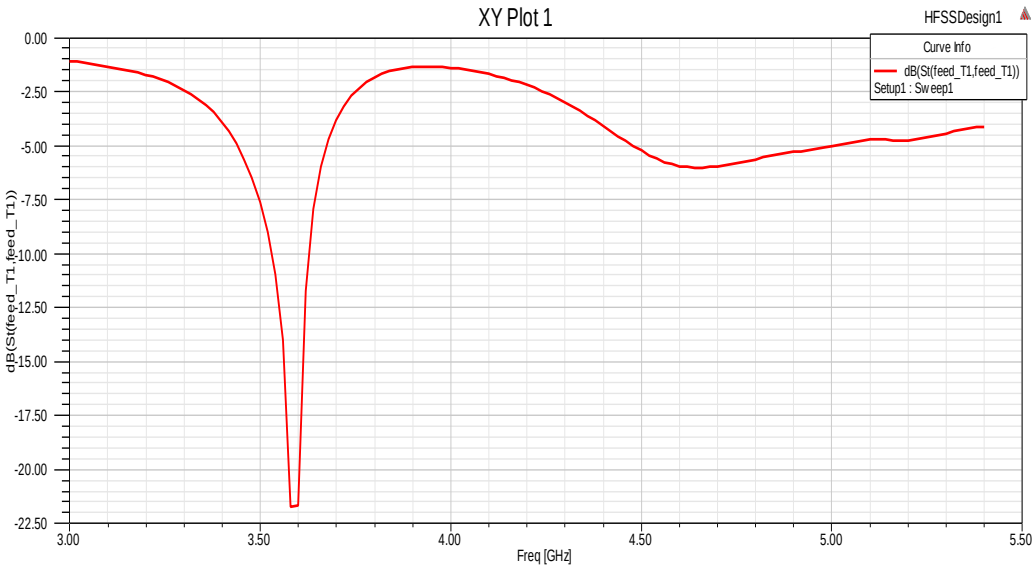


Fig.4.6: Reflection Coefficient of Double Folded I Shaped Metamaterial (1 layer) Embedded RMPA

- **Effect of Adding Three Layer of Metamaterial Beneath RMPA**

When the three layers of patch antenna is placed underneath the RMPA, the resonant frequency shift further towards the lower side as shown in Fig. 4.7. Different layers of metamaterial are placed at optimum distance d=2 mm obtained using simulation software HFSS. After adding three layers under the RMPA it resonates is 2.95 GHz and has bandwidth of 80 MHz. Gain of this metamaterial loaded antenna is 2.25 dB and efficiency is 46%.

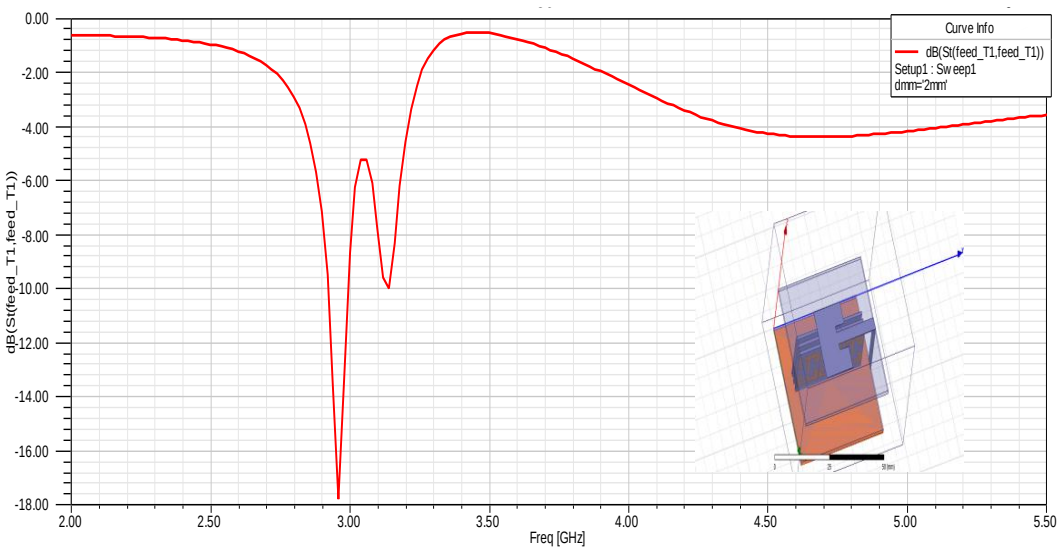


Fig 4.7: Reflection Coefficient of Double Folded I Shaped Metamaterial (3 layer) Embedded RMPA

- **Effect of Adding Five Layers of Metamaterial Beneath RMPA**

As the more layers of metamaterials are added underneath the patch antenna, resonant frequency shifts more to lower side. The addition of five layers under the patch antenna, following parameters of antenna results

- Resonant frequency of patch antenna is 2.71 GHz and bandwidth is 120 MHz as shown in Fig. 4.8.
- Gain of patch antenna is 1.64 dB.
- Efficiency of patch antenna is 72%.

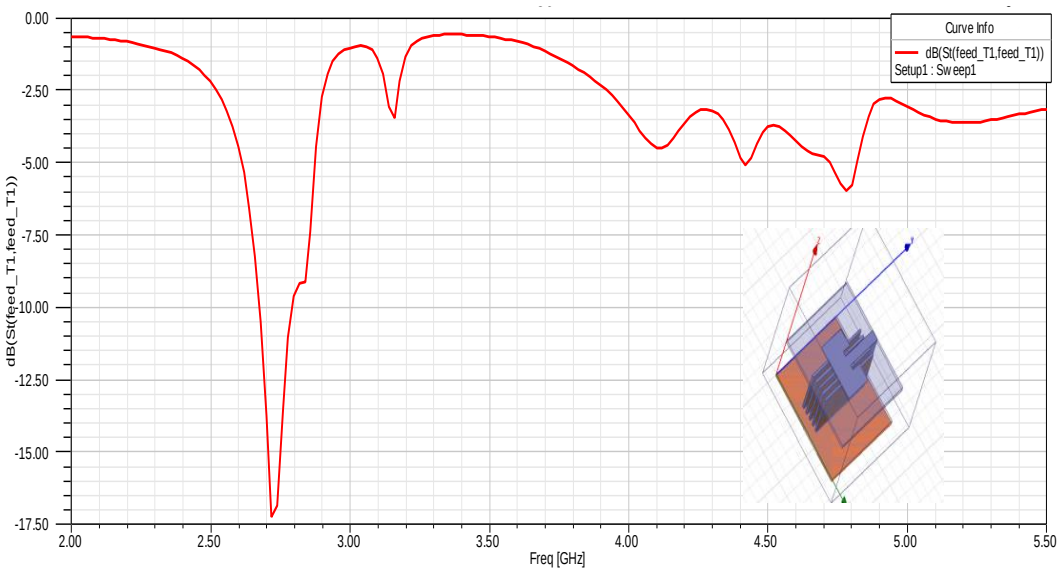


Fig 4.8: Reflection Coefficient of Double Folded I shaped Metamaterial (5 layer) Embedded RMPA

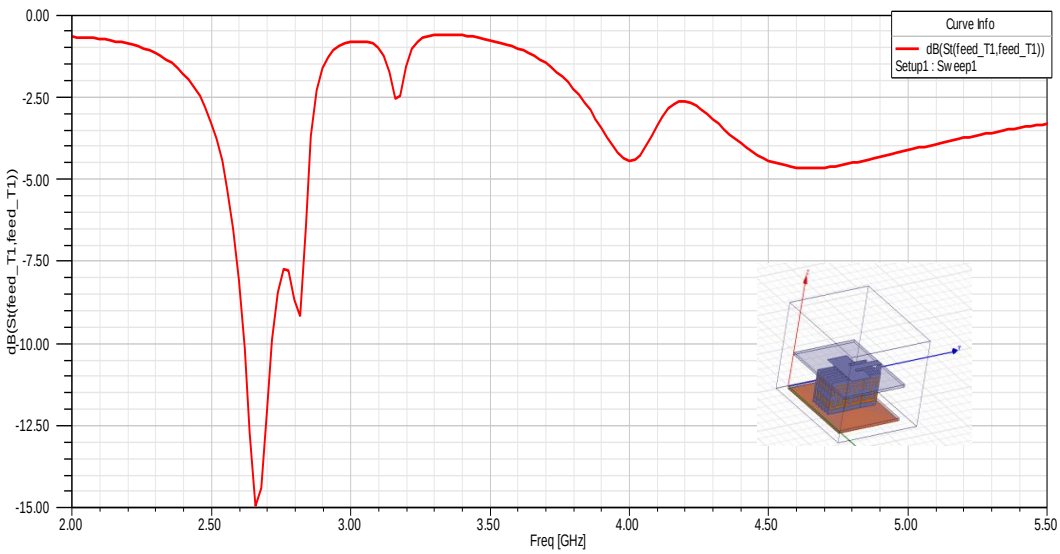


Fig 4.9: Reflection Coefficient of Double Folded I Shaped Metamaterial (7 layer) Embedded RMPA

- **Effect of Adding Seven Layers of Metamaterial Beneath RMPA**

The addition of the seven layers beneath the reference RMPA, results in following performance parameters:

- Metamaterial loaded antenna resonates at 2.59 GHz as shown in Fig.4.9
- Gain of this antenna is 1.58 GHz.
- Bandwidth of antenna is 80 MHz and efficiency is 75%.

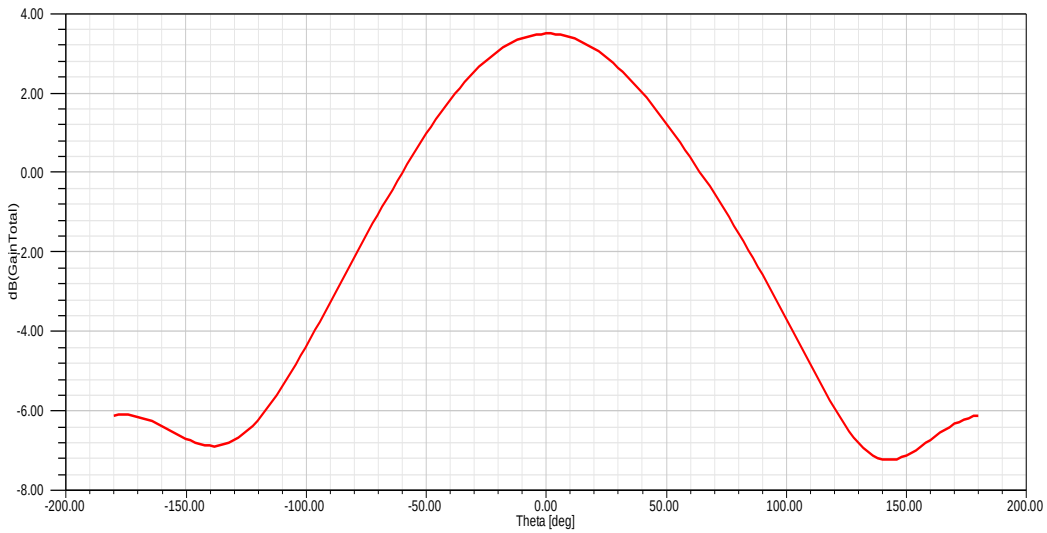


Fig. 4.10 (a): Gain of RMPA Embedded with One Layer of Double Folded I Shaped Metamaterial at Resonant Frequency of 3.53 GHz

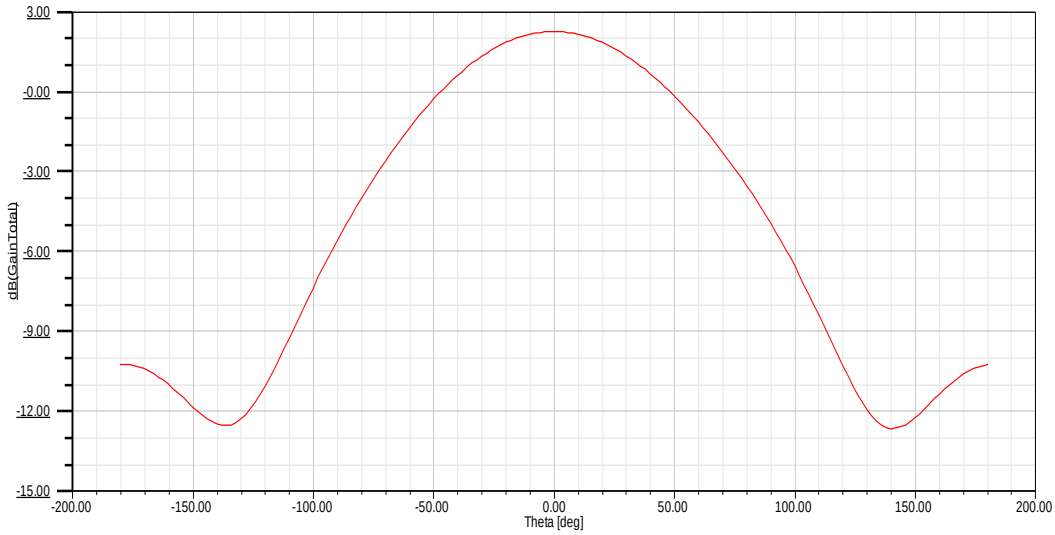


Fig. 4.10 (b): Gain of RMPA Embedded with Three Layers of Double Folded I Shaped Metamaterial at Resonant Frequency of 2.95 GHz

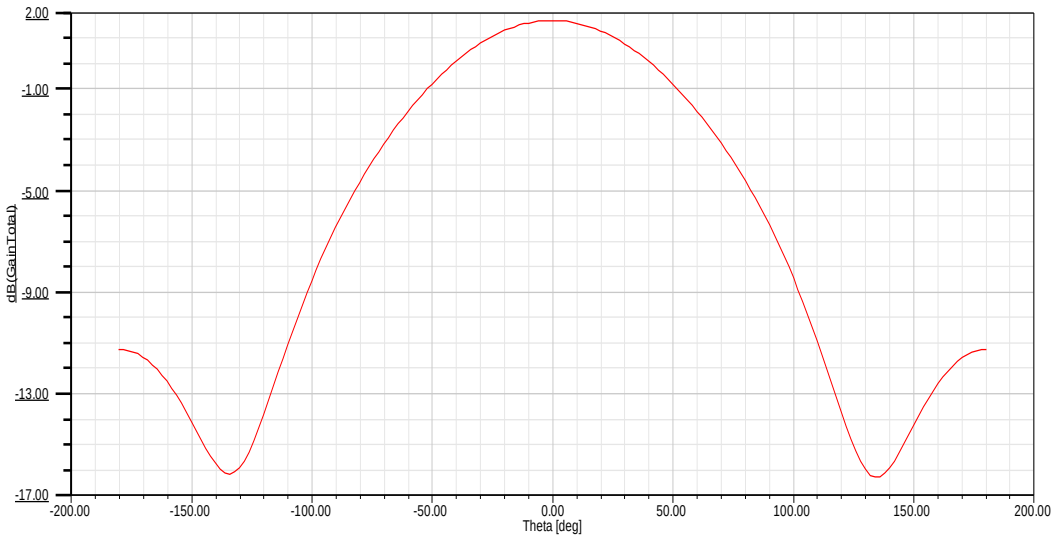


Fig. 4.10 (c): Gain of RMPA Embedded with Five Layers of Double Folded I Shaped Metamaterial at Resonant Frequency of 2.71 GHz

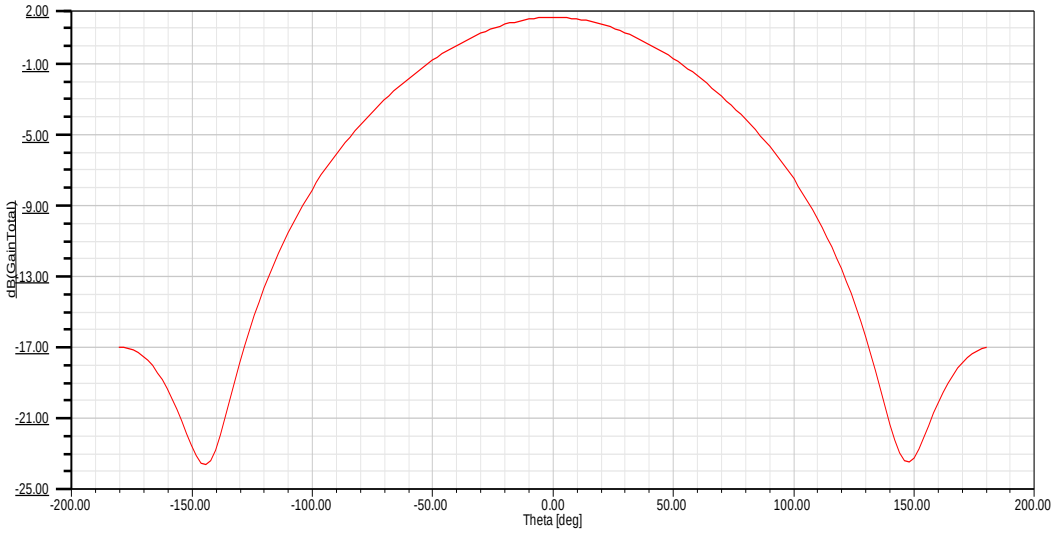


Fig. 4.10 (d): Gain of RMPA Embedded with Seven Layers of Double Folded I Shaped Metamaterial at Resonant Frequency of 2.59 GHz

Fig. 4.10 represents the gain of RMPA with different layers of double folded I shaped metamaterial added under it. From the graphs, it can be seen as the number of layers of double folded ENG metamaterial under the patch increases, gain reduces. Addition of eighth layer underneath the patch antenna results in return loss less than 10 dB which is not desirable. The prototype of optimized metamaterial and patch antenna are fabricated and tested.

Fabricated Metamaterial Layers and Patch Antenna

The top and bottom layer of fabricated double folded I shaped ENG metamaterial layer is shown in Fig. 4.11.

Seven such metamaterial layers are fabricated and placed underneath the fabricated patch antenna as shown in Fig. 4.12.

Fig. 4.11(a): Top layer of Double Folded I shaped ENG Metamaterial

Fig.4.11(b): Bottom layer of Double Folded I shaped ENG Metamaterial

The fabricated antenna is tested using Vector Network Analyzer and measured reflection coefficient for different layers of metamaterial is shown in Fig. 4.13. These measured results are in close agreement with simulated results.

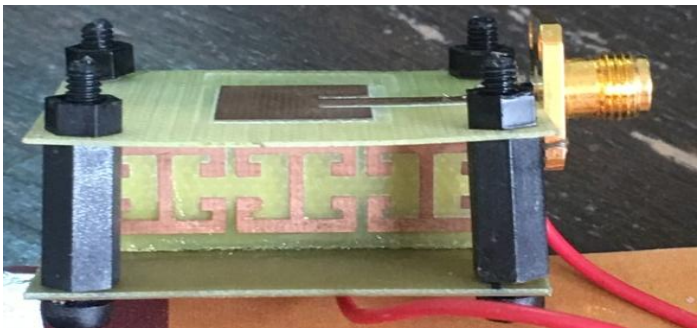


Fig.4.12: Fabricated RMPA with Double Folded I Shaped Metamaterial

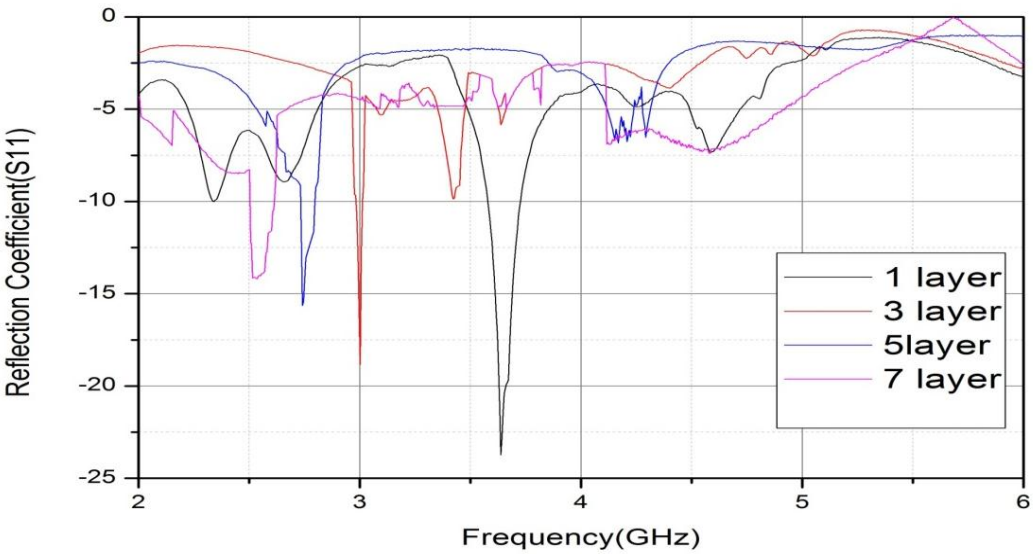


Fig.4.13: Measured Reflection Coefficient of RMPA with Different Layers of Double Folded I Shaped Metamaterial

Table 4.1 shows the performance parameters of reference RMPA and double folded I shaped loaded RMPA. From table, it can be concluded that addition of this metamaterial makes the reference patch antenna to resonate at subwavelength frequency. An increase in number of layer of double folded I shaped ENG metamaterial under the reference patch antenna makes the resonant frequency to shift more towards lower side. Return loss, bandwidth and efficiency of metamaterial loaded antenna improve as compared to reference antenna, but the gain reduces as number of layers of metamaterial beneath the reference patches increases.

Layers	**Resonant Frequency (GHz)**	**Gain (dB)**	**Bandwidth (MHz)**	**Efficiency**	**Reflection Coefficient (dB)**
Reference antenna	5.2	4.48	70	57.62%	-11.68
1 layer	3.53	3.02	110	56.3%	-44.44
3 layers	2.95	2.25	80	46%	-17.69
5 layers	2.71	1.64	120	72%	-17.1
7 layers	2.59	1.58	80	75%	-13.14

Table 4.1: Performance Parameters of Reference Antenna and Metamaterial Loaded Antenna

In next section, mu negative C shaped metamaterial is embedded in patch antenna to design and improve its performance.

4.4. DESIGN AND RESULTS OF C SHAPED MNG METAMATERIAL

C shaped metamaterial (as shown in Fig.4.16) is a resonant metamaterial and have negative permeability. C arms of this metamaterial behave as inductor and gap between them work as capacitor. Thus this LC circuit makes this metamaterial a resonating particle. Unit cell of C shaped metamaterial is modelled in HFSS as shown in Fig. 4.4 and unit cell boundary conditions are applied in x and y direction and wave ports are defined in z direction.

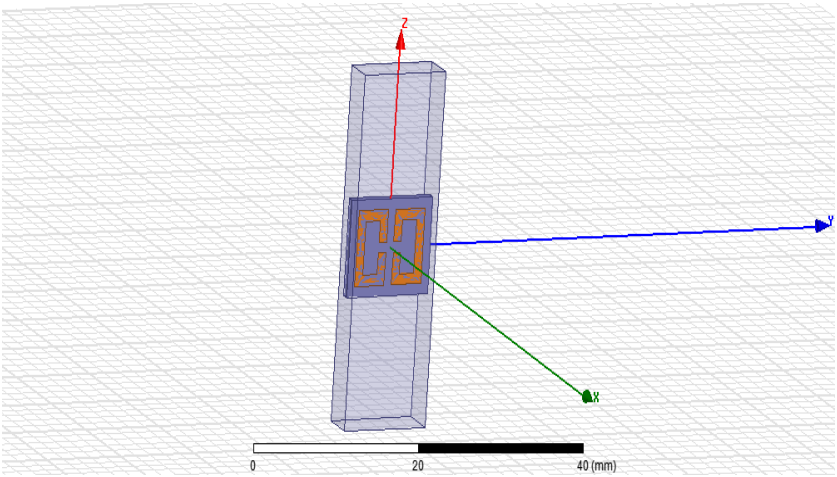


Fig 4.14: Simulation Model of C Shaped Metamaterial

After applying boundary conditions and wave ports to optimally designed unit cell of C shaped metamaterial in frequency range of reference patch antenna, S parameters are obtained. From S parameters, permeability is extracted using the equations (4.1)- (4.3). Fig. 4.15 shows the real and imaginary permeability of C shaped metamaterial. It can be seen from this figure, permeability is negative in frequency range of reference patch antenna and thus this c shaped metamaterial is called mu negative or MNG metamaterial.

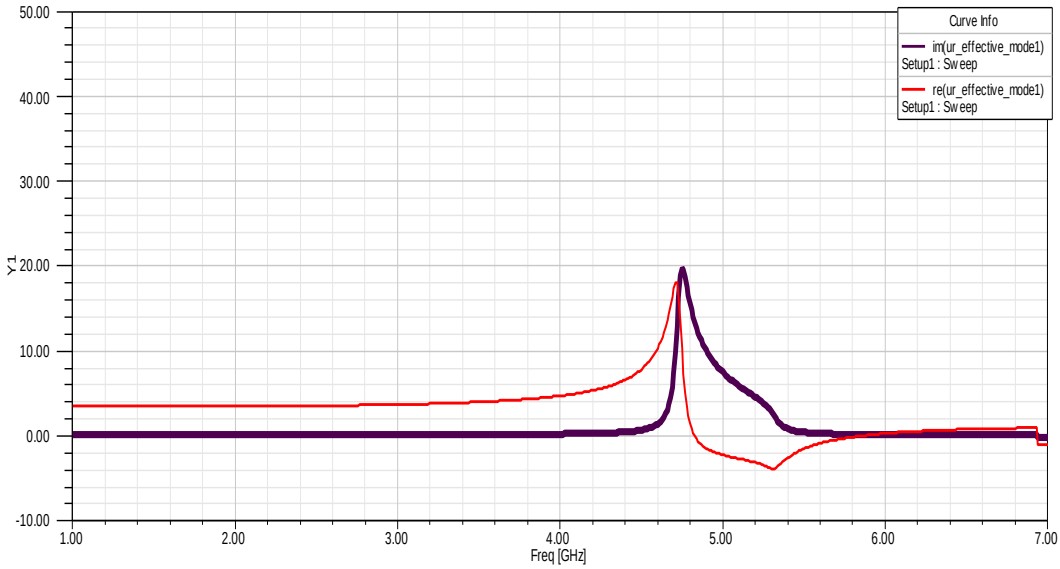


Fig. 4.15: Real and imaginary Permeability of C Shaped Metamaterial

Fig. 4.16 shows the Optimum geometric design parameters of C shaped metamaterial. Unit cell of C shaped metamaterial is optimized using HFSS software.

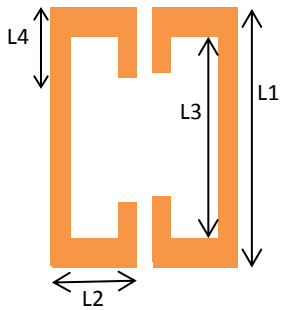


Fig. 4.16: Geometric Parameters of C shaped Metamaterial
(L1=9 mm, L2=4 mm, L3= 7mm, L4= 3mm)

4.5. DESIGN AND RESULTS OF PATCH ANTENNA WITH C SHAPED MNG METAMATERIAL

After optimizing the C shaped metamaterial, it is placed under the reference patch antenna. Introduction of different layers of C shaped metamaterial layer has different effects on the resonant frequency and performance parameter of patch antenna as described below:

- **Addition of Single Layer of C Shaped Metamaterial**

When the single layer of C shaped metamaterial is placed under the patch antenna as shown in Fig.4.17, subwavelength mode resonates in patch antenna at 4.17 GHz with return loss of 21.12 dB as shown in Fig. 4.18. Therefore embedding of MNG metamaterial in patch antenna shifts the resonant frequency of patch antenna from 5.2 GHz to 4.17 GHz. Impedance bandwidth of C shaped metamaterial embedded patch antenna is 300 MHz and gain is 4.18 dB.

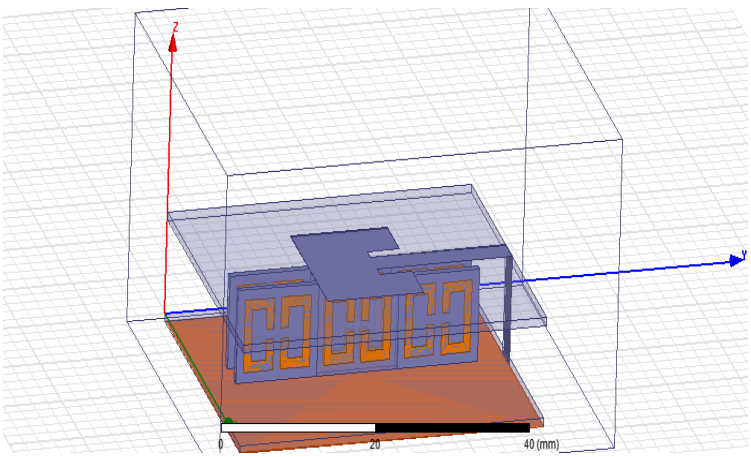


Fig 4.17: Simulation Model of C Shaped Metamaterial
Embedded RMPA

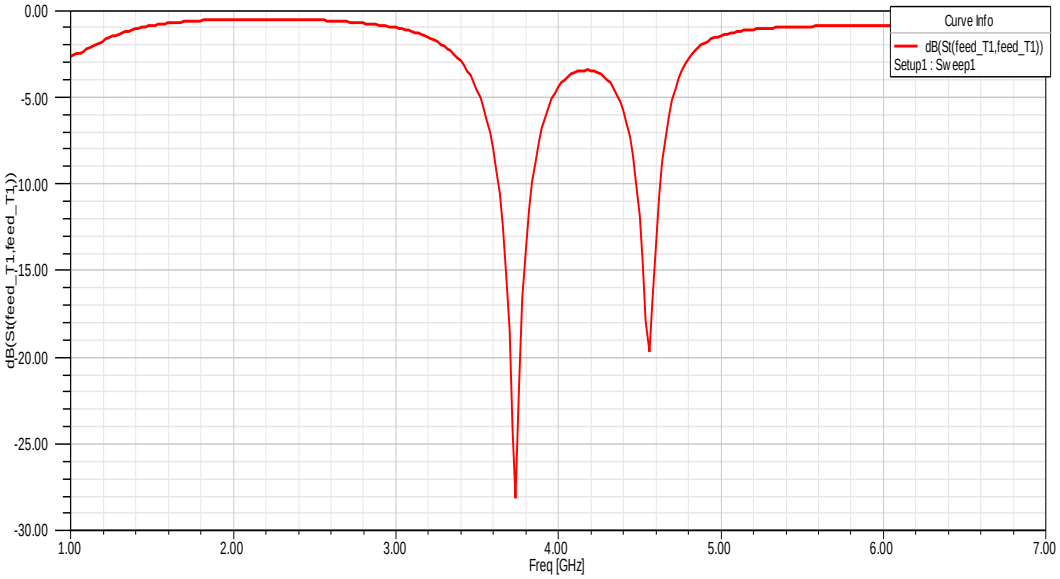


Fig. 4.18: Reflection Coefficient of C Shaped Metamaterial (1 layer) Embedded RMPA

- **Addition of Three Layers of C Shaped Metamaterial**

The addition of three layers of C shaped metamaterial under the reference patch antenna makes the antenna resonates at frequency of 3.56 GHz with impedance bandwidth of 210 MHz. Gain of metamaterial embedded antenna is 3.69 dB and efficiency is 79.2%.

- **Addition of Five Layers of C Shaped Metamaterial**

Addition of five layers of C shaped metamaterial beneath the patch antenna shifts the resonant frequency more towards lower side. This patch antenna resonates at 3.35 GHz with return loss of 13.82 dB as shown in Fig. 4.19 and gain at resonating frequency is 3.89dB.

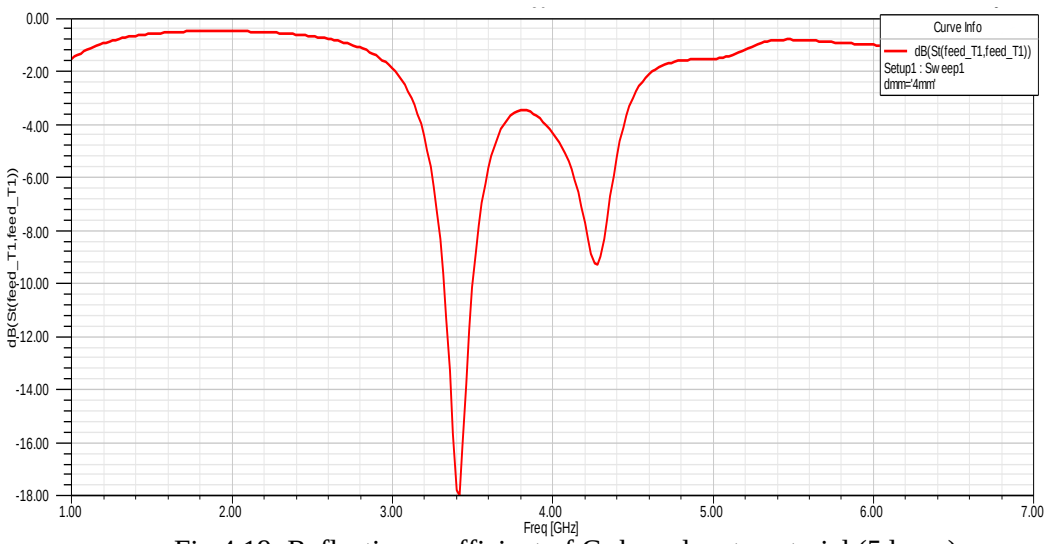


Fig.4.19: Reflection coefficient of C shaped metamaterial (5 layer) Embedded RMPA

Impedance bandwidth of antenna is 140 MHz and efficiency is 85.3%.

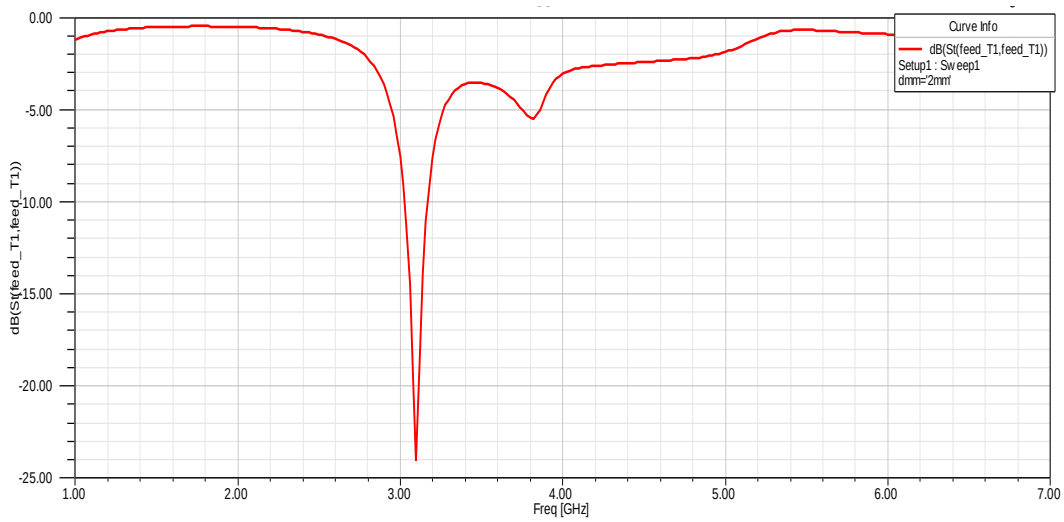


Fig.4.20: Reflection coefficient of C shaped Metamaterial (7 layer) Embedded RMPA

- **Addition of Seven Layers of C Shaped Metamaterial**

Seven layers embedded patch antenna resonates at a frequency of 3.09 GHz with impedance bandwidth of 150 MHz as shown in Fig. 4.20. Gain of this antenna is 2.88 dB and efficiency is 77.9%.

Fabricated C Shaped Metamaterial Layers and Patch Antenna

Optimized C shaped embedded patch antenna is fabricated. Fig 4.21 shows the different layers of C shaped metamaterial and Fig. 4.22 shows the patch antenna with C shaped metamaterial layers embedded under it. The fabricated metamaterial is tested.

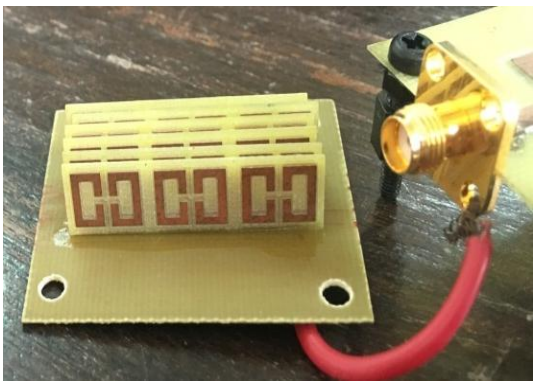


Fig.4.21: Fabricated C Shaped Metamaterial Layers

The graph between measured reflection coefficient and frequency is shown in Fig. 4.23. The measured resonant frequency of proposed antenna having three layers of metamaterial is 3.57 GHz and that of seven layers is 3.08 GHz.

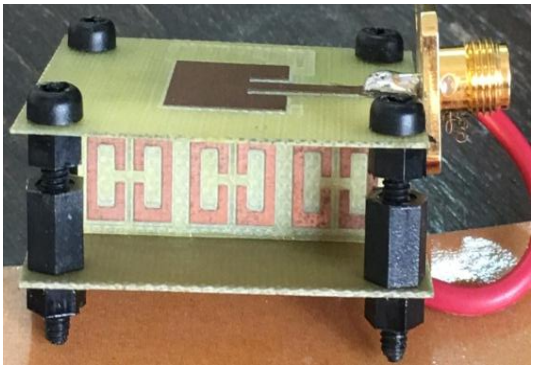


Fig.4.22: Fabricated C shaped Metamaterial Embedded RMPA

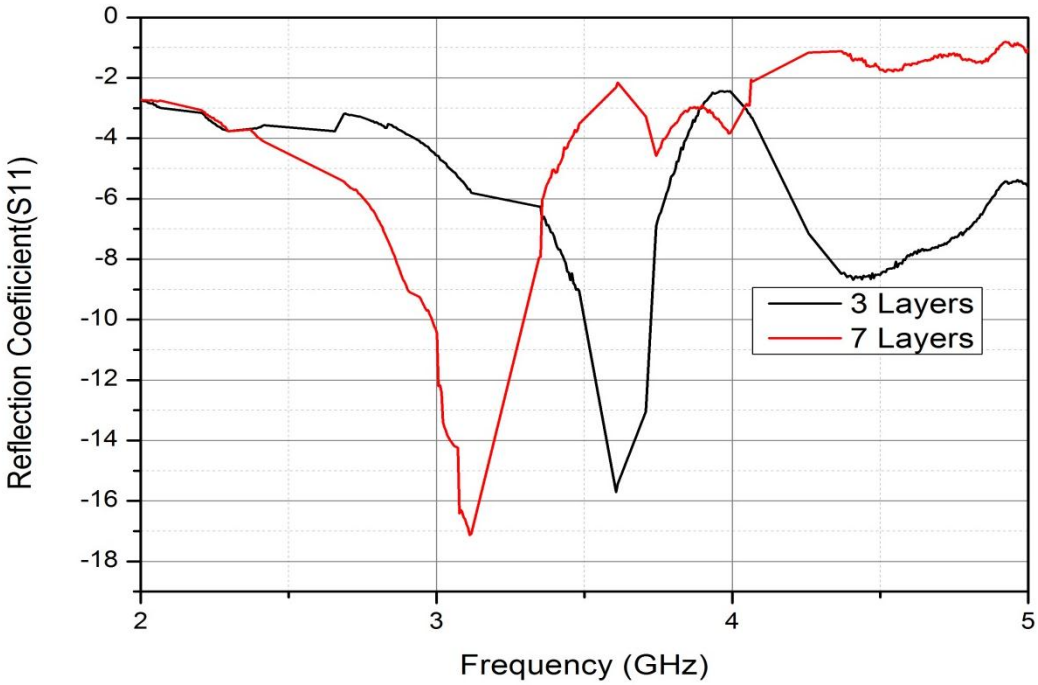


Fig.4.23: Measured Reflection Coefficient of C shaped Metamaterial Embedded RMPA

Table 4.2 shows performance parameters of C shaped loaded patch antenna. From the table it can conclude that MNG metamaterial can be used to design a subwavelength antenna. Embedding of C shaped metamaterial in patch antenna results in improved return loss, increased bandwidth and increased efficiency as compared to reference patch antenna.

Layers	Resonant Frequency (GHz)	Gain (dB)	Bandwidth (MHz)	Efficiency (%)	Reflection Coefficient (dB)
Reference antenna	5.2	4.48	70	57.62	-11.68
1 layer	4.17	4.18	300	89.59	-21.12
3 layers	3.56	3.69	210	79.2	-18.62
5 layers	3.35	3.89	140	85.3	-13.82
7 layers	3.09	2.88	150	77.9	-23.89

TABLE 4.2: PERFORMANCE PARAMETERS OF REFERENCE ANTENNA AND C SHAPED METAMATERIAL LOADED ANTENNA

In the next section, MNG metamaterial split ring resonator is used to design and improve the performance of patch antenna.

4.6. DESIGN AND RESULTS OF SPLIT RING RESONATOR

Split ring resonator has initially been by Pendry [79]. It consists of two concentric metallic rings printed on substrate as shown in Fig. 4.24. . When it is excited by time varying external magnetic field along the z axis, it causes the electric current to flow from one ring to another across the slots between them. Thus a strong displacement current flows in this structure and slots in the rings behave like distributed capacitance. Thus an LC equivalent circuit results and makes the split ring resonator as resonating type metamaterial.

The Unit cell of split ring resonator is designed and optimized in HFSS as shown in Fig. 4.24. Extracted real value of permittivity and permeability from S parameters is shown in Fig. 4.25.

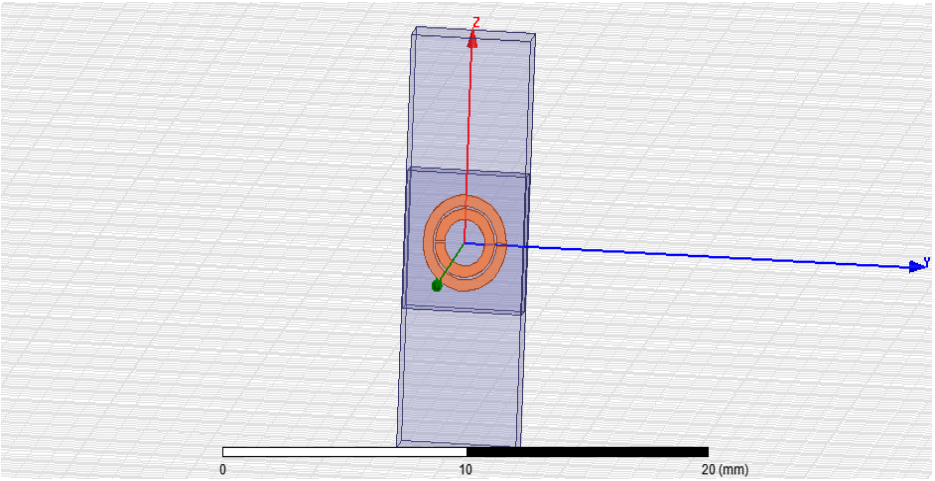


Fig.4.24: Simulation Model of Unit Cell of Split Ring MNG Metamaterial

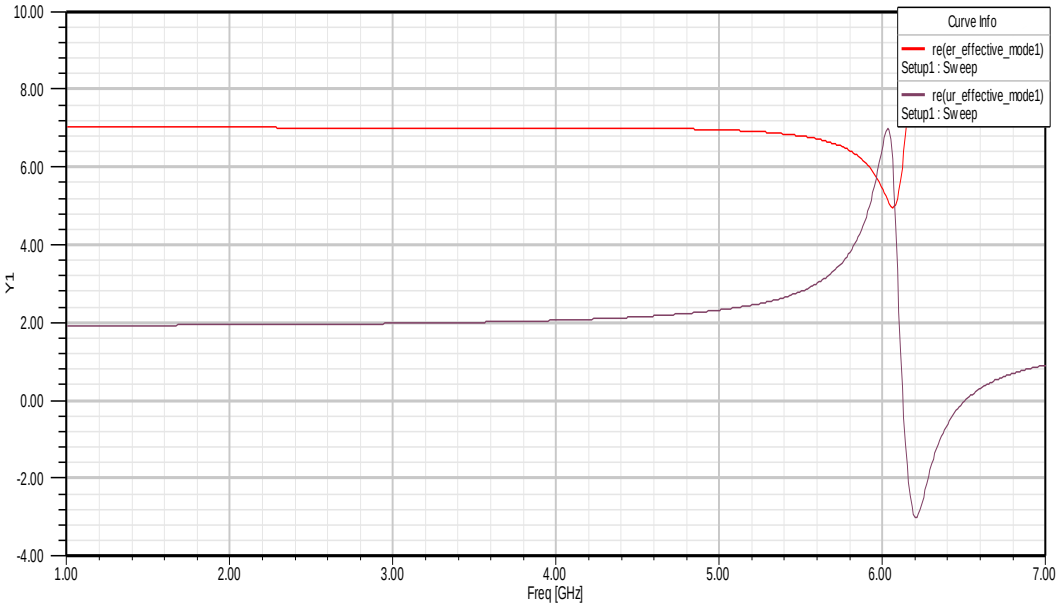


Fig.4.25: Real Permittivity and Permeability of Split Ring MNG Metamaterial

4.7. DESIGN AND RESULTS OF PATCH ANTENNA WITH SPLIT RING RESONATOR

After designing the split ring resonator, it is applied under the patch antenna as shown in Fig. 4.26. The graph of reflection coefficient of Proposed RMPA with three layers of split ring resonator is shown in Fig. 4.27 and it resonates at 3.8 GHz.

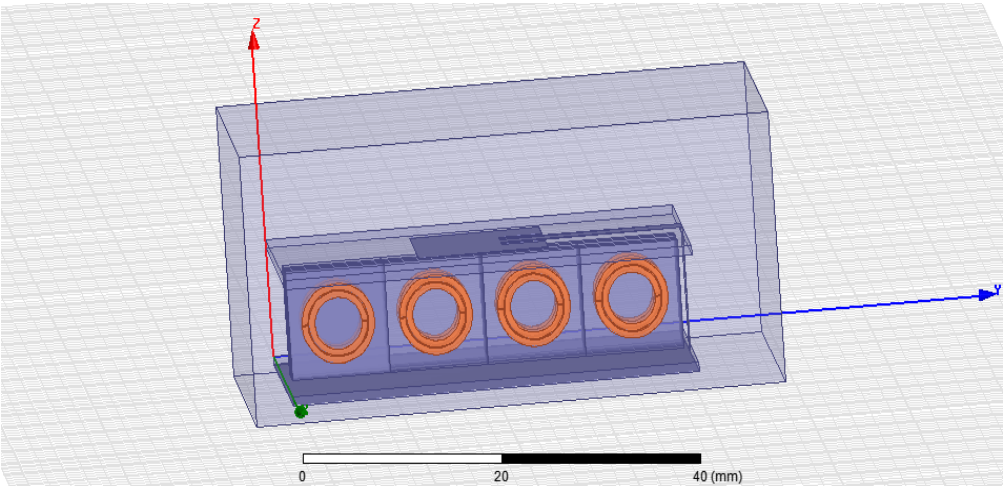


Fig.4.26: Simulation Model Proposed RMPA with Split Ring MNG Metamaterial Placed Under it

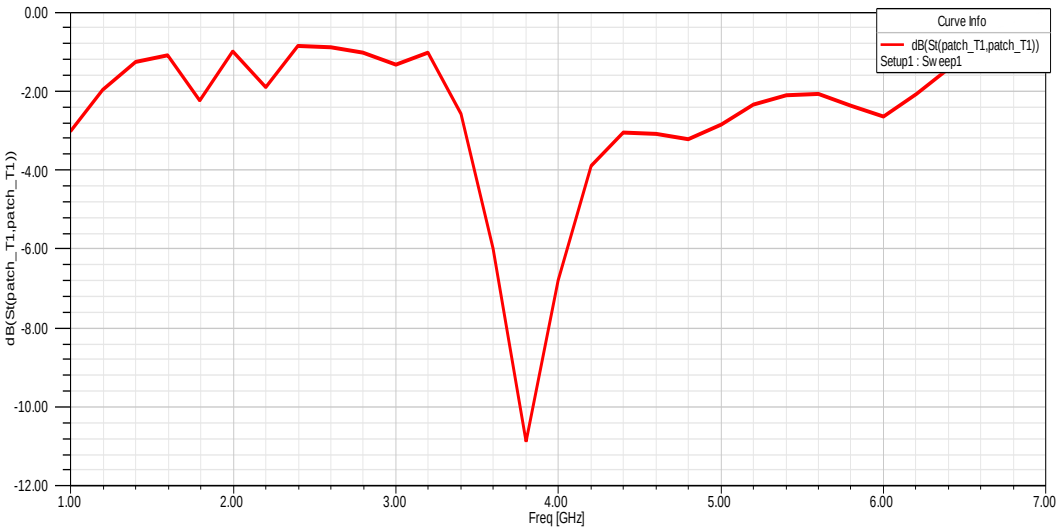


Fig. 4.27: Reflection Coefficient of RMPA with three layer of split ring resonator placed under it

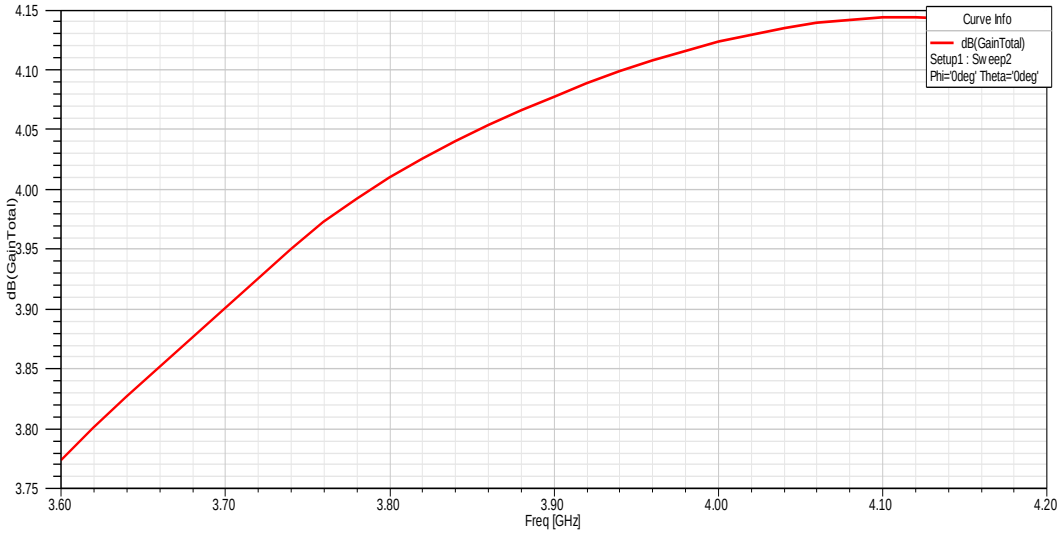


Fig. 4.28: Gain of RMPA with Three Layer of Split Ring Resonator Placed under it

Fig. 4.29 shows the gain of RMPA embedded with three layers of split ring resonator. Gain of antenna at resonant frequency of 3.8 GHz is 3.96 dB. As more layers of split ring resonator is added under the patch antenna, resonating frequency shifts more towards the lower side. Fig. 4.27 shows the graph of reflection coefficient of RMPA antenna with seven layers of split ring resonators. This antenna resonates at 3.6 GHz and has impedance bandwidth of 280 MHz. It has a gain of 4.34 dB as shown in Fig. 4.30. The efficiency of proposed antenna is 81.7% at the resonating frequency.

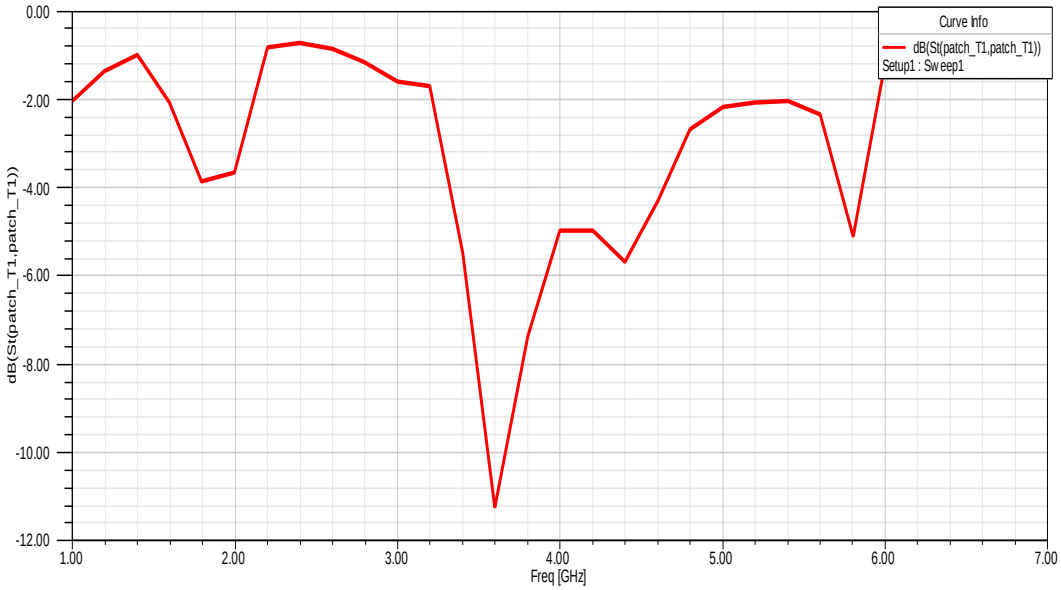


Fig. 4.29: Reflection Coefficient of RMPA with Seven Layer of Split Ring Resonator Placed under it

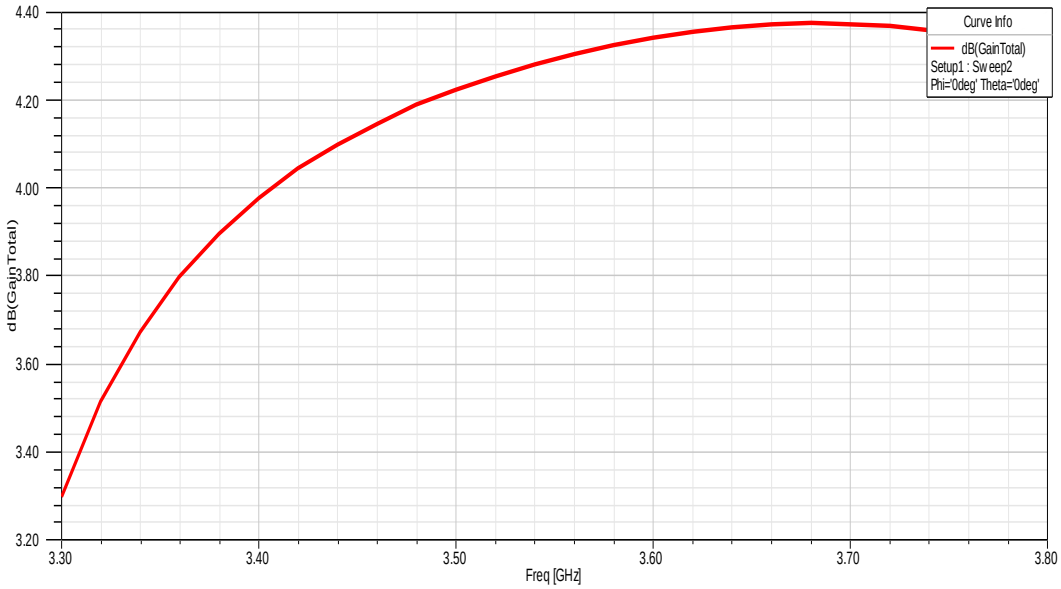


Fig. 4.30: Gain of RMPA with Seven Layer of Split Ring Resonator Placed under it

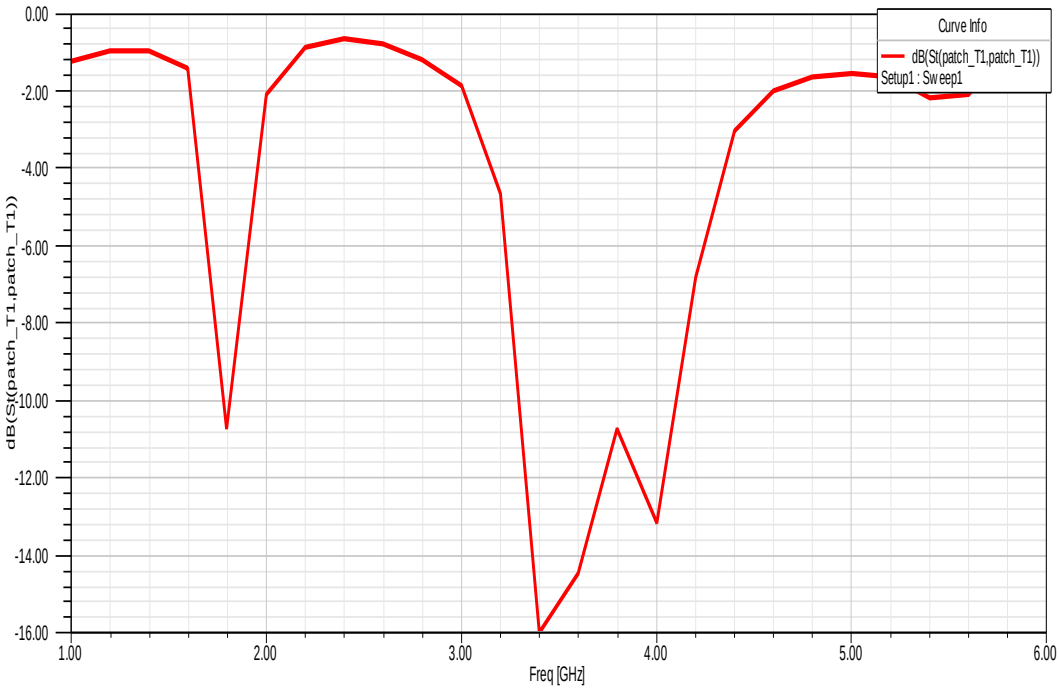


Fig. 4.31: Reflection Coefficient of RMPA with Eleven Layers of Split Ring Resonator Placed under it

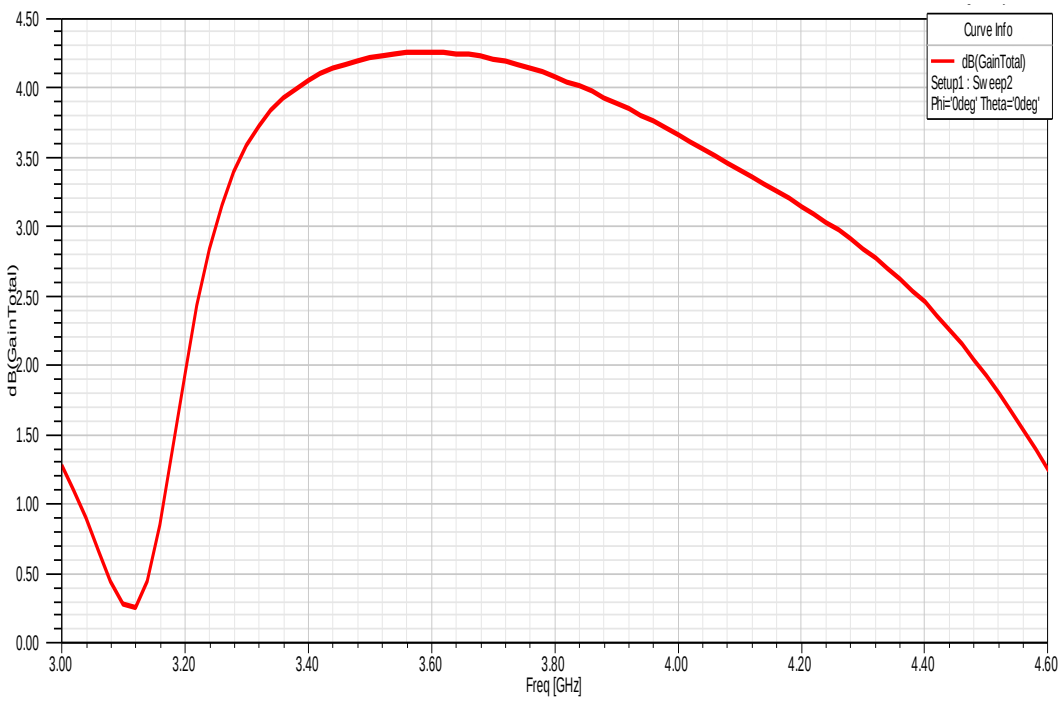


Fig. 4.32: Gain of RMPA with Eleven Layer of Split Ring Resonator Placed under it

When nine layers of split ring resonator are added two subwavelength modes in RMPA results as listed in Table 4.3. When eleven layers of split ring resonators are added under the patch antenna both the modes merge and a broadband subwavelength resonance mode as desired is obtained which is shown in Fig. 4.31. The proposed

RMPA with eleven layers of split ring resonator resonates at 3.5 GHz and has broad bandwidth of 800 MHz. The gain of proposed antenna is 4.39 dB as shown in Fig. 4.32 and efficiency is 84%.

Fabricated Antenna

Prototype of subwavelength broadband RMPA with eleven layers of split ring resonator is fabricated. Fig. 4.33 shows the metamaterial layer of split ring resonator. Layers of metamaterial are placed over the ground plane of RMPA as shown in Fig. 4.34.

The prototype of RMPA antenna with eleven layers of split ring resonators placed under it is shown in Fig. 4.35. Fabricated antenna is tested and measured results are presented. Simulated and measured results are in close agreement.

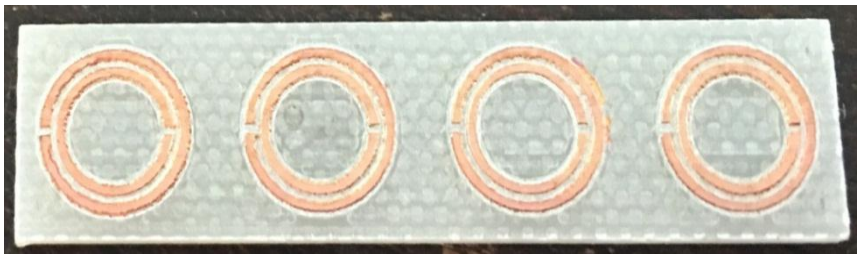


Fig. 4.33: Fabricated Layer of Split Ring Resonator

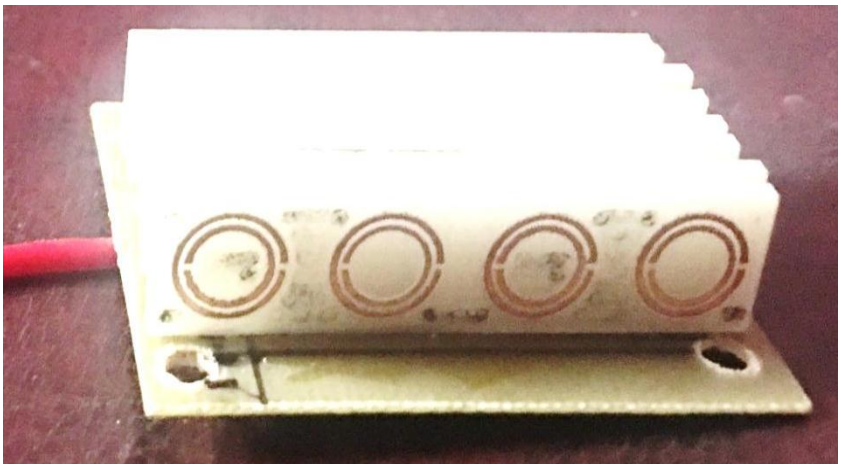


Fig. 4.34: Fabricated Layers of Split Ring Resonator Placed on Ground Plane of RMPA

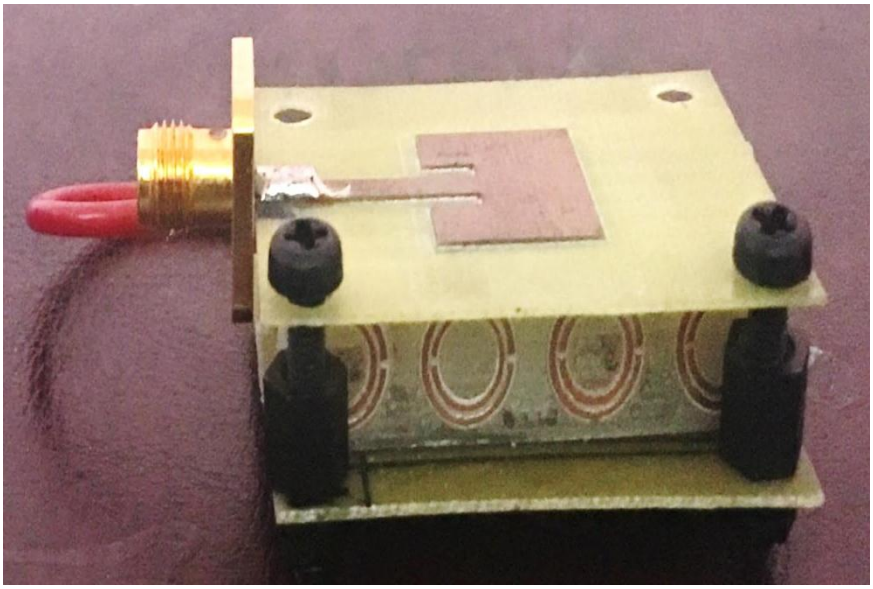


Fig. 4.35: Fabricated RMPA with Layers of Split Ring MNG Metamaterial Placed under it

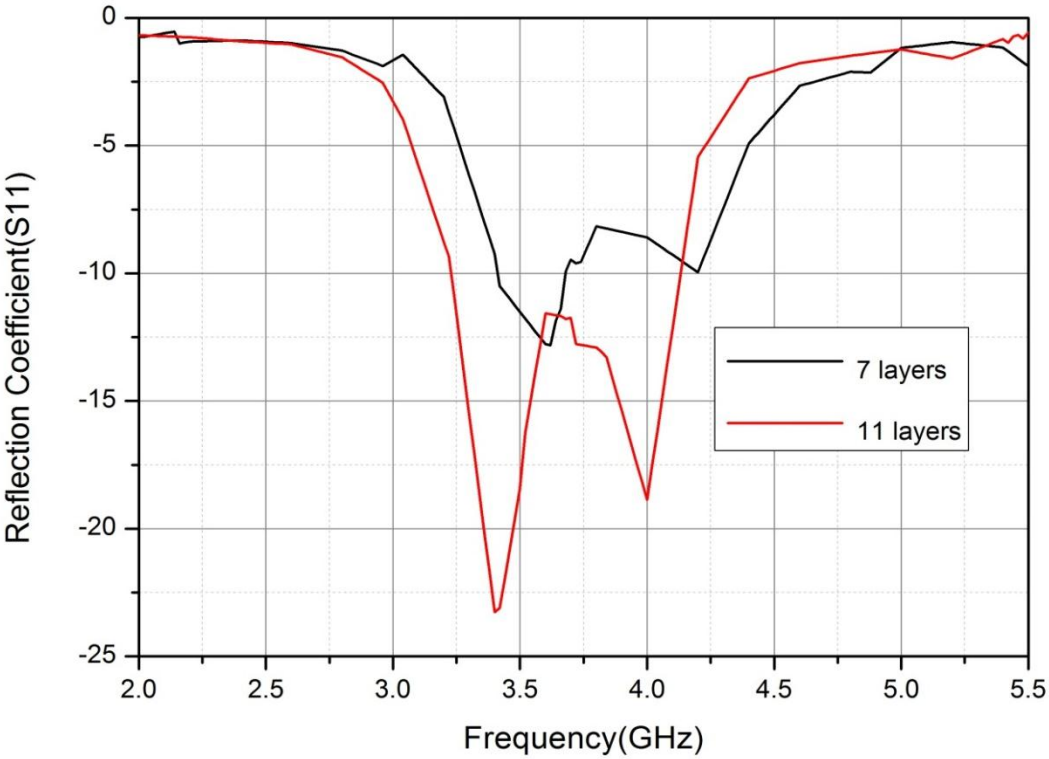


Fig.4.36: Measured Reflection Coefficient (S11) of Proposed Antenna for 7 layers and Eleven Layers of Split Ring MNG Metamaterial

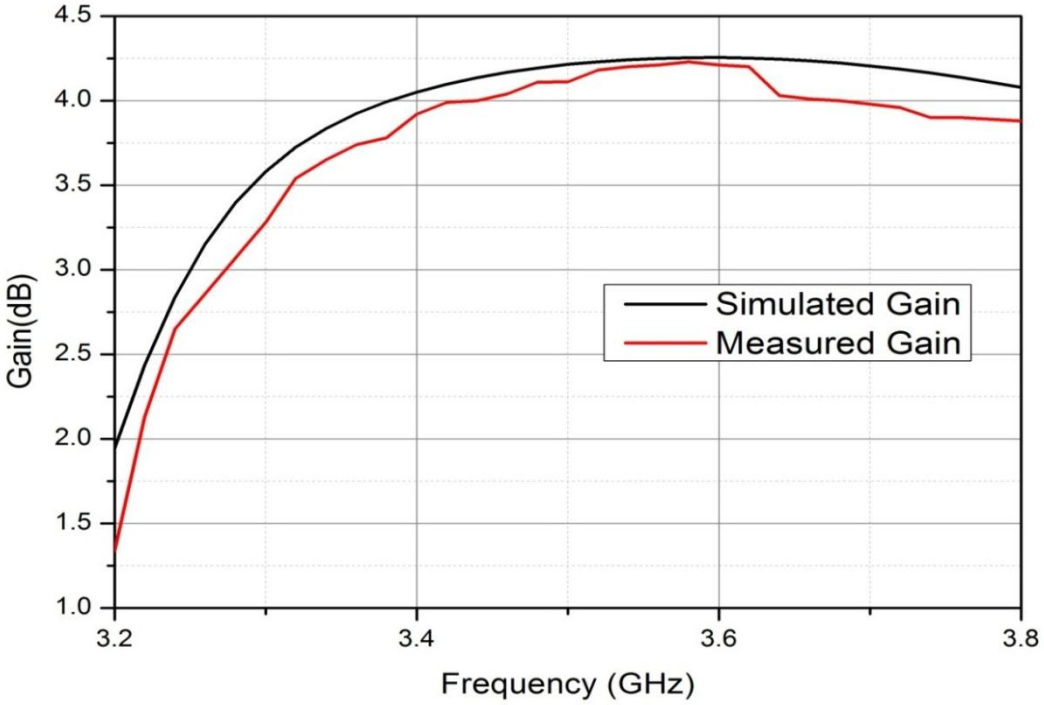


Fig. 4.37: Simulated and Measured Gain of Proposed RMPA with Eleven Layers of SRR placed under it

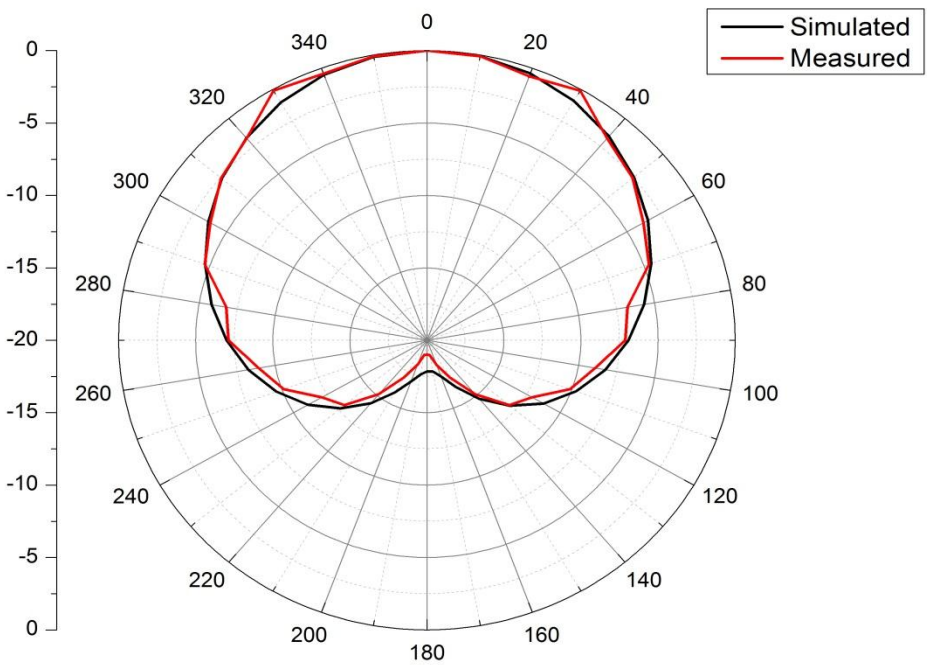


Fig. 4.38: Simulated and Measured Radiation Pattern ($\varphi=0^0$) of Proposed RMPA with Eleven Layers of SRR placed under it

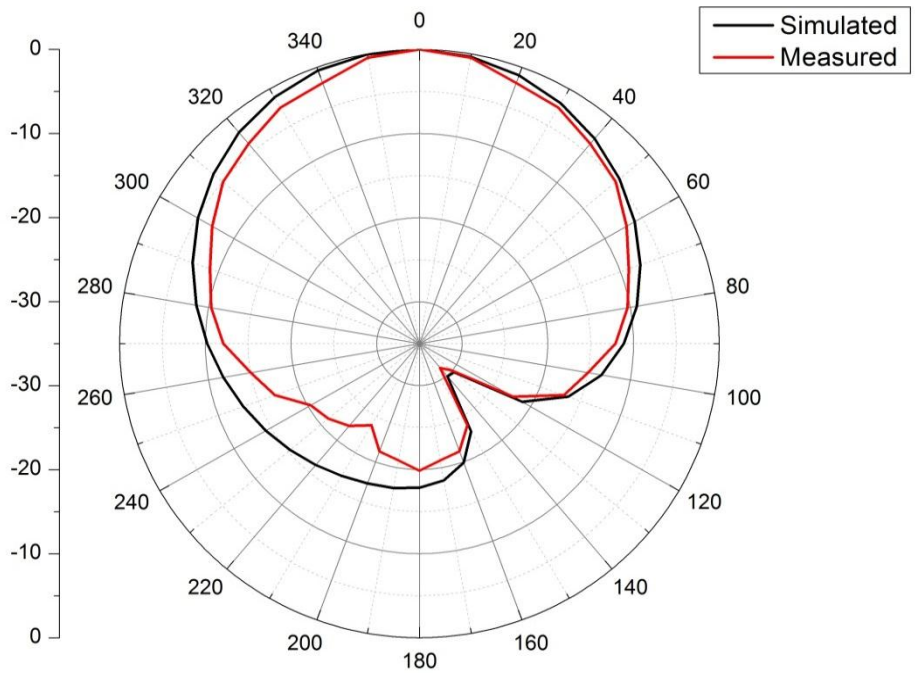


Fig.4.38: Simulated and Measured Radiation Pattern ($\varphi=90^0$) of Proposed RMPA with Eleven Layers of SRR placed under it

Fig. 4.36 shows the measured reflection coefficient graphs for rectangular patch antenna loaded with seven layers and eleven layers of split ring resonator metamaterial. One layer of this metamaterial consists of four resonators. Fig. 4.37 shows the simulated and measured gain of proposed RMPA with eleven layers loading of the Split ring resonator. Proposed antenna has approximately same gain as reference antenna. Thus this metamaterial loading provides a subwavelength and broad bandwidth antenna without reduction in gain, which is the problem of antennas, designed using double folded I shaped and C shaped metamaterial loading. Fig. 4.38 and Fig. 4.39 show the radiation pattern of proposed antenna in E- Plane and H- plane respectively. Simulated and measured radiation pattern of proposed antenna are approximately same as can been seen from the graphs.

Table 4.3 shows the results of reference antenna and proposed RMPA with different layers of split ring resonators placed under it. Bandwidth of reference patch antenna improves from 70 MHz to 800 MHz. Broad bandwidth is obtained by combining the two modes of antenna. The proposed antenna resonates at subwavelength frequency of 3.5 GHz with a gain of 4.39 dB. Efficiency of antenna improves from 58.3 % to 84%.

No. of layers of SRR	Resonant frequency (GHz)	Bandwidth (MHz)	Reflection Coefficient (S11)(dB)	Gain (dB)	Efficiency (%)
3 layers	3.8	70	-10.23	3.96	81.74
5 layers	3.65	170	-11.67	4.23	80.8
7 layers	3.6	280	-15	4.34	81.7
9 layers	3.55 and 4.09	400 and 230	-21.13 and -11.66	4.29 and 3.66	83.12 and 84
11 layers	3.5	800	-28.86	4.39	84
Reference antenna	5.2	70	-11.68	4.48	58.3

Table 4.3: Performance Parameters of Reference Antenna and Split Ring Metamaterial Loaded Antenna

	Resonant frequency (GHz)	Bandwidth (MHz)	Reflection coefficient (S11) (dB)	Gain (dB)	Efficiency (%)
Reference antenna without metamaterial	5.2	70	-11.68	4.48	58.3
RMPA with Double folded I shaped Metamaterial	2.59	75	-13.14	1.58	80
RMPA with C Shaped Metamaterial	3.09	150	-23.89	2.88	77.9
RMPA with Split ring metamaterial	3.5	800	-28.86	4.39	84

Table 4.4: Performance Parameters of Reference Antenna and Metamaterial Loaded Antenna

4.8. COMPARISION OF RESULTS AND DISCUSSION

Table 4.4 shows the comparison of performance parameters of reference rectangular microstrip antenna and different types of metamaterial loaded rectangular microstrip antenna. Reference antenna resonates at 5.2 GHz with -11.68 reflection coefficient. Reference RMPA has 70 MHz bandwidth and 4.48 dB gain. Efficiency of this antenna is 58.3 %.

Loading of the reference antenna with double folded I shaped ENG metamaterial shift the resonant frequency towards the lower side. As the number of layers of this metamaterial under the reference antenna increases, resonant frequency shifts more towards the lower side. From the table, it can seen that shift in the resonant frequency is maximum with the loading of this metamaterial. But gain reduces with this ENG metamaterial loading as the frequency shift more towards the lower side. There is small enhancement in bandwidth also using this metamaterial. Patch antenna can be loaded with maximum seven layers of this metamaterial as after this reflection coefficient become less than -10 dB. Reference RMPA with seven layers of loading of this metamaterial resonates at 2.59 GHz with -13.14 dB reflection coefficient. Thus the resonant frequency of antenna shifts significantly from 5.2 GHz to 2.59 GHz. Bandwidth of this antenna increases slightly by 5 MHz as compared to reference antenna and gain of antenna is 1.58 dB.

Both C shaped and split ring resonators are MNG metamaterial and loading of RMPA with these metamaterial provides optimum solution. Shift in resonant frequency to lower side is less as compared to ENG metamaterial, but bandwidth enhancement is more. C shaped loaded RMPA resonates at 3.09 GHz with -23.89 dB reflection coefficient and 150 MHz bandwidth. Efficiency of this metamaterial loaded antenna is 77.9 % and gain is 2.88dB. Split ring resonator loaded RMPA antenna resonates at 3.5 GHz with -28.86 dB reflection coefficient and 800 MHz bandwidth. Efficiency of this antenna is 84 % and gain is almost same as reference antenna. Loading of reference RMPA with split ring resonator provides less shifts in resonant frequency, but it provides a very broad bandwidth, without reduction in gain of antenna.

Thus among all the three metamaterial which are used for loading RMPA, best results are obtained by embedding patch antenna with split ring resonators. Split ring resonators embedded patch antenna has bandwidth of 800 MHz and gain of 4.39 dB

and it resonates at subwavelength frequency of 3.5 GHz. in short, if antenna designer requirement is only to design subwavelength antenna and to achieve maximum miniaturization, then ENG metamaterial loading can be used and for optimum solution MNG metamaterial loading should be used.

4.9. CONCLUDING REMARKS

In this chapter, investigation to design a subwavelength and broad-band RMPA using C shaped, split ring MNG metamaterial and double folded I shaped ENG metamaterial is done. ENG metamaterial provides better compactness as compared to MNG metamaterial but at the cost of gain. MNG metamaterial give optimum solution for designing subwavelength and broadband antenna. Performance enhancement in terms of subwavelength radiating patch, broad-bandwidth, better and radiation efficiency, optimum gain are obtained and verified experimentally.

Among the investigated metamaterial of double folded I shape, C shape and split ring, the split ring resonator gives the best results. Reference patch antenna resonates at 5.2 GHz with the impedance bandwidth of 1.3% and has gain of 4.48 dB. Whereas the proposed split ring embedded patch antenna resonates at subwavelength frequency of 3.5 GHz with impedance bandwidth of 22.8% .the proposed antenna has a gain of 4.39 dB with the marginal reduction in gain as compared to reference antenna.

CHAPTER 5

DESIGN OF COMPACT & HIGH PERFORMANCE PATCH ANTENNA USING LEFT HANDED DOUBLE H SHAPED METAMATERIAL

In this chapter, a compact double H shaped metamaterial embedded patch antenna is designed, fabricated and analyzed. Method to improve the return loss, bandwidth and gain of patch antenna using double H metamaterial without altering resonant frequency of antenna is also presented.

5.1. INTRODUCTION

Due to low profile, simple structure, low cost, easy fabrication and simple feeding mechanism microstrip patch antennas are found to be extremely useful and are compatible for wireless applications. But these antennas have low gain and narrow bandwidth because of the effect of the surface wave on radiation pattern. These factors limit the applications of patch antennas. Dependence of resonant frequency on dimensions of patch antenna is another factor which limits its application. Techniques like high dielectric constant material, slots on the patch, shorting walls or shorting pin have been discussed in literature for achieving the miniaturization of patch antenna. But these techniques have the problem of impedance matching and cross polarization as discussed earlier in chapter 2.

Metamaterial can be used for enhancing the performance and reducing the profile of patch antenna. In previous chapters, use of ENG and MNG metamaterial has been investigated to improve the performance of patch antenna and to reduce its size. In this chapter, left handed material (LHM) has been used for performance enhancement and size reduction of patch antenna. Double H shaped double negative (DNG) resonant metamaterial is investigated to design the patch antenna. This DNG metamaterial [138] is proposed by Michal Blaha et. al, but no work is presented to design a patch antenna using this metamaterial. In this work, two different antennas are proposed using this metamaterial. First is the design of compact RMPA which results in with good impedance matching and enhanced bandwidth as compared to reference antenna. In designing of this antenna conventional technique of reducing the size of patch using the slots has been combined with metamaterial technique and this result in more compactness and very easy to fabricate.

Second is the design of high performance patch antenna by embedding the double H shaped resonator underneath the patch antenna without altering its resonating frequency.

5.2. DESIGN AND RESULTS OF REFERENCE PATCH ANTENNA

Reference antenna is same as designed in chapter 3. It is designed on FR_4 epoxy substrate having dielectric constant of 4.4 and loss tangent =0.0025. The length and width of patch antenna is 17.6 mm × 13.2mm respectively. The ground size dimensions are 41.59 mm × 35.9 mm and antenna is fed with inset microstrip line.

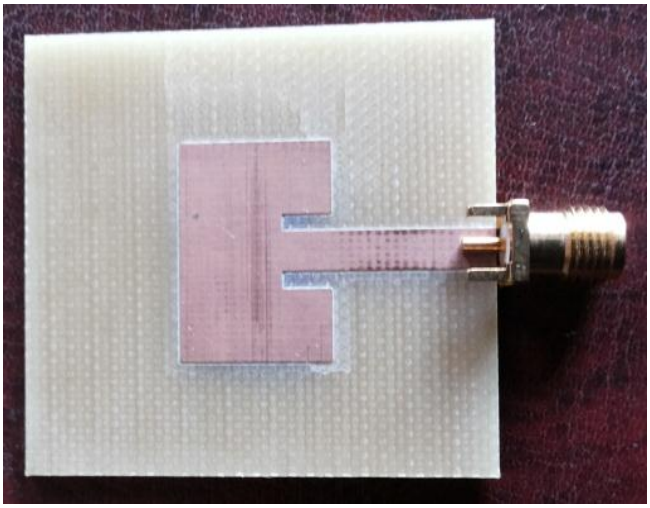


Fig. 5.1: Top View of Fabricated Reference Patch Antenna

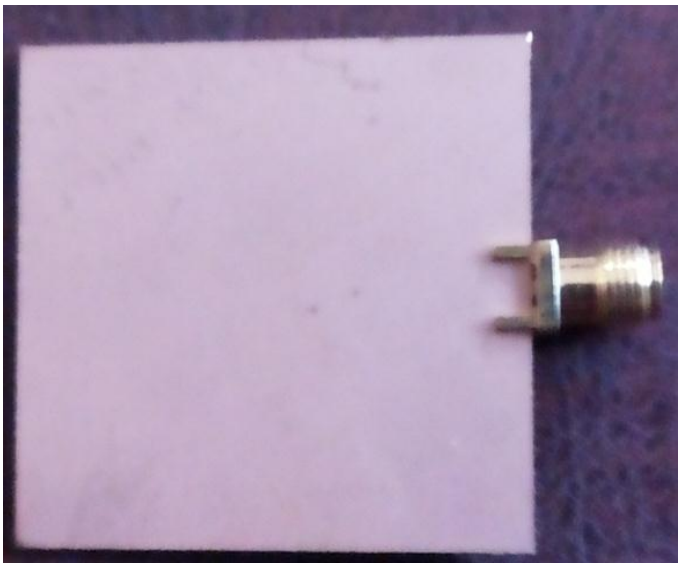


Fig. 5.2: Bottom View of Fabricated Reference Patch Antenna

Top and bottom view of fabricated reference antenna is shown in Fig 5.1 and Fig. 5.2 respectively.

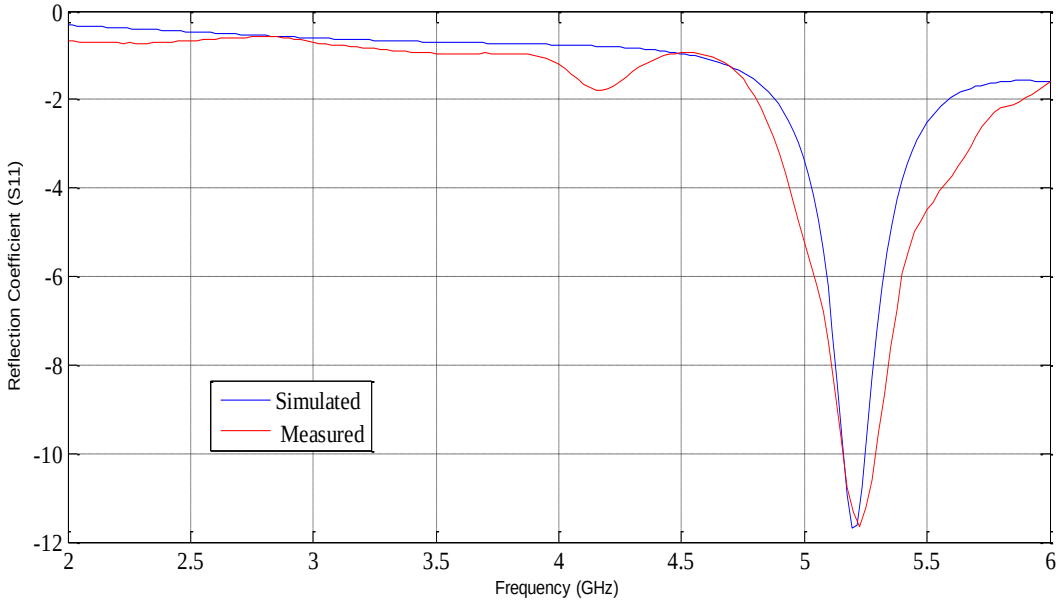


Fig .5.3 Simulated and Measured Reflection Coefficient (S11) of Reference Antenna

Fig. 5.3 depicts the simulated and fabricated reflection coefficient of reference RMPA. Antenna resonates at 5.2 GHz with -11.68 dB return loss and has 70 MHz bandwidth. Fig. 5.4 shows the simulated and measured gain of reference antenna.

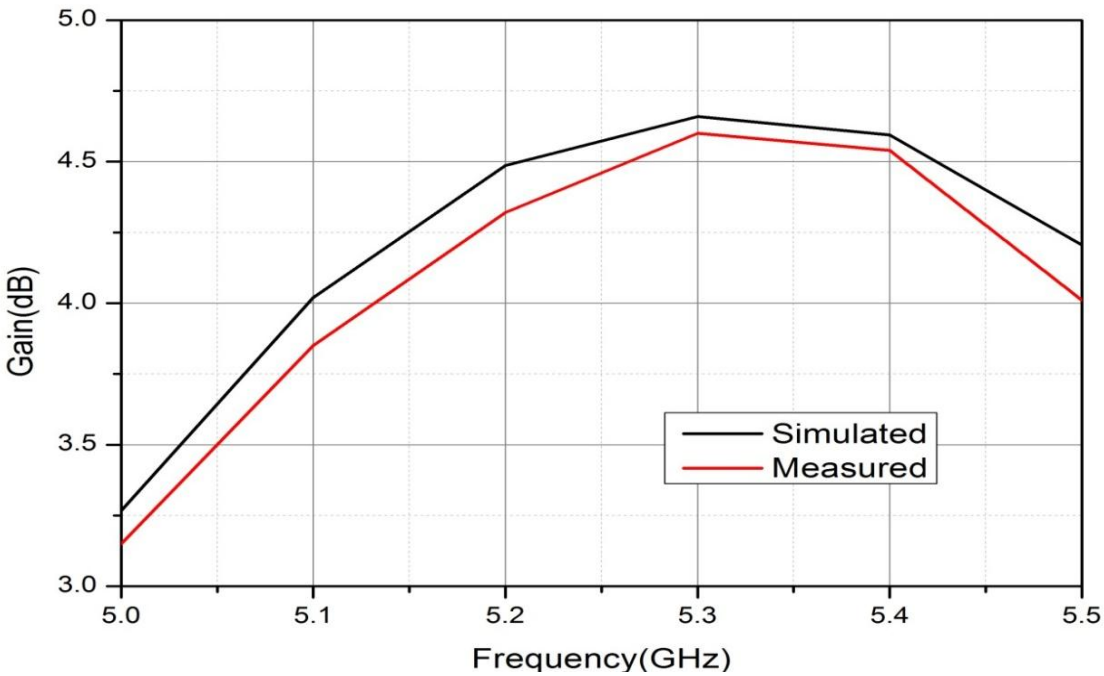


Fig. 5.4: Simulated and Measured Gain of Reference Antenna

Radiation pattern of reference antenna in E and H plane is shown in Fig. 5.5 and Fig. 5.6.

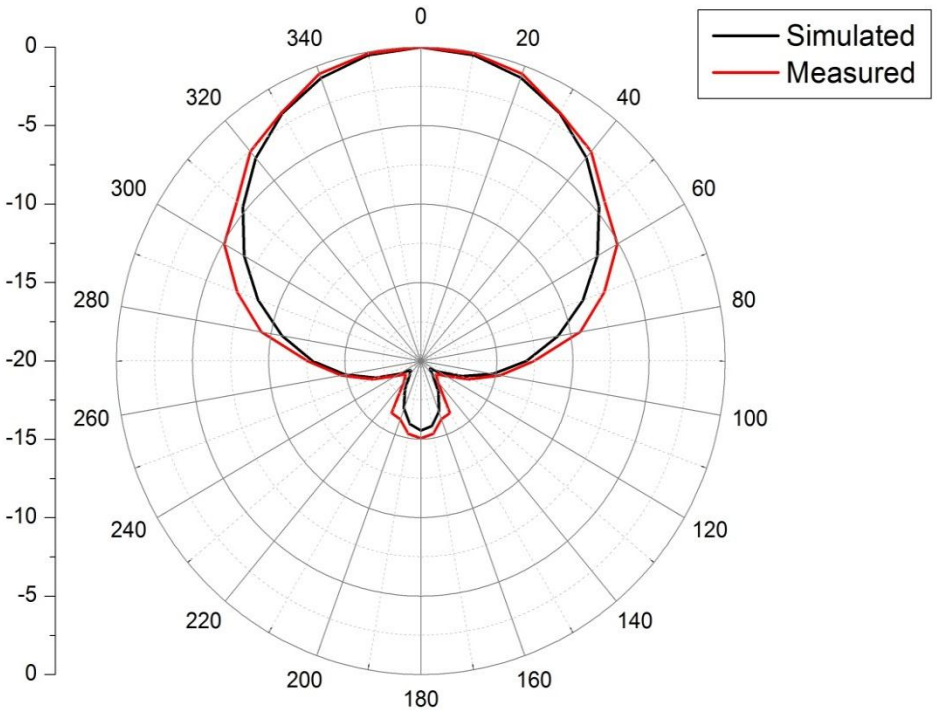


Fig. 5.5: Simulated and Measured Radiation Pattern of Reference Antenna in E Plane

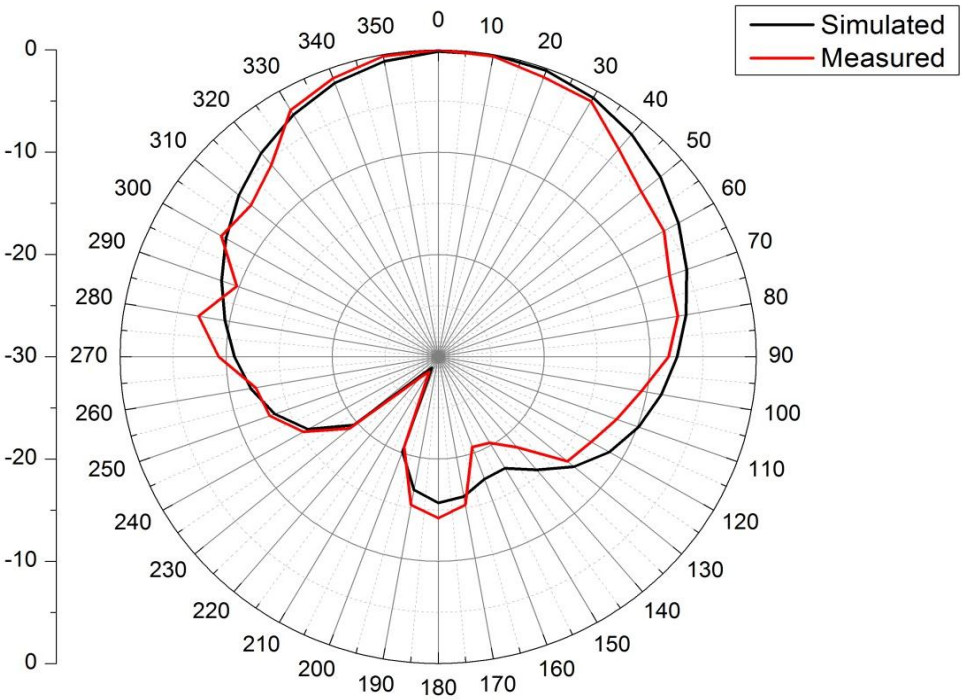


Fig. 5.6: Simulated and Measured Radiation Pattern of reference antenna in H Plane

5.3. DESIGN OF COMPACT PATCH ANTENNA

To achieve miniaturization slots are cut in the rectangular patch antenna as shown in Fig. 5.7 and Fig.5.8. Two rectangular slots of dimension 7.5 mm × 6.5 mm are cut in RMPA which results in shift in resonant frequency to lower side, but reflection coefficient is not less than -10dB, which indicates that antenna is not impedance matched as shown in Fig. 5.9.

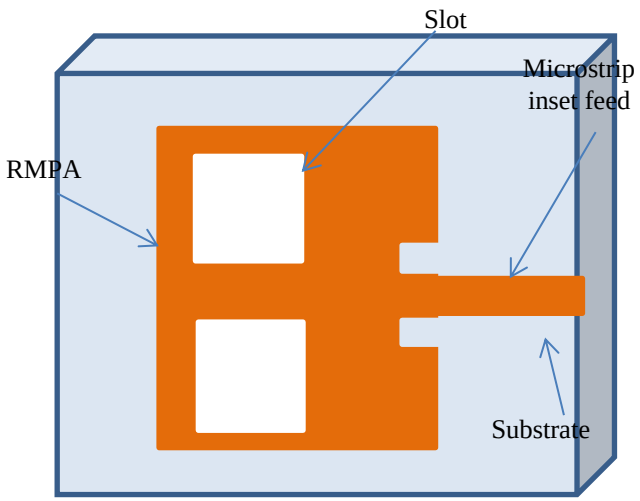


Fig. 5.7: Geometric Structure of RMPA with Slots

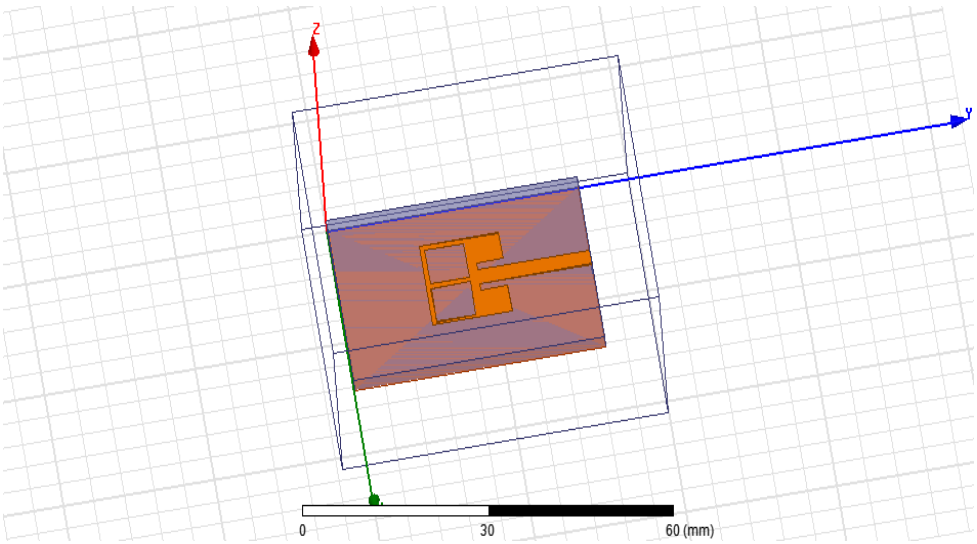


Fig. 5.8: Simulation Model of RMPA with Slots in HFSS

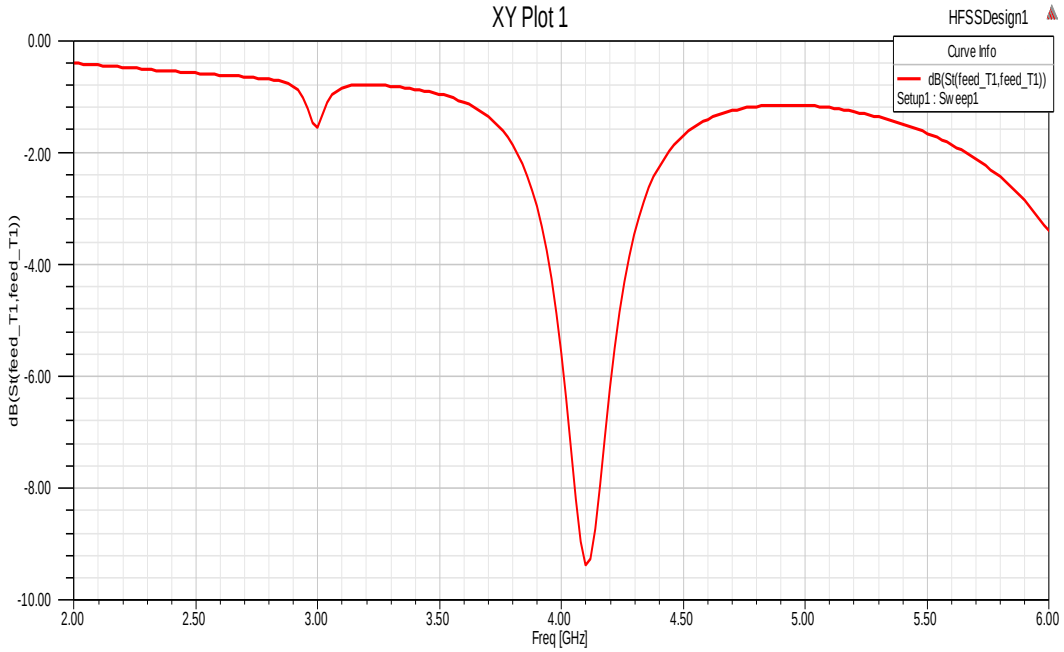


Fig. 5.9: Reflection Coefficient (S11) of RMPA with Slots

5.3.1. Design of Double H Shaped Metamaterial For Compact Antenna

Double H shaped metamaterial is designed to achieve the impedance matching and to obtain sub-wavelength resonance in RMPA. Unit cell of double H shaped resonator as shown in Fig 5.10 is modelled and simulated using HFSS. Fig. 5.11, shows the geometrical structure of optimized double H-shaped resonator with Length L1=5.5.mm, L2=5.5 mm, L3=4.5 mm and width W1=0.5mm.

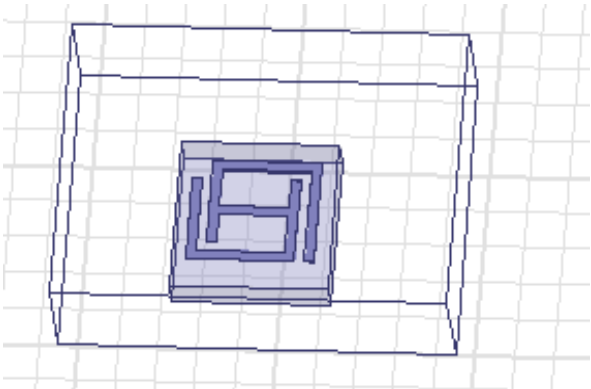


Fig .5.10: Simulated Model of Double H shaped Metamaterial

The effective constitutive parameters permeability (μ_r) and permittivity (ε_r) are calculated from S parameters using the Nicolson-Ross-Weir (NRW) method using the equation (5.1-5.2).

$$\mu_r = \frac{2c(1-v2)}{\omega d.i(1+v2)} \tag{5.1}$$

$$\varepsilon_r = \frac{2c(1-v1)}{\omega d.i(1+v1)} \tag{5.2}$$

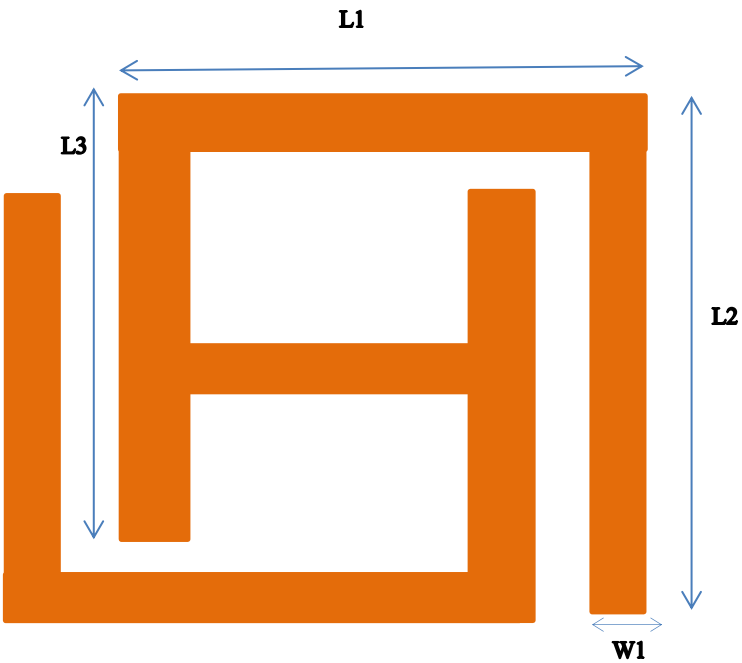


Fig .5.11: Geometric Structure of Double H shaped Metamaterial

Where ω is the frequency in radians, c is velocity of light and d is the thickness of substrate. $v1$ and $v2$ are complex terms and the values of $v1$ and $v2$ are calculated as $v1 = S_{21} + S_{11}$ and $v2 = S_{21} - S_{11}$, where S_{11} and S_{21} are S parameters.

Fig. 5.12 presents the curves showing permittivity and permeability of unit cell of metamaterial reterived using S parameter using the equation (5.1-5.2). Double H is a double negative type metamaterial as both ε_r and μ_r are negative in the frequency band (5.8 GHz-6 GHz). In the frequency band (4 GHz – 5.5 GHz), relative permittivity of double H resonator is greater than relative permittivity of FR_4 substrate, although relative permeabilty of resonator is approximately same as that of FR_4 substrate.

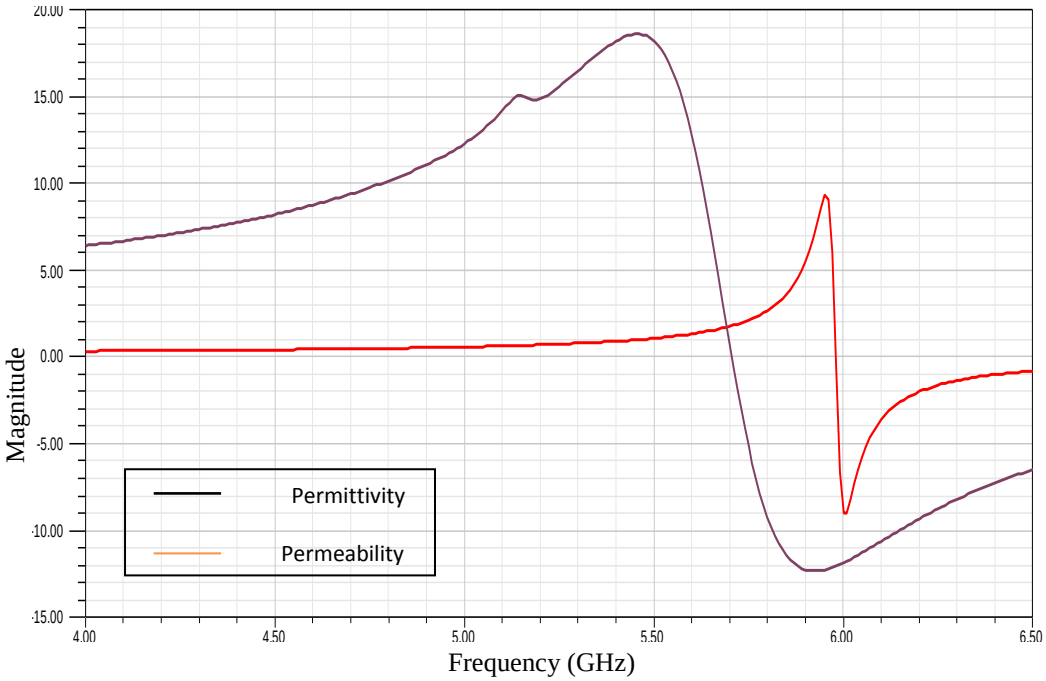


Fig. 5.12: Permittivity and Permeability of Double H shaped Metamaterial

5.3.2. Design of Double H Shaped Embedded Compact Patch Antenna

To achieve the impedance matching and to obtain sub-wavelength resonance double H shaped metamaterial is embedded in slots. Fig. 5.13 shows the geometric structure of proposed RMPA with double H shaped metamaterial embedded in the slots of patch.

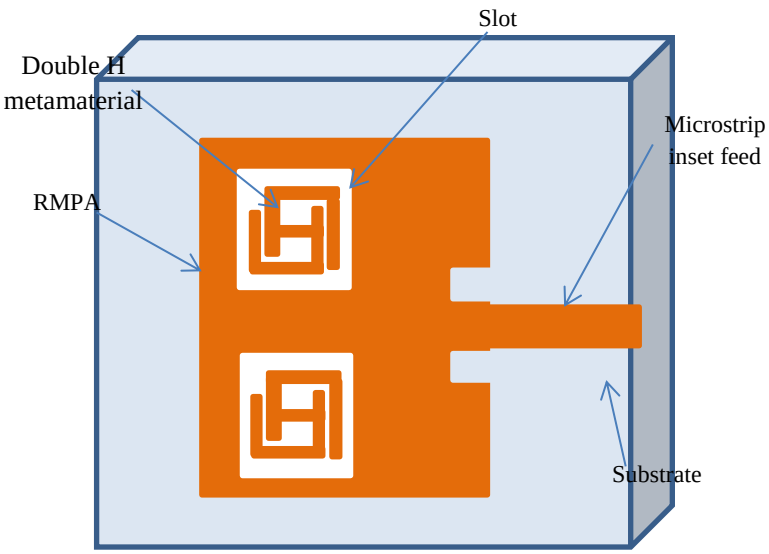


Fig. 5.13: Geometric Structure of Double H shaped Metamaterial Embedded RMPA

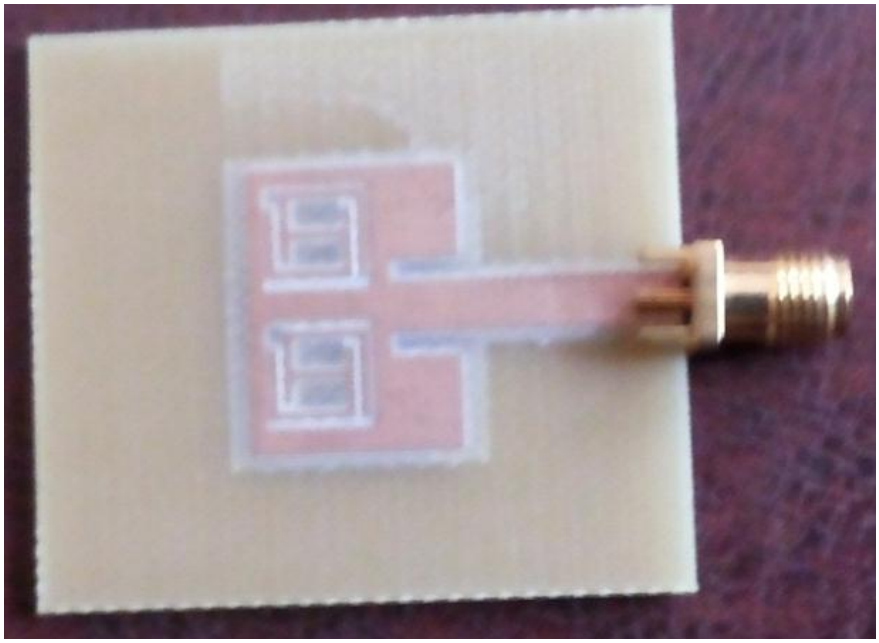


Fig. 5.14: Top view of Double H shaped Metamaterial Embedded Fabricated RMPA

Patch antenna shown in Fig. 5.13 is simulated and optimized in HFSS. Prototype of the proposed optimized antenna is fabricated. Top and bottom view of fabricated antenna is shown in Fig. 5.14 and Fig. 5.15 respectively.

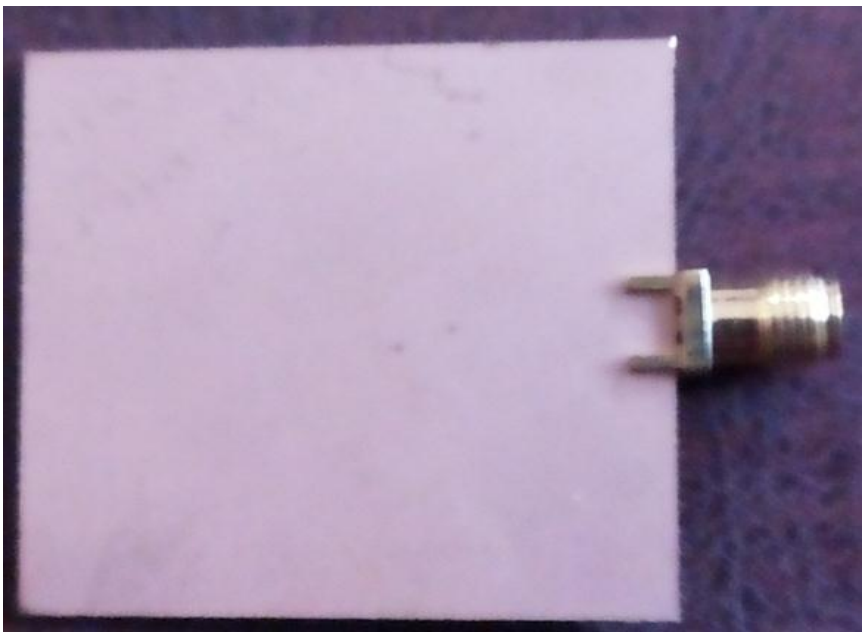


Fig. 5.15: Bottom view of Double H Shaped Metamaterial Embedded Fabricated RMPA

5.4. RESULT AND DISCUSSION OF PROPOSED COMPACT PATCH ANTENNA

RMPA with slots has capacitive reactance near 4.3 GHz which is cancelled by inductive reactance of the double H resonator and thus good impedance matching is achieved. Optimized double H shaped embedded RMPA is fabricated and tested. Fig. 5.16 depicts the simulated and measured reflection coefficient of metamaterial embedded antenna. The proposed antenna resonates at 4.3 GHz with 20.04dB return loss and has 110 MHz bandwidth. From graph shown in Fig. 5.16, it is quite clear that simulated and the measured reflection coefficient of proposed antenna is in good agreement.

Fig. 5.17 shows the simulated gain of proposed compact antenna at $\varphi = 0^0$ and $\varphi = 90^0$ at resonating frequency of 4.38 GHz. Measured and simulated gain is compared for proposed compact antenna at $\varphi = 0^0$ in Fig. 5.18. From this graph it is clear that both simulated and measured gain are approximately same.

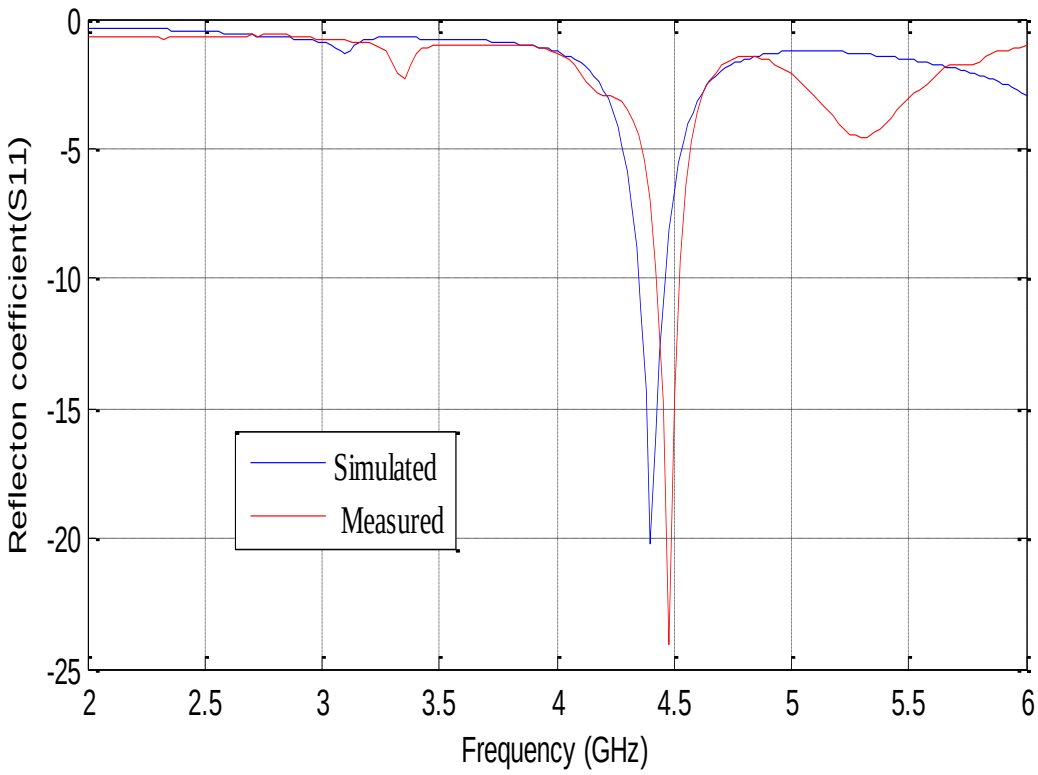


Fig. 5.16: Simulated and Measured Reflection Coefficient (S11) of Double H Shaped Metamaterial Embedded Patch Antenna

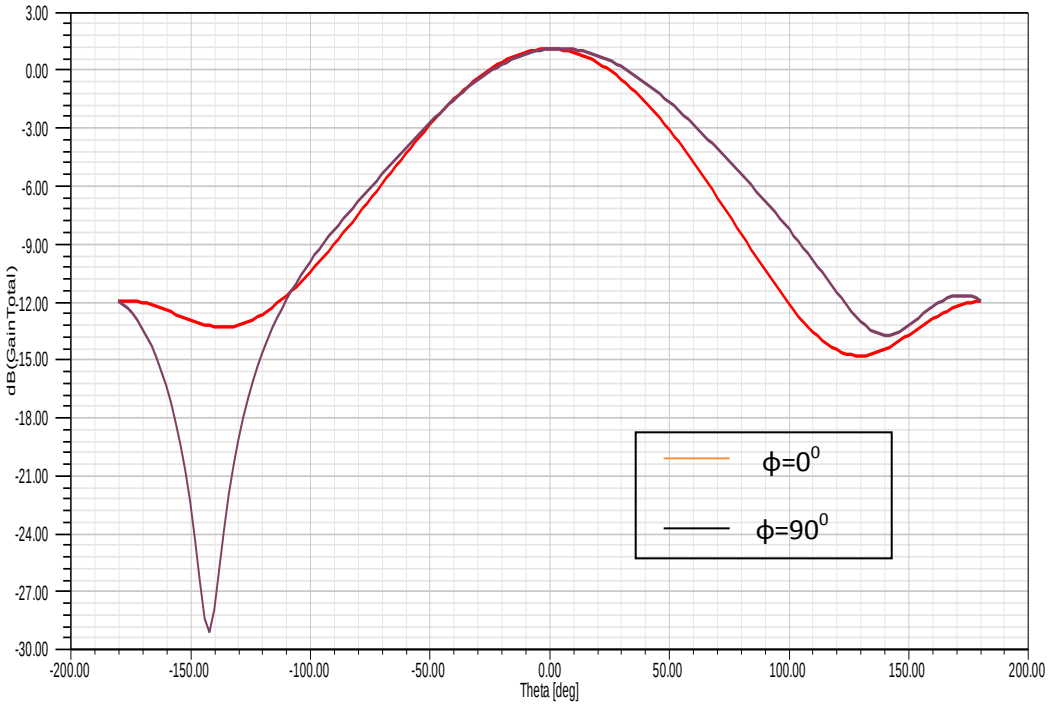


Fig.5.17: Simulated Gain of Double H Shaped Metamaterial Embedded Patch Antenna at Resonating Frequency of 4.38 GHz

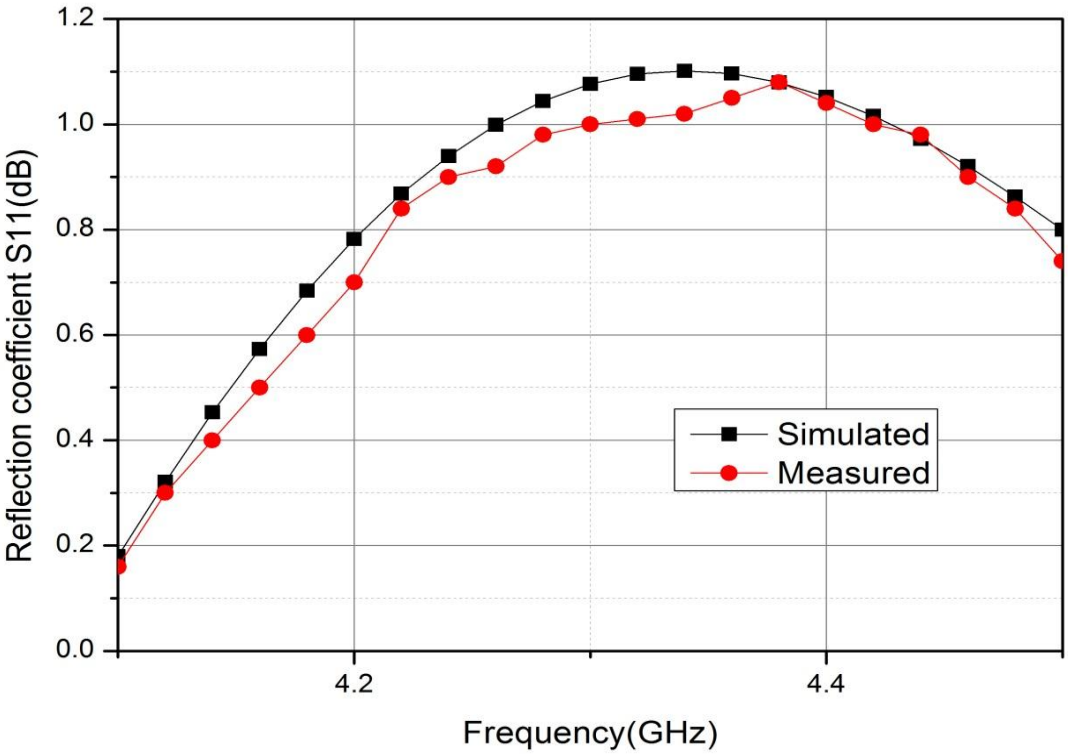


Fig.5.18: Simulated and Measured Gain of Double H Shaped Metamaterial Embedded Patch Antenna at Resonating Frequency of 4.38 GHz

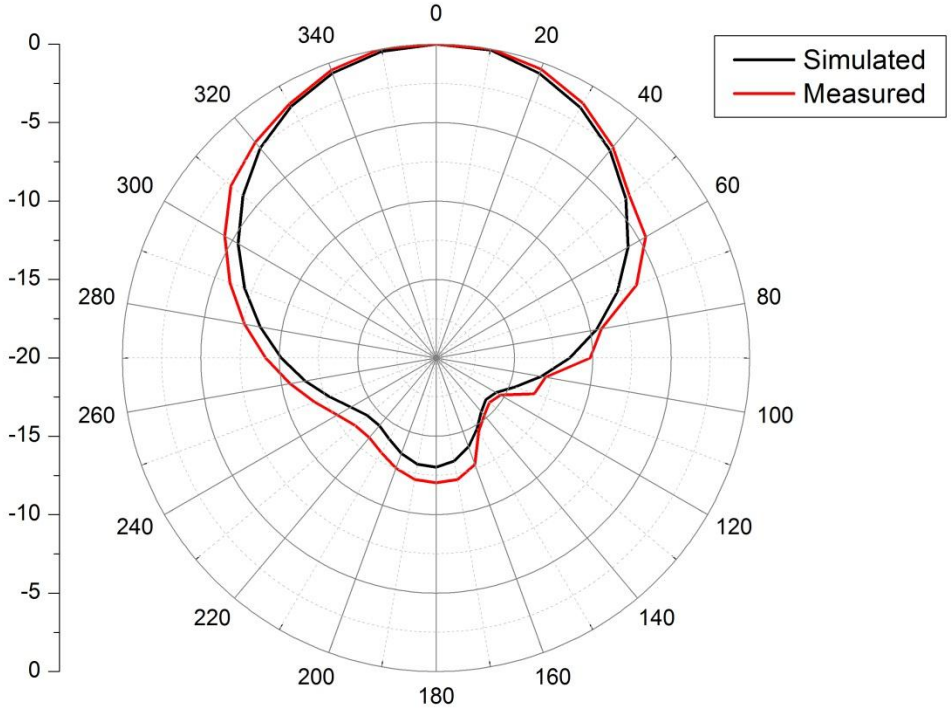


Fig. 5.19: Measured and Simulated Radiation Pattern of Double H Shaped Metamaterial Embedded Patch Antenna in E plane at Resonating Frequency of 4.38 GHz

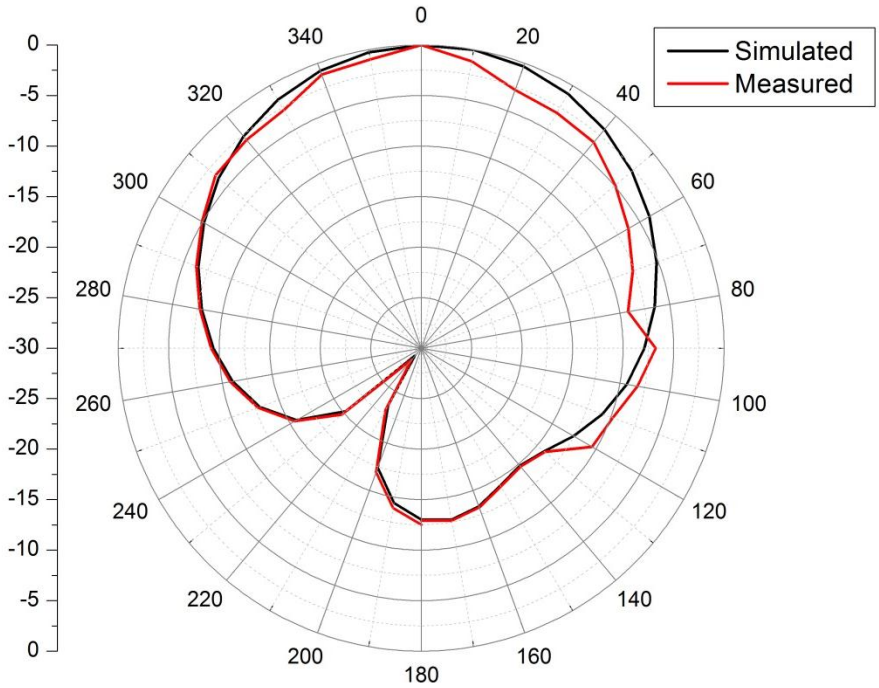


Fig. 5.20: Measured and Simulated Radiation Pattern of Double H Shaped Metamaterial Embedded Patch Antenna in H plane at Resonating Frequency of 4.38 GHz

Fig. 5.19 and 5.20 shows the measured and simulated radiation pattern of proposed compact antenna in E plane and H plane respectively.

Thus a compact double H shaped metamaterial-embedded rectangular microstrip patch antenna is designed and verified experimentally. The slots are cut in rectangular microstrip patch antenna (RMPA) to decrease the resonant frequency, but this leads to impedance mismatch. To overcome this effect a double H shaped metamaterial is embedded inside the slot. This technique not only provides a good impedance matching and bandwidth, but also provides the 34% compactness in size. The proposed antenna is simulated and optimized using HFSS software. The prototype antenna has been fabricated and measured results of the proposed antenna are in good agreement with simulated results.

Embedding a double H metamaterial in reference patch antenna is a useful technique to achieve better impedance match at desired resonance frequency. Antenna miniaturization is normally achieved by loading the metamaterial underneath the substrate which is difficult to fabricate. But antenna designed using proposed technique is very simple to fabricate. In proposed antenna 34% miniaturization is achieved and bandwidth improves form 70 MHz to 110 MHz as compared to reference antenna.

In the next section, design and analysis of high performance patch antenna without altering the resonant frequency of reference antenna using double H shaped metamaterial is presented.

5.5. DESIGN AND RESULTS OF HIGH PERFORMANCE RMPA USING DOUBLE H SHAPED RESONATOR

To improve the performance parameters of reference RMPA as shown in Fig. 5.1 and Fig. 5.2 without altering its resonant frequency, double H shaped metamaterial is designed such that its permittivity and permeability are negative at resonant frequency (5.2GHz) of reference antenna.

Unit cell of double H shaped resonator is modelled and simulated using HFSS as shown in Fig. 5.10 and Fig. 5.11. But now this metamaterial is designed such that it resonates at 5.2 GHz.

The optimized geometric parameters of resonator are Length L_1=5.8.mm, L_2=5.8 mm, L_3=4.8 mm and width W_1=0.5mm in this case. The effective constitutive parameters permeability (μ_r) and permittivity (ε_r) as shown in Fig. 5.21 are calculated

from S parameters using the Nicolson-Ross-Weir (NRW) approach using the equation (5.1) and (5.2).

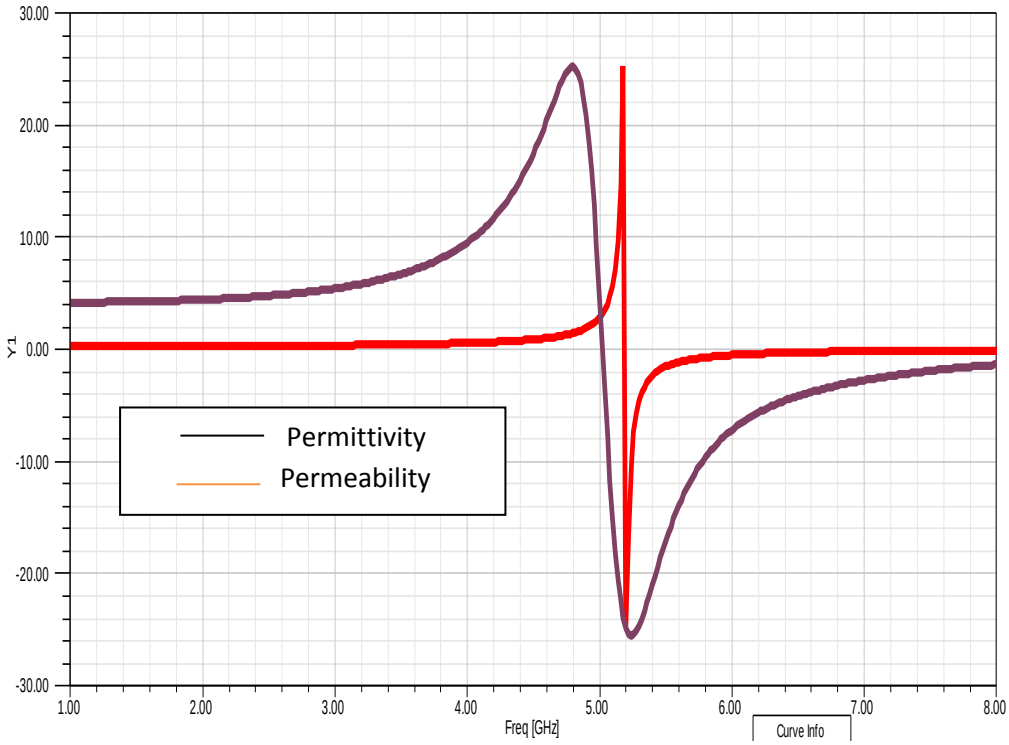


Fig. 5.21: Real Permittivity and Permeability of Double H shaped Resonator

5.5.1. DOUBLE H SHAPED METAMATERIAL EMBEDDED BENEATH THE PATCH

The optimized double H shaped resonator is placed within the substrate at a height of 1.56 mm from ground as shown in Fig. 5.22. Antenna resonates at 5.2 GHz with reflection coefficient of -21.99 dB as shown Fig. 5.23. impedance bandwidth of this double H shaped metamaterial embedded antenna is 220 MHZ. Gain of antenna is 4.47 dB as shown in Fig 5.24, which is approximately same as reference antenna.

Thus by embedding metamaterial the reflection coefficient improves from -11.68 dB to -21.99 dB because of better impedance matching. Bandwidth of the designed antenna increases from 70 MHz to 220 MHz as compared to reference antenna. The radiation pattern of metamaterial embedded antenna is shown in Fig. 5.25 which is same as the reference antenna.

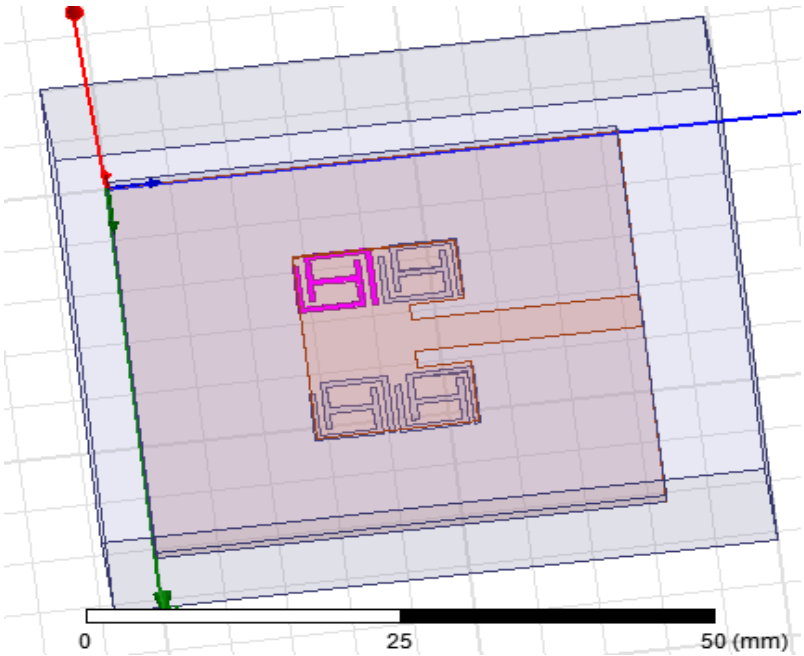


Fig. 5.22: Double H Shaped Metamaterial Embedded Microstrip Patch Antenna

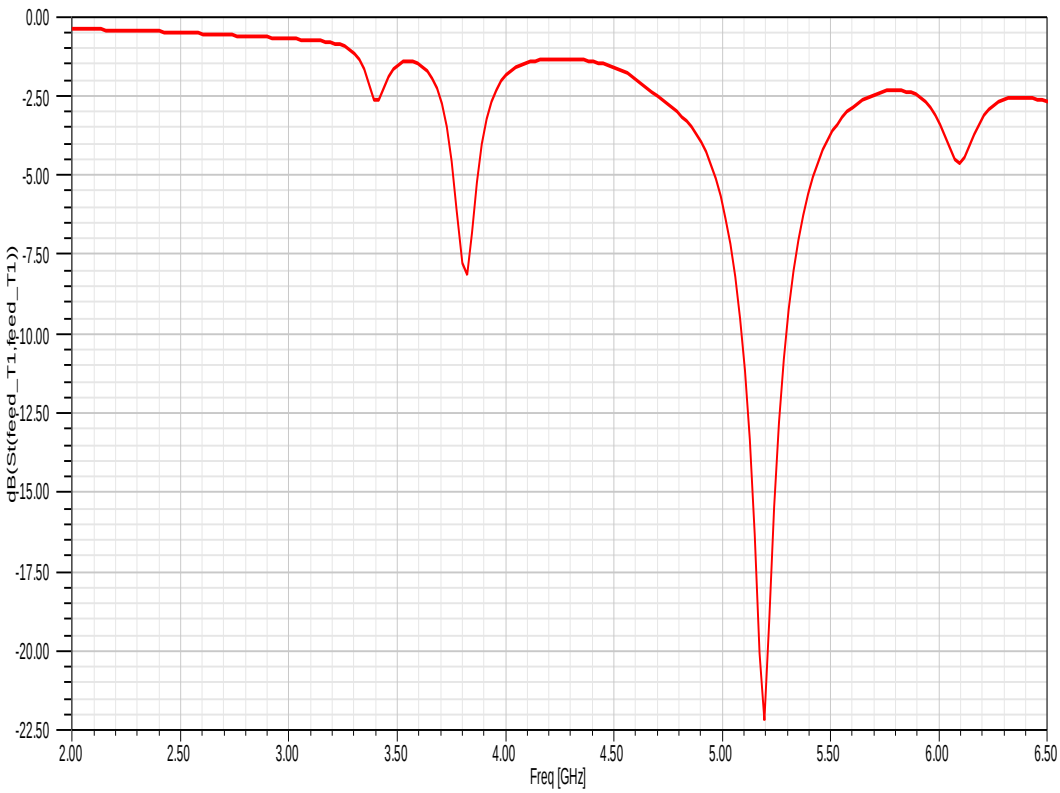


Fig.5.23: Simulated Reflection Coefficient (S11) of Metamaterial Embedded Patch Antenna

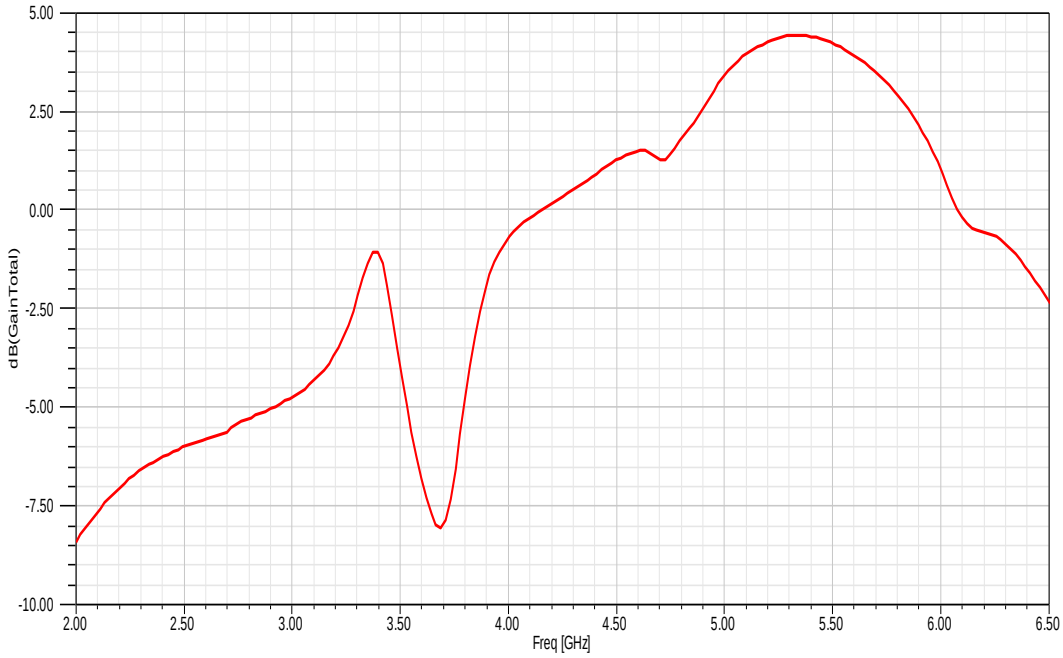


Fig. 5.24: Gain of Metamaterial Embedded Patch Antenna

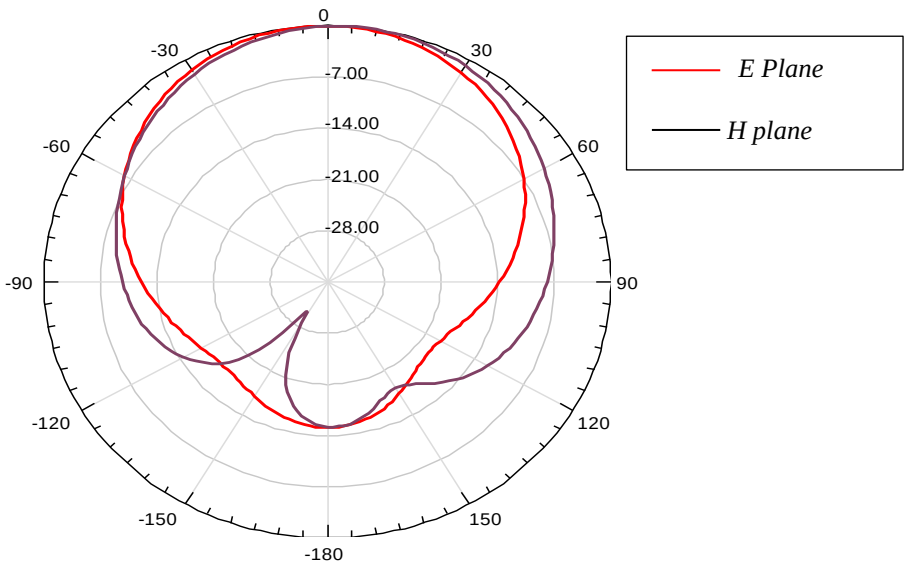


Fig. 5.25: Radiation Pattern of Metamaterial Embedded Patch Antenna in E-plane and H-plane

5.5.2. Double H Shaped Metamaterial Embedded RMPA With Superstrate

To further increase the gain, a superstrate of double H shaped resonator is applied over the metamaterial embedded patch antenna. From Fig. 5.21, we can see the permittivity of resonator is zero close the resonating frequency and hence the refractive index

$$n = \pm\sqrt{\varepsilon\mu}$$

will be zero. Here n is refractive index and ε and μ are permittivity and permeability of metamaterial. As refractive index is zero near resonant frequency, all the rays coming from the antenna will be very almost normal to the surface and all the refracted rays will be in almost in the same direction around the normal and thus the better gain and efficiency can be achieved.

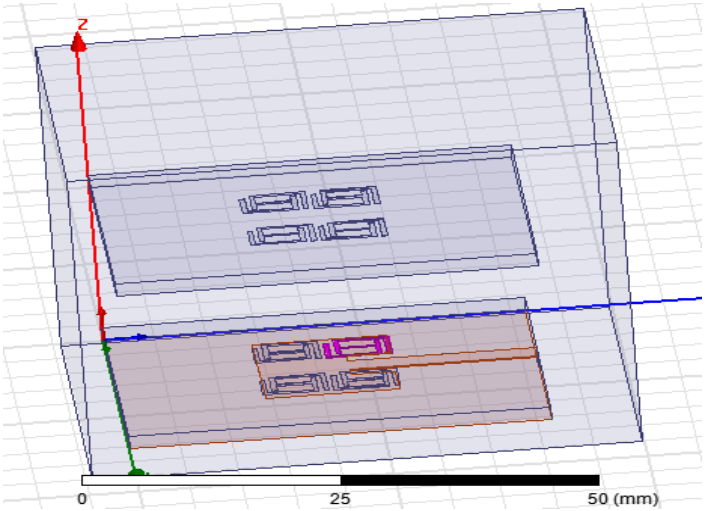


Fig. 5.26: Simulated model of Metamaterial Embedded Patch Antenna with Superstrate

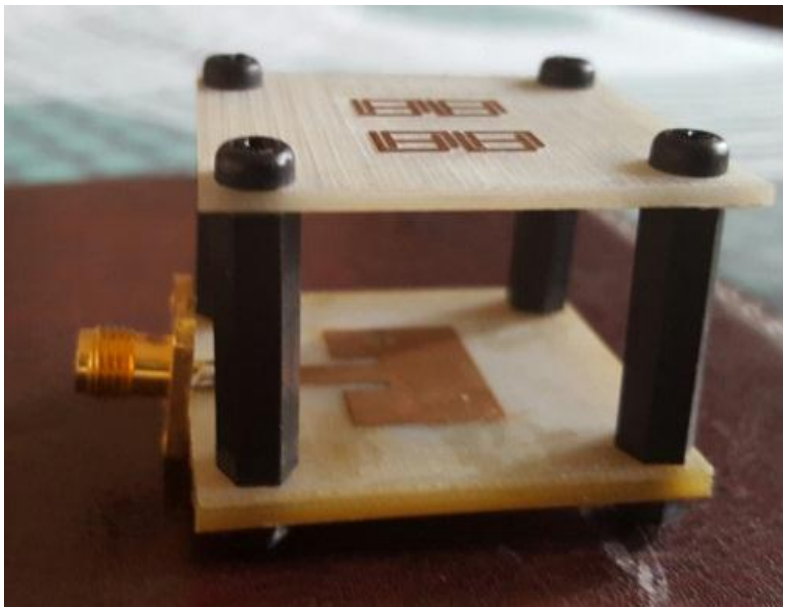


Fig. 5.27: Fabricated Metamaterial Embedded Patch Antenna with Superstrate

Fig. 5.26 and Fig 5.27 show the simulated and fabricated metamaterial embedded antenna with superstrate of double H resonator. The fabricated antenna is tested using Vector Network analyser and measured and simulated results are shown in Fig. 5.28.

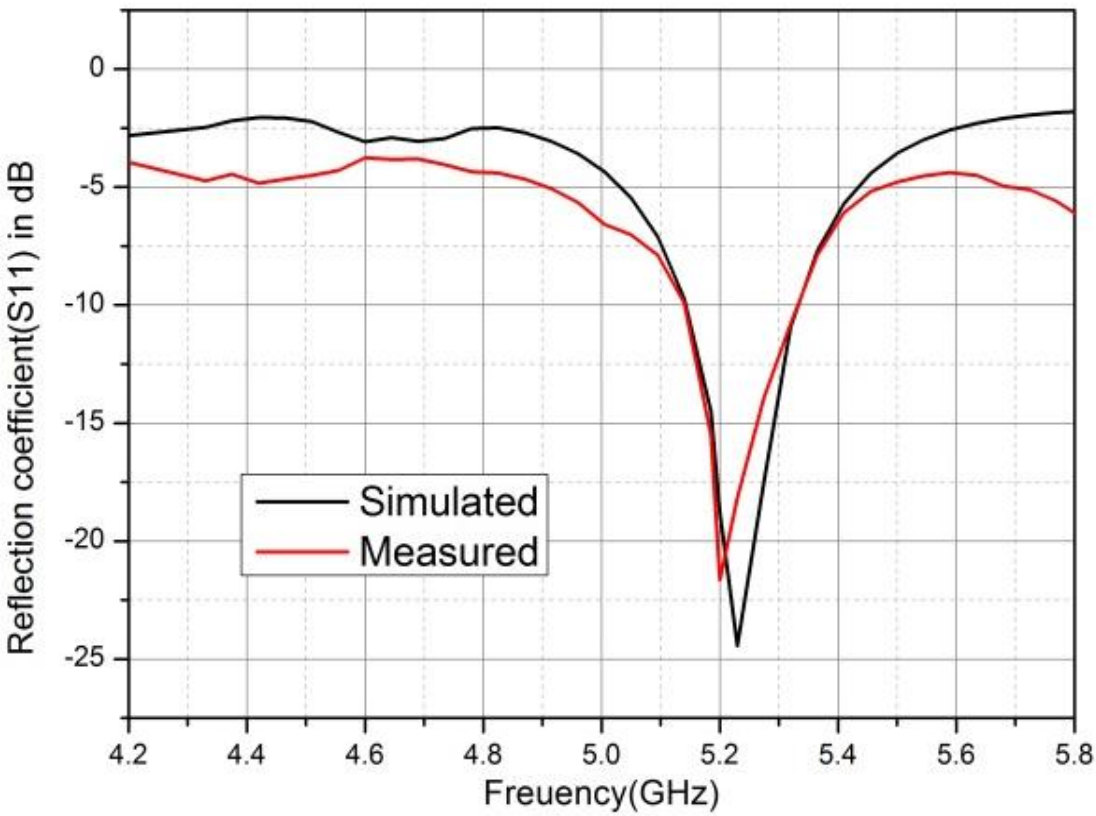


Fig. 5.28: Simulated and Measured Reflection Coefficient (S11) of Proposed RMPA

From the graph 5.28, it can be seen that resonant frequency of metamaterial embedded antenna does not change by adding the superstrate. The gain of fabricated antenna is measured in anechoic chamber and experimental and simulated results are shown in Fig.5.29.

Gain of proposed antenna improves from 4.48dB to 6.72 dB because of the addition of superstrate of metamaterial and efficiency improves from 57.3% to 80.2%. The simulated and measured radiation pattern of antenna in E-plane and H-plane is shown in Fig. 5.30 and Fig. 5.31 respectively. Simulated and measured gains are approximately same as can be seen from the graph shown in Fig. 5.29. Shape of radiation pattern of the proposed antenna in E plane and H plane are same as that of the reference antenna.

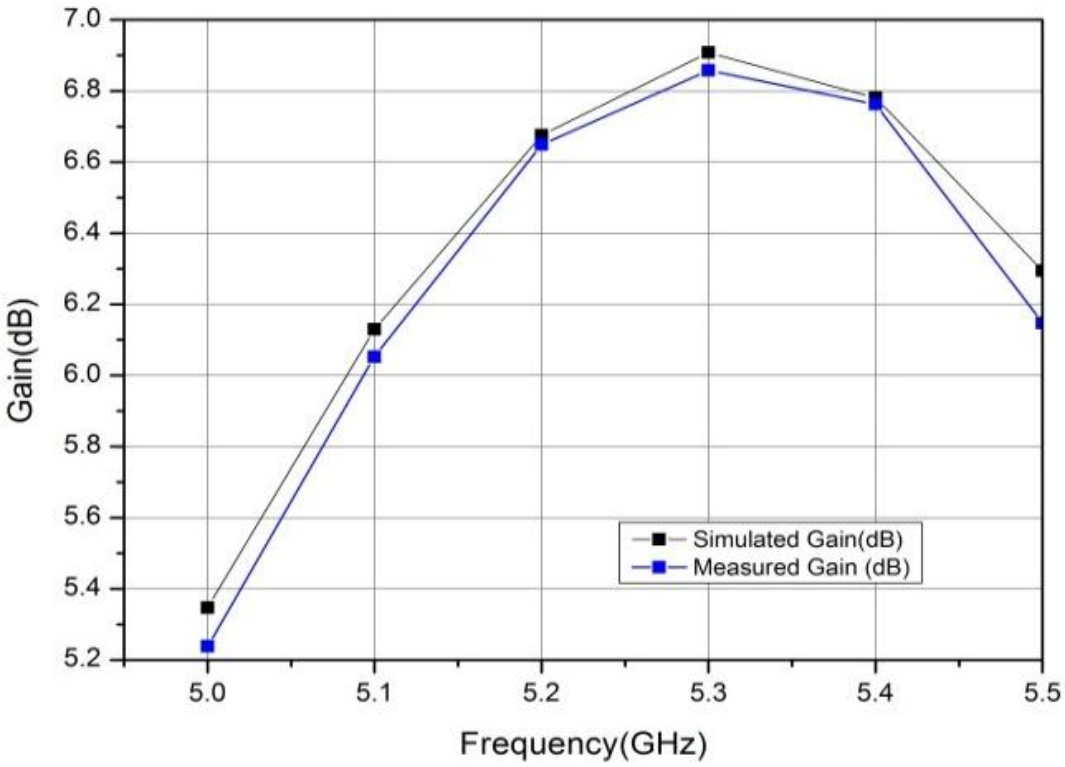


Fig .5.29: Simulated and Measured Gain of Proposed RMPA

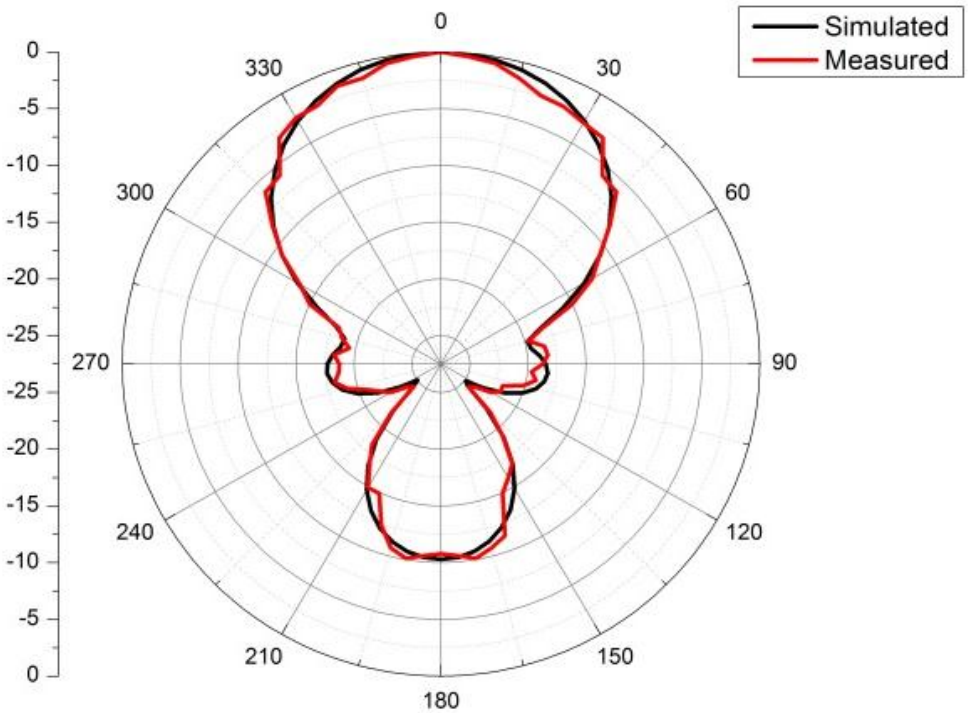


Fig. 5.31: Simulated and Measured Radiation Pattern of Proposed RMPA in E-plane

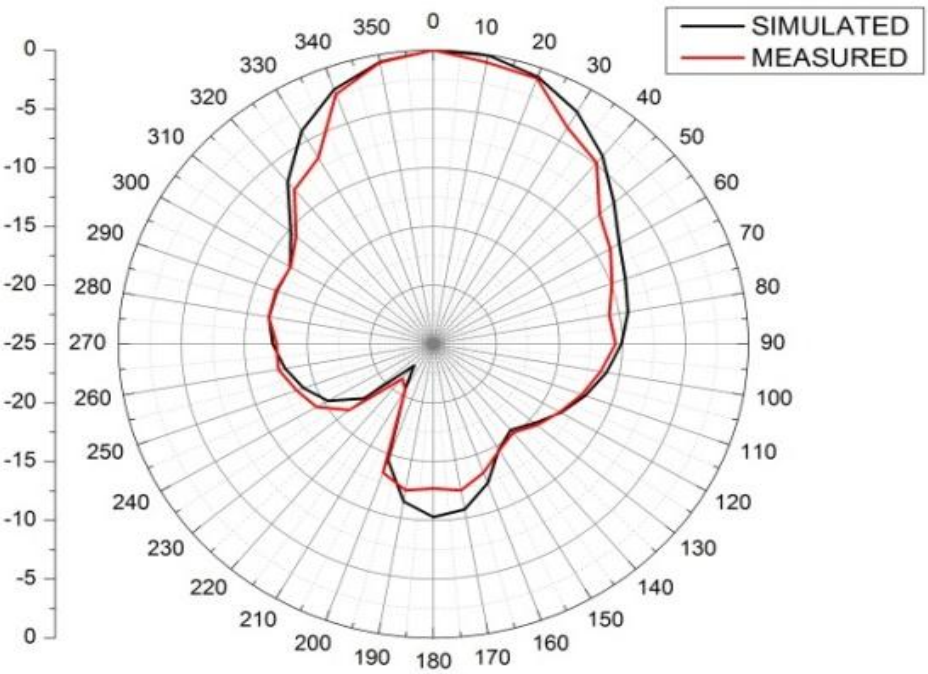


Fig. 5.30: Simulated and Measured Radiation Pattern of Proposed RMPA in H-plane

Thus a high performance RMPA is designed using double H shaped metamaterial. Firstly, the double H shaped metamaterial is designed and optimized at 5.2 GHz at the resonant frequency of patch antenna and it is found that embedding of this metamaterial in the substrate beneath the reference patch antenna, improves its return loss and bandwidth without changing the resonant frequency and gain.

To further enhance the gain and efficiency of the metamaterial embedded RMPA a superstrate of double H shaped metamaterial is applied at distance of λ/3 over it. Finally, a high gain, broadband and good impedance matched metamaterial inspired RMPA is presented. The proposed antenna is simulated and optimized using HFSS software. The prototype antenna has been fabricated and measured results of the proposed antenna are found to be in good agreement with simulated results

Table 5.1 shows the comparison of performance parameters of proposed antenna with reference antenna.

Parameter	Reference RMPA		Double H shaped metamaterial embedded RMPA		RMPA with embedded substrate and superstrate of double H metamaterial (Proposed antenna)	
Resonating Frequency	5.2 GHz		5.1941GHz		5.22 GHz	
Return loss	-11.68 dB		-21.99dB		-22.78 dB	
Bandwidth	70 MHz		220 MHz		220 MHz	
Gain	4.48dB		4.47dB		6.72 *dB*	
3dB Beamwidth	78.63^0 at $\varphi = 0^0$	85.69^0 at $\varphi = 90^0$	78.65^0 at $\varphi = 0^0$	85.79^0 at $\varphi = 90^0$	63.3^0 $\Phi=0^0$	58.83^0 $\Phi=90^0$
Radiation Efficiency	57.3%		57.2%		80.2%	

Table 5.1: Comparison of various performance parameters of reference and proposed RMPA

5.6. CONCLUDING REMARKS

In this chapter, design of compact antenna by embedding double H shaped metamaterial in slots of patch antenna and design of good performance patch antenna without altering its resonant frequency is presented. Designing a compact antenna by embedding a double H metamaterial in reference patch antenna is a useful technique as it provides better impedance match at desired resonance frequency. Antenna miniaturization is normally achieved by loading the metamaterial underneath the substrate which is difficult to fabricate, but antenna designed using proposed technique is very simple to fabricate. In proposed antenna miniaturization of 34% is achieved and bandwidth improves form 70 MHz to 110 MHz as compared to reference antenna.

A high gain RMPA with good impedance matching and better bandwidth as compared to reference antenna is also designed using DNG (double Negative) double H shaped metamaterial. The proposed antenna return loss improves from 11.68 dB to 22.78 dB and efficiency improves from 57.3% to 80.2% relating to reference antenna. These improvements depict the better impedance matching of metamaterial embedded antenna as compared to reference antenna. The proposed antenna has 6.72 dB gain at resonance frequency and more directive than reference antenna. Bandwidth of metamaterial embedded antenna improves from 70 MHz to 220 MHz. Thus it can be concluded that performance parameters of antenna like gain, return loss, bandwidth, efficiency and directivity can be improved by proper designing and embedding of metamaterial according to reference antenna.

CHAPTER 6

DESIGN OF CIRCULARLY POLARIZED ANTENNA USING CHIRAL METAMATERIAL

Circularly polarized antennas have gained much attention in wireless communication, radar systems and satellite communications as these antennas are more reliable as compared to linearly polarized (LP) antennas. Aim of this chapter is to convert a linearly polarized RMPA to circularly polarized antenna using chiral metamaterial without using complex feeding mechanism.

6.1. INTRODUCTION

Circular polarized antennas have achieved much consideration in wireless communication due to their characteristics which make them more reliable as compared to linearly polarized antennas. The waves produced by CP antennas have better mobility, penetration and less vulnerable to harsh weather conditions as compared to linear waves. Other advantages of CP antennas are elimination of alignment issues, better connectivity, reduced multipath effects and better signal strength through obstacles [97] [39].

Circular polarized antennas can be designed in different shapes and orientation like monopole antenna [36], helix antenna and horn antenna etc. But CP Microstrip patch antennas [125] [208] [194] [114] are more popular in today's rapid developing scenario of wireless industry because of small size, low cost, light weight and low profile. They are easily mountable and can be easily integrated with other planer components.

Several techniques have been reported in literature to design a patch antenna with CP [215] [101-102] [220]. All of these techniques use the complex feeding mechanism to produce two degenerate orthogonal modes of equal amplitude and 90^0 phase shift. In Conventional designing methods as reported above, feeding mechanism makes the design and fabrication of CP antenna difficult.

Recently, researchers have proposed the use of chiral metamaterial for designing the CP antenna [216] [222]. This technique exploits the unique inherent properties of chiral metamaterial to produce CP and eliminates the use of complex feeding mechanism as used in conventional techniques.

Chiral metamaterials [186] are the metamaterials [166] [11] [9] which lack the structural mirror symmetry in any plane. This property results in breaking the degeneracy between the two CP waves known as left hand circularly polarized wave and right handed circularly polarized wave. Due to this property, when the LP wave which can be assumed to be composed of opposite circularly polarized wave impinges on Chiral metamaterial, it generates two possible effects in LP wave: Circular dichroism and optical activity. Optical activity means the rotation of polarization plane of wave and circular dichroism means change of polarization from linear to elliptical. These two affect in chiral metamaterial are produced to due following extraordinary relationship [121] [193].

$$D = \varepsilon\varepsilon_0 E + j\kappa\sqrt{\varepsilon_0\mu_0 H} \tag{6.1}$$

$$B = -j\kappa\sqrt{\varepsilon_0\mu_0 E} + \mu\mu_0 H \tag{6.2}$$

Where ε and μ are the relative permittivity and permeability of the chiral medium, and κ is the dimensionless chirality parameter. ε_0 and μ_0 are the permittivity and permeability of vacuum. This equation suggests that there is cross coupling between electric and magnetic field in chiral medium and it behaves differently for left and right circular polarized wave passing through it.

The circular dichroism and optical activity effect of chiral metamaterial can be exploited to change polarization of RMPA from linear to circular. Chiral metamaterial with Y shape [213], twisted and nested U shape [126], wheel shaped [221], fractal shaped [82] and spiral shape [214] [90] etc. are proposed in literature.

In this chapter, Bilayer twisted cross wire chiral metamaterial (CM) is published in [48] has been used. Zarifi. et. al. [21] has used this CM to improve the performance of circularly polarized antenna, but in this research work, it is used to change the polarization of rectangular patch antenna from linear to circular. Parameters of unit cell of CM and all the performance parameters like antenna transmission, axial ratio, radiation pattern, and gain are thoroughly investigated.

Gammadion chiral metamaterial is also used in this chapter to design a circularly polarized antenna from linearly polarized rectangular patch antenna. Prototype of this designed antenna is fabricated and simulated results are also verified expertimentally.

6.2. DESIGN OF CIRCULARLY POLARIZED ANTENNA USING BILAYER TWISTED CROSS WIRE CHIRAL METAMATERIAL

Twisted cross wire chiral metamaterial is used to convert linearly polarized RMPA to circularly polarized antenna. Firstly, the reference RMPA is designed at 6.2 GHz at wireless communication frequency band and then unit cell of chiral metamaterial is designed at the resonant frequency of reference RMPA. After designing the RMPA and chiral metamaterial, a cover of chiral metamaterial is placed over the RMPA to change its polarization from linear to circular.

6.2.1. Design and Result of Reference Patch Antenna

Reference RMPA antenna is designed at resonant frequency of 6.2 GHz using transmission line equations [179] on FR_4 epoxy substrate having dielectric constant (ε_r = 4.4) and loss tangent (δ =0.0025). The designed reference rectangular patch antenna is simulated and optimized using HFSS as shown in Fig 6.1. The patch antenna has length (L) = 10.02mm and width (W) =14.72mm. The ground size dimensions are 75 mm × 75mm and are fed by coaxial probe situated at (35.4mm, 39.22 mm) in Cartesian coordinates.

Fig 6.2 depicts the reflection coefficient of RMPA, it resonates at 6.24 GHz with reflection coefficient of -25 dB.

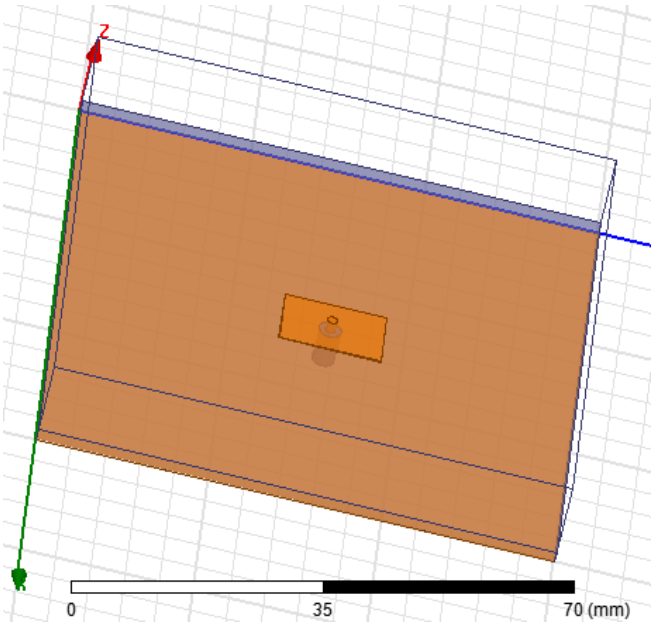


Fig 6.1: Simulated Model of Reference RMPA Fed by Coaxial Feed

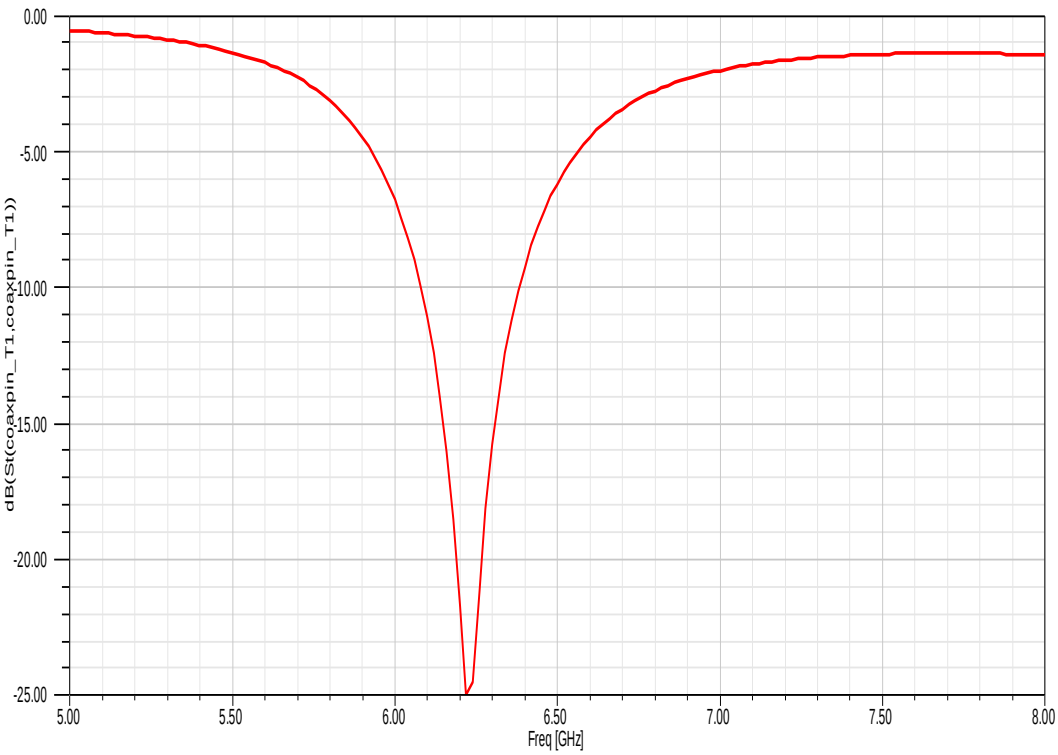


Fig 6.2: Simulated Reflection Coefficient (S11) of Reference RMPA

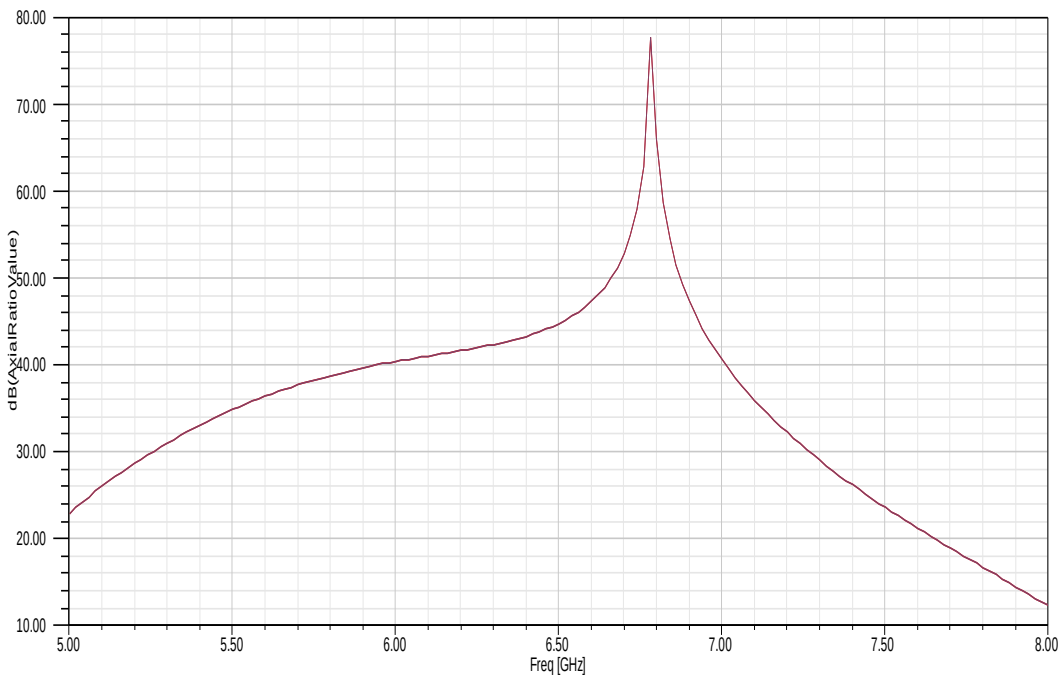


Fig .6.3: Axial Ratio of Reference Rectangular Microstrip Patch Antenna

The reference antenna has the axial ratio of 41 dB at resonant frequency as shown in Fig 6.3. Fig. 6.4 represents the LCP and RCP gain of reference antenna,

which is same for both modes. From axial ratio and gain graph it is clear that reference RMPA is linearly polarized.

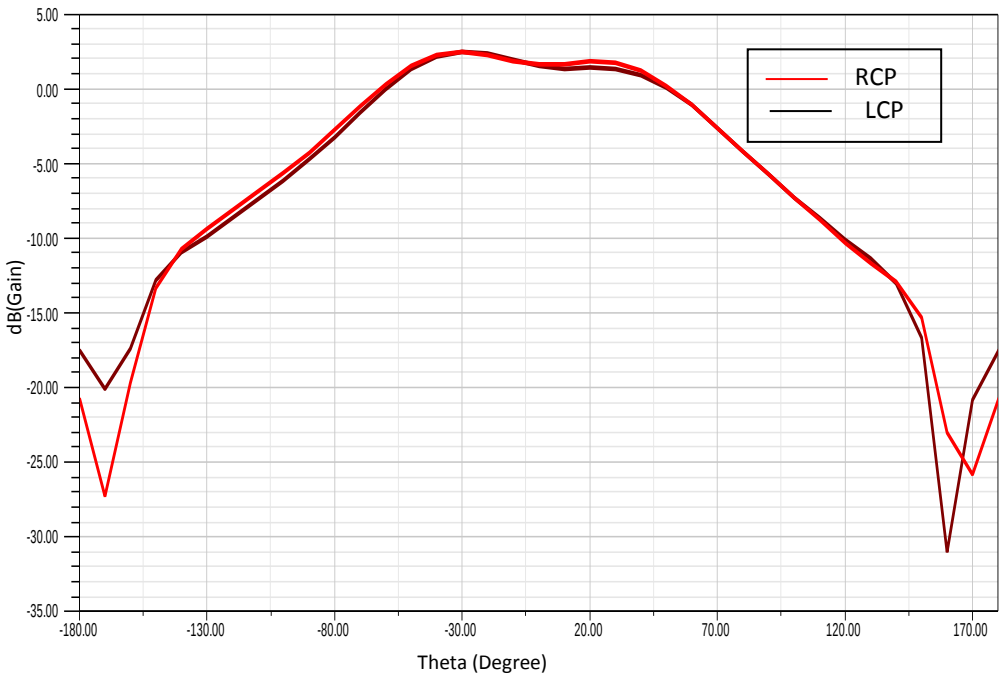


Fig .6.4: LCP and RCP Gain of Reference RMPA

6.2.2. Design and Investigation of Unit Cell Of Chiral Metamaterial

After designing the reference RMPA bilayer twisted cross chiral metamaterial is designed according to resonance frequency**.** Unit cell of CM consist of twisted cross wires printed on both side of FR_4 substrate having ε_r = 4.4 and loss tangent (δ) =0.0025 and thickness =1.6mm.

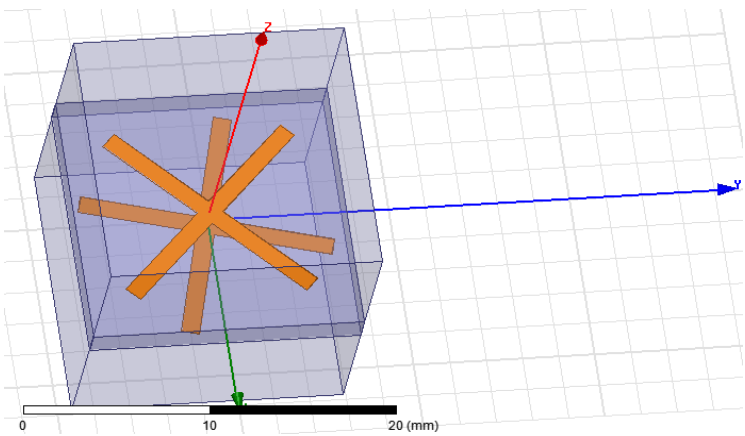
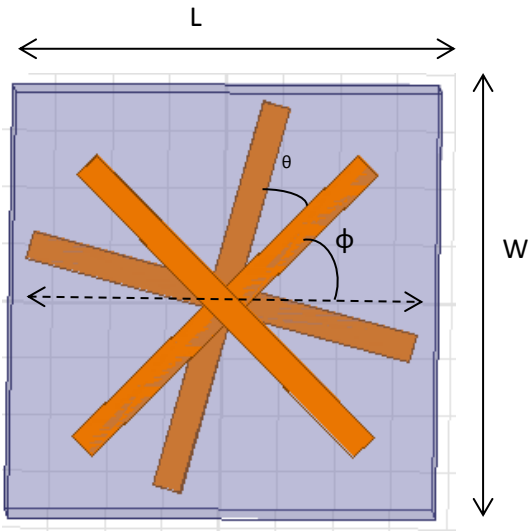


Fig 6.5: Unit Cell Simulation Model of Bilayer Twisted Cross Wire Chiral Metamaterial

The length and width of twisted cross wires are 14 mm and 15 mm respectively as shown in Fig. 6.5 and Fig 6.6.



-

Fig 6.6: Bilayer Twisted Cross Wire CM with Geometric Parameters (L= 15mm,W= 15mm, θ = 15^0, φ =45^0)

For simulation, unit cell boundaries are applied to x and y direction and absorbing boundary conditions are applied to z axis. Linearly polarized (LP) wave is allowed to incident on the CM. As the LP is a combination of LCP and RCP.

$$LP = \frac{1}{2}LCP + \frac{1}{2}RCP \tag{6.3}$$

To achieve good CP wave, either of the LCP or RCP wave need to be small. Two Eigen modes of electromagnetic wave are nothing but two circularly polarized wave i.e. left hand circularly polarized wave (LCP) and right hand circularly polarized (RCP) wave in CM. The four circular transmission coefficients T_{++}, T_{+-}, T_{-+}, T_{--} which describe the response of chiral metamaterial can be expressed in terms of four linear coefficients T_{xx}, T_{xy}, T_{yx}, ,T_{yy} by following transformation [28].

$$\begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \begin{pmatrix} (T_{xx} + T_{yy}) - i(T_{xy} - T_{yx}) & (T_{xx} - T_{yy}) + i(T_{xy} + T_{yx}) \\ (T_{xx} - T_{yy}) - i(T_{xy} + T_{yx}) & (T_{xx} + T_{yy}) - i(T_{xy} + T_{yx}) \end{pmatrix} \tag{6.4}$$

Where the first subscript shows the transmitted field polarization and second subscript shows incident field polarization.

Fig. 6.7 shows the transmission coefficient of RCP and LCP wave in chiral metamaterial. The CM is designed at resonant frequency of reference patch antenna at 6.24 GHz. In this frequency range it offers different media to both the waves. LCP wave is allowed to pass through the chiral metamaterial and RCP wave is suppressed.

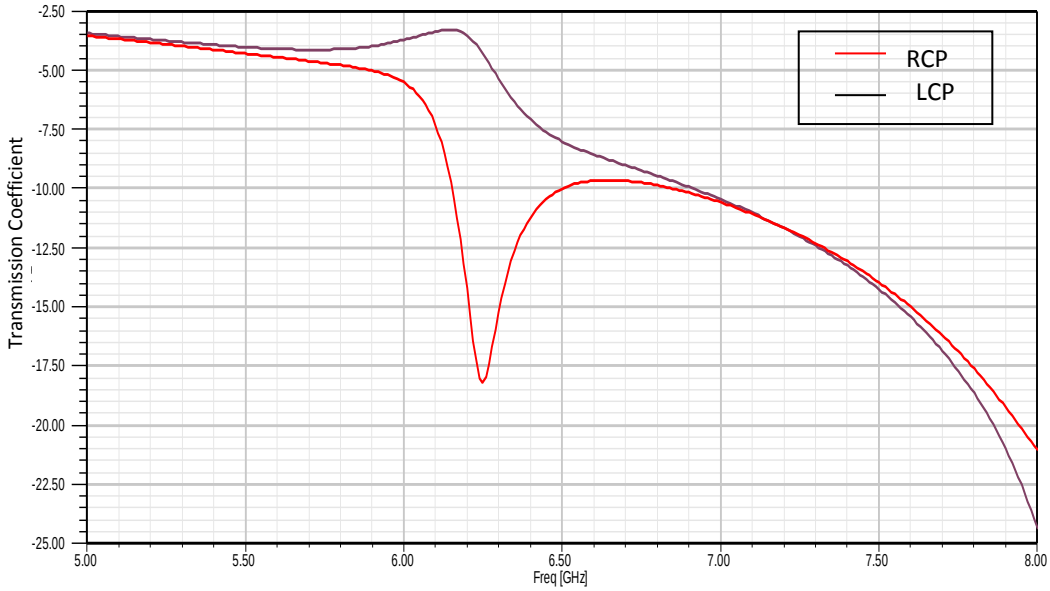


Fig .6.7: Transmission Coefficient of LCP and RCP Wave in Chiral Metamaterial

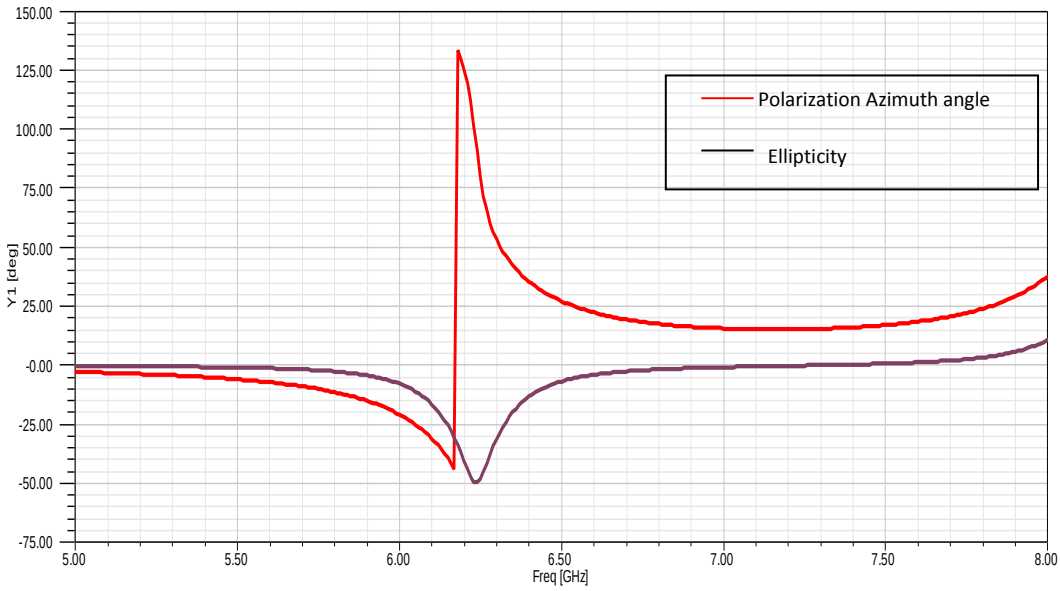


Fig .6.8: Ellipticity and Azimuth Rotation Angle of Electromagnetic Wave after Passing through Chiral Metamaterial

Chiral metamaterial offers different refractive index to LCP and RCP waves and due to this polarization of the wave after passing through chiral metamaterial Linear Polarization changes to left hand Circular Polarization.

Difference between amplitude and phase of RCP and LCP transmission coefficient is characterized by ellipticity η and azimuth rotation angle θ and can be expressed in terms of transmission coefficients as given in equation (6.5) and (6.6).

$$\eta = arctan\left(\frac{|T_{++}|-|T_{--}|}{|T_{++}|+|T_{--}|}\right) \tag{6.5}$$

$$\theta = \frac{1}{2}\left[\arg(T_{++}) - \arg\left(T_{\_}\right)\right] \tag{6.6}$$

Fig. 6.8, shows the ellipticity and azimuth rotation angle of EM wave obtained using equation 6.3 and 6.4. The resultant wave from CM has ellipticity 45^0 and azimuth rotation angle is 90^0, which depicts that the resulting wave is circularly polarized.

After designing the twisted cross unit cell of chiral metamaterial, a 5×5 array of unit cells is applied over the RMPA at a spacing d as shown in Fig. 6.9. Numerical simulation is performed using HFSS in the range of 4 GHz to 6 GHz shows that optimum value of the spacing between the RMPA and CM cover is 20 mm. The dimension of CM cover consisting of 5 ×5 unit cells is same as the substrate size of RMPA.

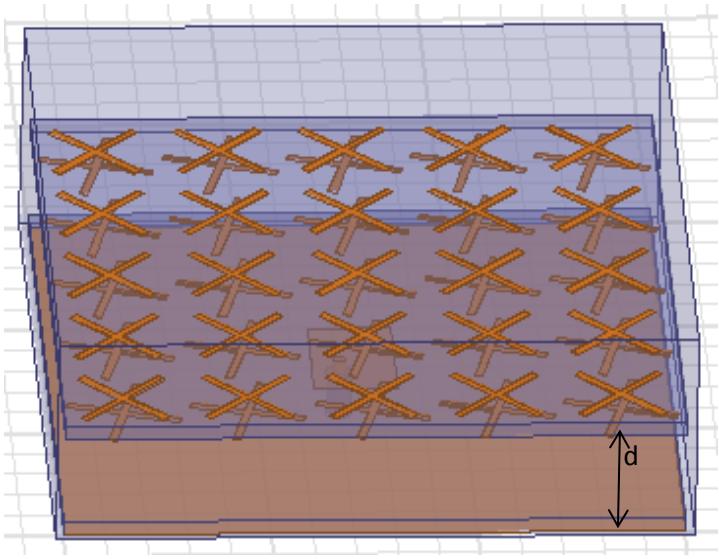


Fig .6.9: Proposed CP coaxial Fed RMPA with Chiral Metamaterial Cover

6.3. RESULT AND DISCUSSION OF CP ANTENNA DESIGNED USING BILAYER TWISTED CROSS WIRE CHIRAL METAMATERIAL

The optimized RMPA with chiral metamaterial cover is shown in Fig. 6.9. Fig. 6.10 shows the reflection coefficient of RMPA antenna with CM cover. It can be seen from this graph that after applying CM cover over the patch antenna reflection coefficient

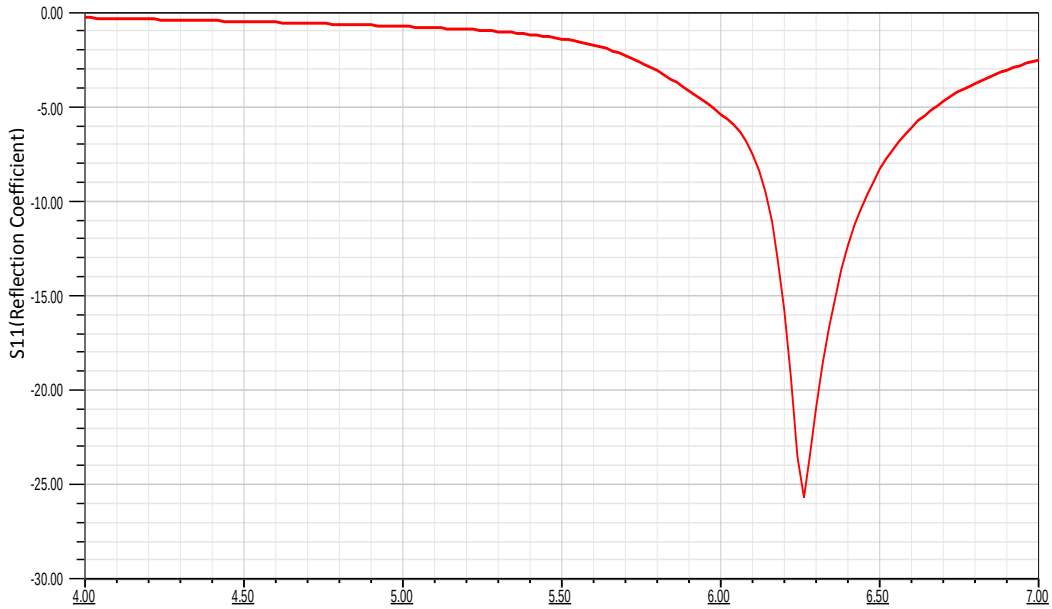


Fig .6.10: Reflection Coefficients (S11) of RMPA with CM Cover

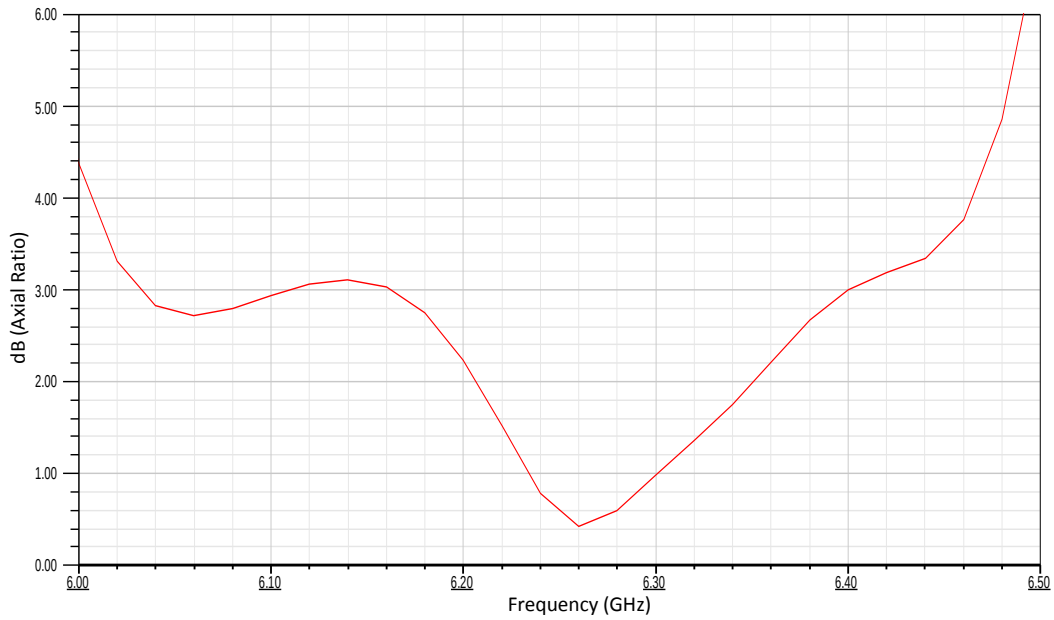


Fig .6.11: Axial Ratio of RMPA with CM Cover

improves slightly as compared to reference antenna and the resonant frequency remains the same, 6.24 GHz. Fig. 6.10 shows the reflection coefficient of RMPA antenna with CM cover. It can be seen from this graph that after applying CM cover over the patch antenna reflection coefficient improves slightly as compared to reference antenna and resonant frequency remains the same, 6.24 GHz.

Fig**.** 6.11 gives the rectangular patch antenna axial ratio, which depicts that 3 dB axial-ratio bandwidth is ranges from 6.16 GHz to 6.40 GHz. The effect of applying the CM cover over the patch antenna changes its axial ratio 41 dB to 0.46dB at resonant frequency of 6.24 GHz.

Thus the antenna polarization changes from linear to circular due to CM cover. Fig. 6.12 depicts the LCP and RCP gain of proposed antenna. In reference antenna both LCP and RCP gain are approximately same as shown in Fig. 6.4 and hence the antenna is LP. But the application of CM over patch antenna excites the

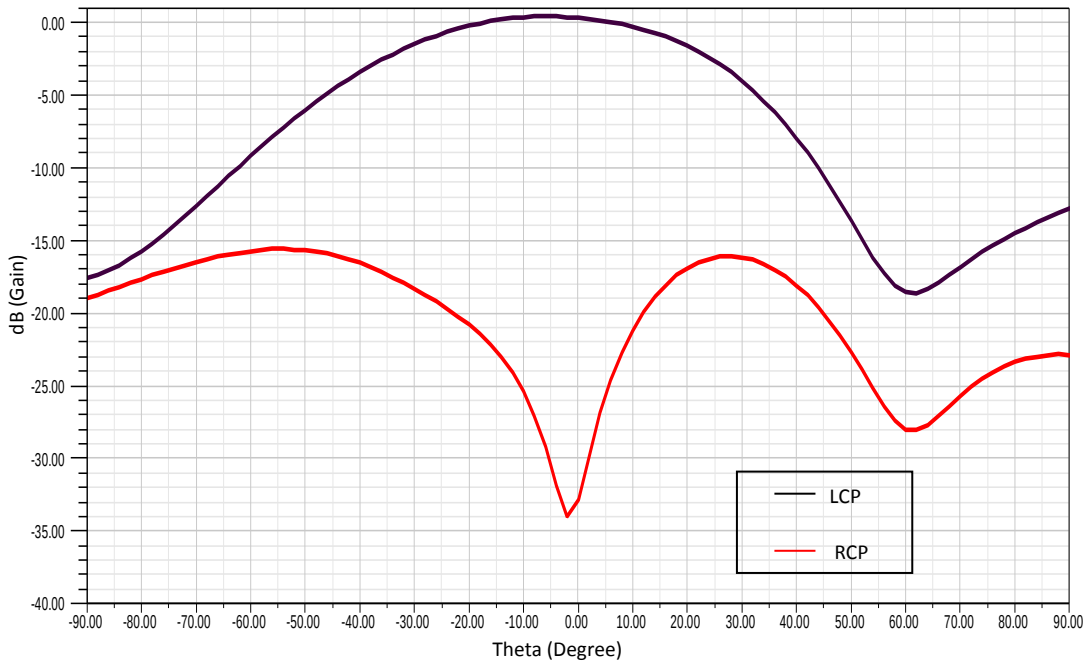


Fig .6.12: Gain of RMPA with CM Cover

LCP and supresses the RCP as can be seen from graph shown in Fig. 6.12. Thus antenna polarization mode changes from LP to CP and LCP mode excites in proposed antenna.

The proposed CP patch antenna consists of traditional rectangular patch antenna and bilayer twisted cross wire CM. Investigation and results shows that

polarization of conventional RMPA changes from linear to circular, when CM cover is placed over it.

This CM based antenna radiates the LCP wave at 6.24 GHz with the 3dB axial ratio bandwidth (6.16 GHz to 6.40 GHz). The designed antenna has advantage of simple structure, low cost and it is expected to benefit the applications in wireless and satellite communication.

In the next section, design of circularly polarized antenna using gammadion structure is presented.

6.4. DESIGN OF CIRCULARLY POLARIZED ANTENNA USING GAMMADION CHIRAL METAMATERIAL

Design and investigation of circularly polarized antenna using gammadion chiral metamaterial is presented. Steps for designing the CP antenna using this structure is same as bilayer twisted cross wire CM, but this gammadion structure provides better results than bilayer twisted cross wire CM.

6.4.1. Design of Gammadion Chiral Metamaterial

Unit cell of Gammadion chiral metamaterial is printed on both side of FR_4 substrate having ε_r = 4.4 and loss tangent (δ) =0.0025 and thickness 1.6mm as shown in Fig. 6.13.

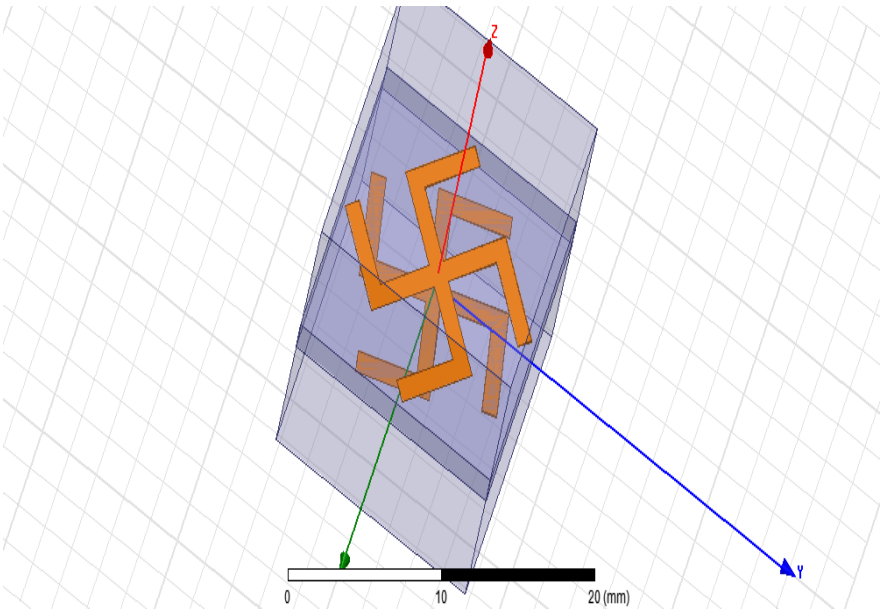


Fig 6.13: Unit Cell Simulation Model Gammadion Chiral Metamaterial

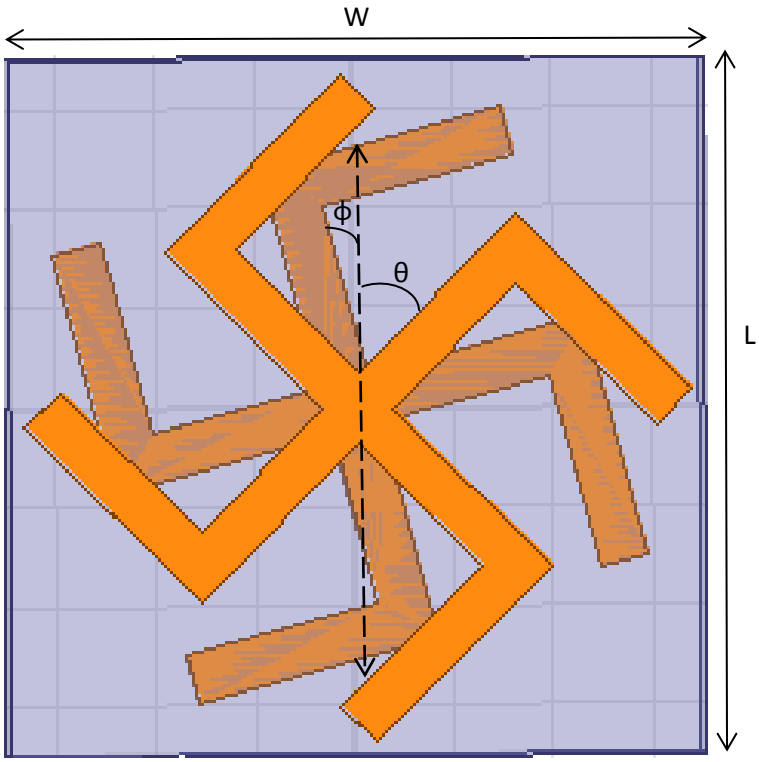


Fig 6.14: Gammadion Chiral Metamaterial with Geometric Parameters (L= 14 mm, W=14 mm, θ = 45 ^{0}, φ = 15^0)

Unit cell of this chiral metamaterial is simulated and optimized in HFSS. Optimized geometric parameters of gammadion chiral metamaterial is shown in Fig. 6.14.

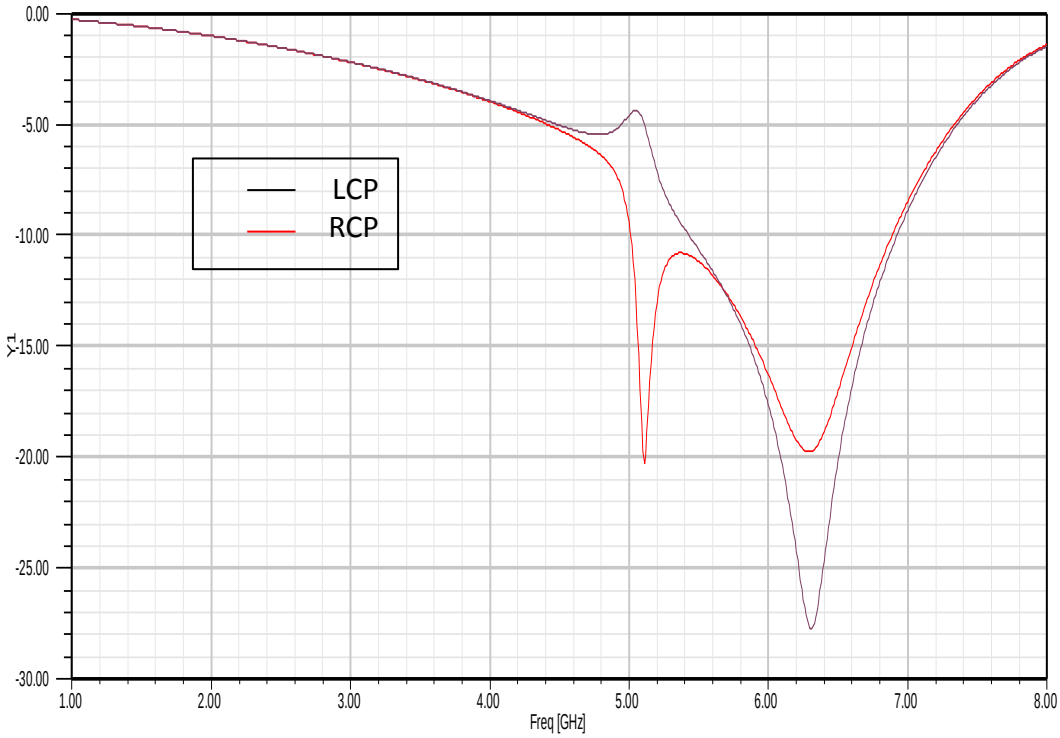


Fig: 6.15: Transmission Coefficient of LCP and RCP Wave after Passing through Chiral Metamaterial

Four circular transmission coefficients T_{++}, T_{+-}, T_{-+}, T_{--} which describe the response of chiral metamaterial are from four linear coefficients T_{xx}, T_{xy}, T_{yx}, ,T_{yy} by using transformation given in equation 6.2. Transmission coefficient of RCP (T_{++}) and LCP (T_{--}) wave after passing through chiral metamaterial is shown in Fig. 6.15. From the graph 6.15, it can be seen that at 5.15 GHz gammadion chiral metamaterial passes the LCP wave and stops the RCP wave while at 6.25 GHz it offer different media to RCP and LCP wave and different transmission amplitude are obtained for both of these waves.

Difference between amplitude and phase of RCP and LCP transmission coefficient is characterized by ellipticity η and azimuth rotation angle θ and can be obtained using transmission coefficients from equation (6.3) and (6.4). Fig. 6.16 shows the variation of ellipticity and azimuth rotation angle of the EMW after passing through chiral metamaterial in frequency range of 1GHz to 8 GHz. At 5.15 GHz the resultant EMW after passing from chiral metamaterial has ellipticity is 45^0 and azimuth rotation angle is 180^0 which shows that wave is circularly polarized at this frequency. At 6.24GHz chiral metamaterial shows discrimination between LCP and RCP wave, but ellipticity is 27^0 at this frequency, so wave is not circularly polarized at that frequency.

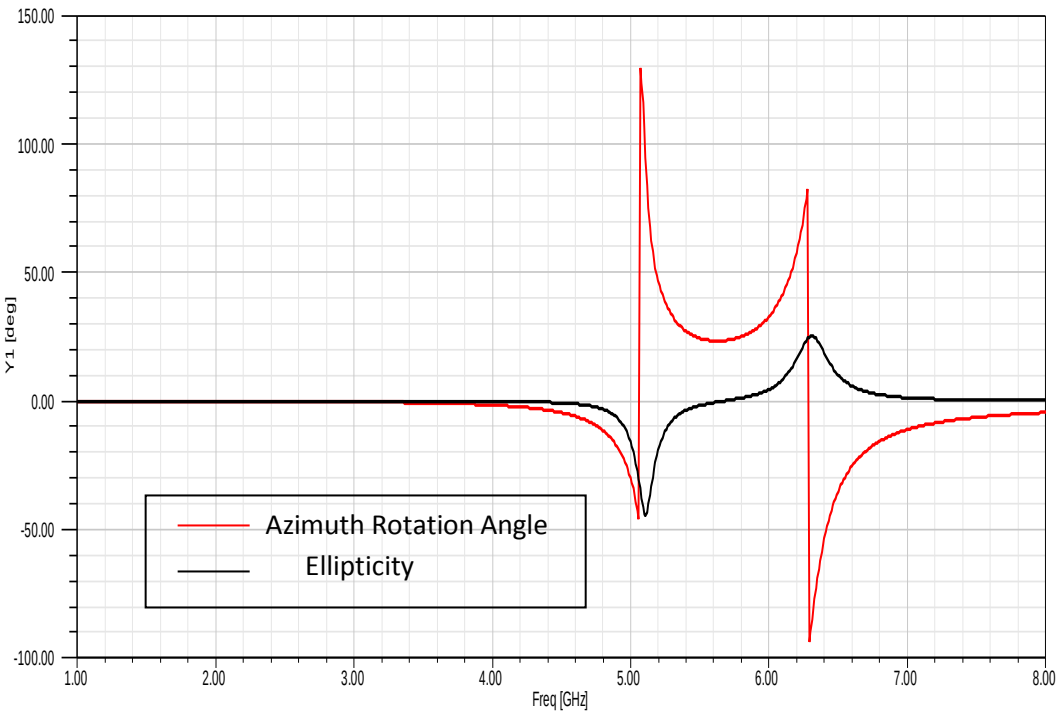


Fig .6.16: Ellipticity and Azimuth Rotation Angle of Electromagnetic Wave after passing through Chiral Metamaterial

6.4.2. Design And Result of Reference Patch Antenna

Reference RMPA is designed on FR_4 epoxy substrate having dielectric constant (ε_r) = 4.4 and loss tangent (δ) =0.0025 using transmission line equations at resonating frequency of 5.15 GHz. The designed reference patch antenna is modelled and optimized using HFSS as shown in Fig. 6.17. The patch antenna has length (L) = 17.56 mm and width (W) = 13 mm. The ground size dimension is 70 mm × 70 mm and is fed by inset microstrip line.

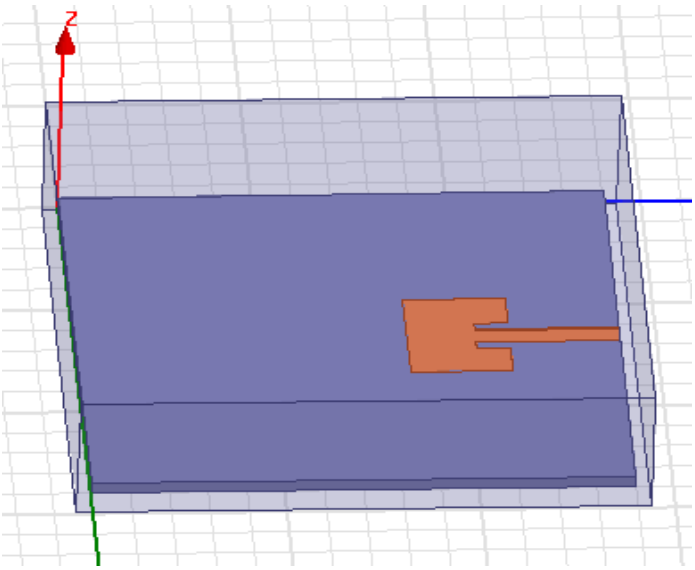


Fig 6.17: Simulated Model of Reference RMPA Fed by Coaxial Feed

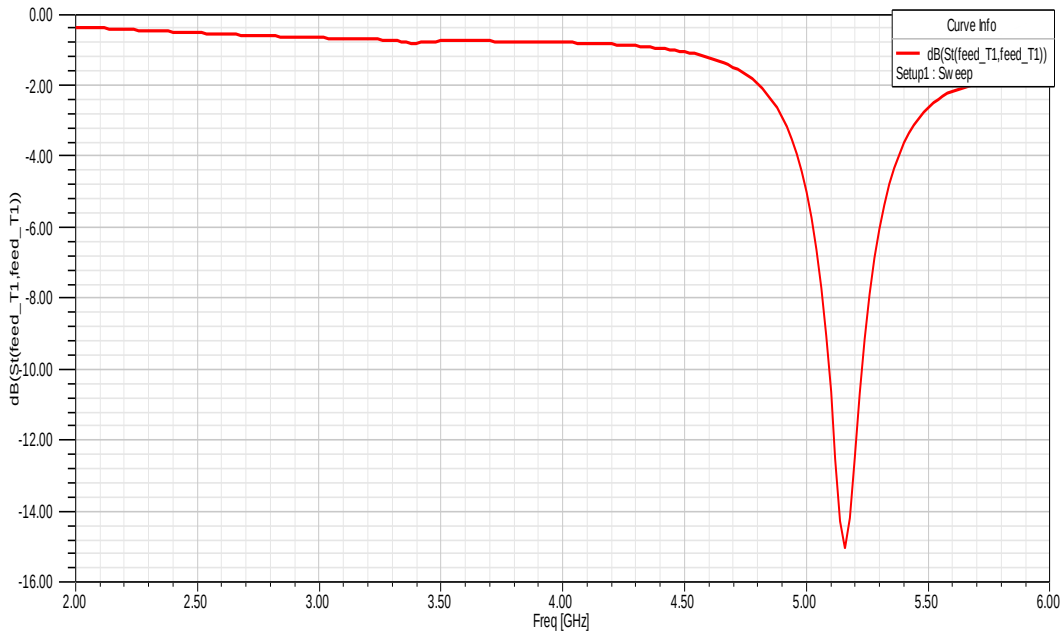


Fig. 6.18: Reflection Coefficient of Reference RMPA Resonating at 5.15 GHz

Fig. 6.18 shows the reflection coefficient of reference rectangular patch antenna. The designed patch antenna resonates at 5.15 GHz with return loss of 15.16 dB. Fig. 6.19 shows the axial ratio of reference patch antenna. Patch antenna has axial ratio of 45.75 dB at resonant frequency of 5.15 GHz and thus this antenna is linearly polarized.

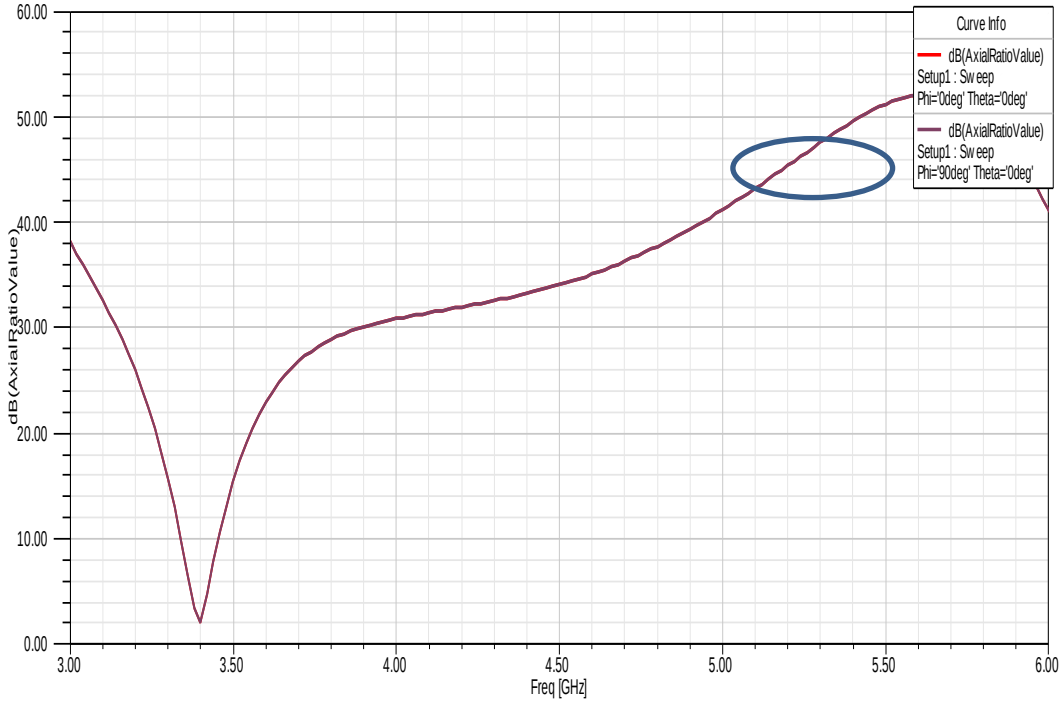


Fig. 6.18: Axial ratio of Reference RMPA

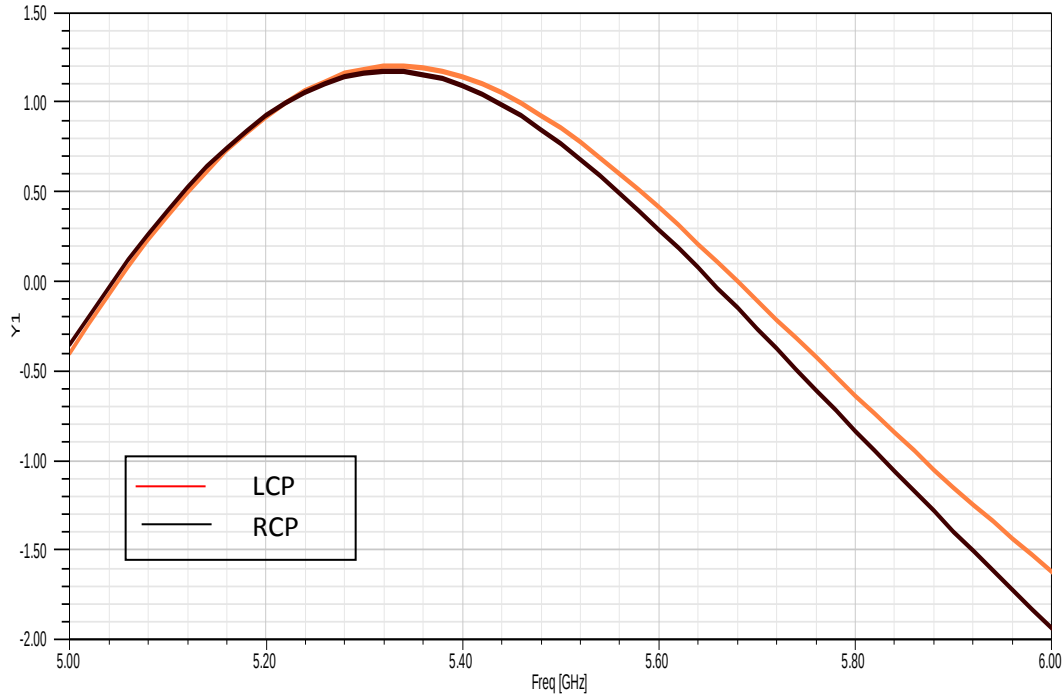


Fig. 6.20: LCP and RCP Gain of Reference RMPA

Fig. 6.20 shows the LCP and RCP gain of reference patch antenna. As this antenna is linearly polarized so LCP and RCP component of electromagnetic wave has same gain.

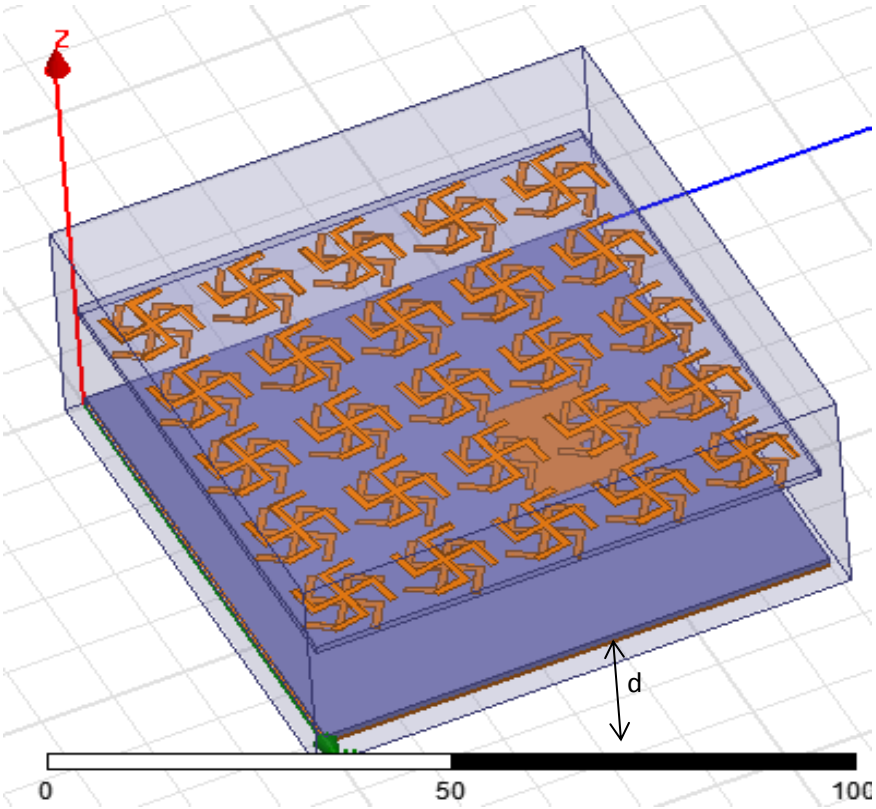


Fig.6.21: Simulation Model of Reference RMPA with Chiral Metamaterial Cover

After designing the reference patch antenna and the unit cell of gammadion chiral metamaterial, an array of 5×5 unit cells of gammadion structure is applied over the RMPA at a spacing d =33mm . Optimized distance d is obtained using the optimetrics in HFSS software. Simulation model of proposed RMPA with gammadion chiral metamaterial cover is shown in Fig. 6.21. The size of substrate of chiral metamaterial cover is same as substrate size of the patch antenna and gammadion structures are printed on the substrate.

6.5. RESULT AND DISCUSSION OF SIMULATED CP ANTENNA DESIGNED USING GAMMADION CM

RMPA with chiral metamaterial cover as shown in Fig. 6.21 is simulated and optimized in HFSS and results are obtained.

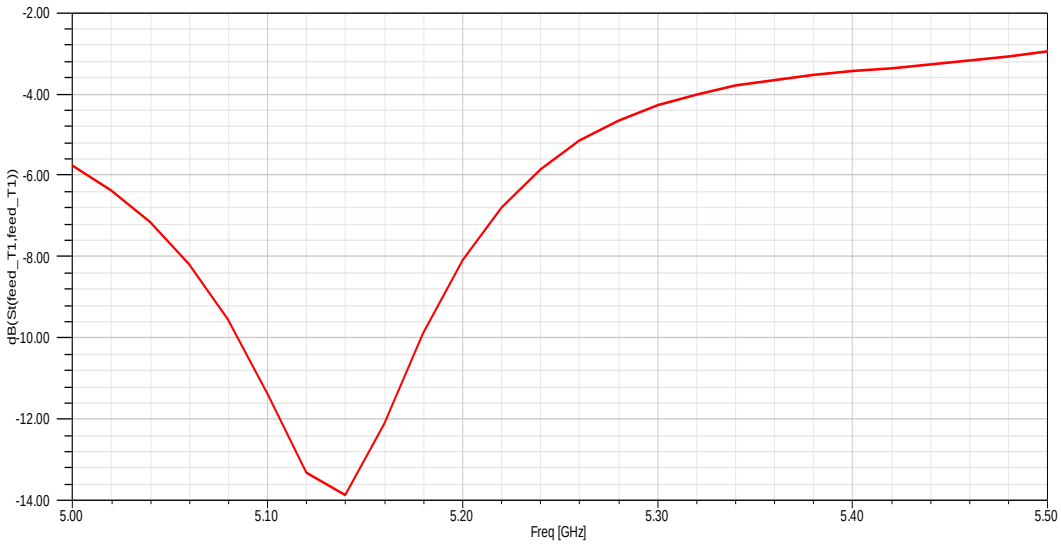


Fig. 6.22: Reflection Coefficient of RMPA with Chiral Metamaterial Cover

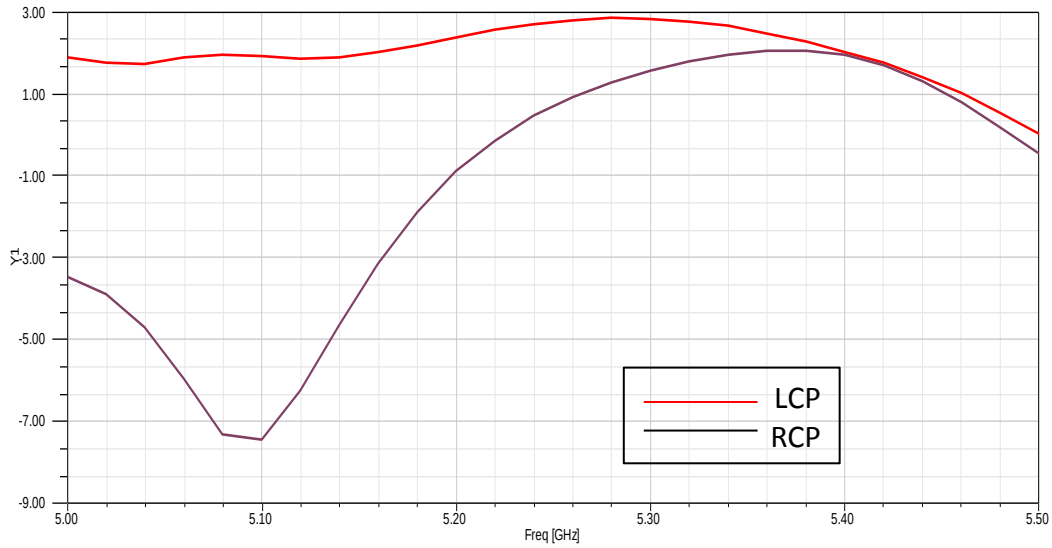


Fig. 6.23: LCP and RCP Gain of RMPA with Chiral Metamaterial Cover

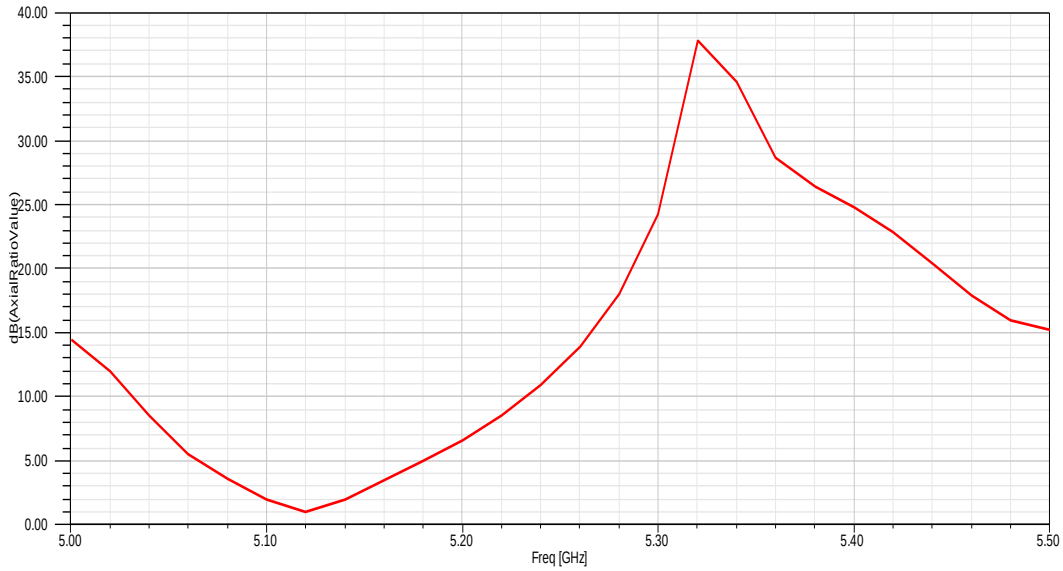


Fig. 6.24: Axial Ratio of RMPA with Chiral Metamaterial Cover

Fig. 6.22 shows the reflection coefficient of proposed antenna. From this graph it can be seen that antenna resonates at 5.14 GHz with a return loss of 13.93 dB. Fig. 6.23 shows the LCP and RCP gain of proposed antenna. LCP wave has gain of 1.93 dB and RCP wave has gain of -5.16 dB.

Fig. 6.24 shows the axial ratio of proposed RMPA with chiral metamaterial cover. Axial ratio value at the resonant frequency is 1.01 dB. Thus axial ratio of reference RMPA reduces from 45.75 dB to 1.01 dB in proposed antenna. As the axial ratio of proposed antenna is less than 3 dB, so it is circularly polarized antenna. From gain and axial ratio graph of proposed antenna it is clear that application of CM over patch antenna excites the LCP and supress the RCP. Thus antenna polarization mode changes from LP to CP and LCP mode excites in proposed antenna.

6.6. DESIGN AND RESULTS OF FABRICATED CP ANTENNA USING GAMMADION CM:

Prototype of the proposed antenna as shown in Fig. 6.21 is fabricated. Fig. 6.25(a) and (b) shows the top and bottom layer of chiral metamaterial cover. Fig. 6.26 shows the proposed fabricated antenna.

Fig. 6.25(a): Top layer of Chiral Metamaterial

Fig. 6.25(b): Bottom Layer of Chiral Metamaterial

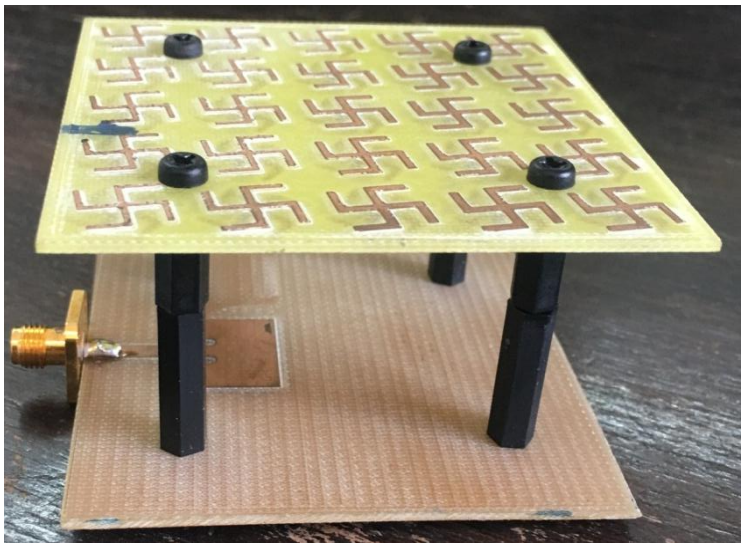


Fig. 6.26: Fabricated RMPA with Gammadion Chiral Metamaterial Cover

Fabricated antenna is tested and measured reflection coefficient graph along with the simulated reflection coefficient is shown in Fig. 6.27. Simulated and Measured graph of reflection coefficient are approximately same. Fig. 6.28 shows the simulated and measured axial ratio of proposed fabricated antenna. Axial ratio is less than 3 dB in impedance bandwidth range of proposed antenna. Fig. 6.29 shows simulated and measured LCP radiation pattern of proposed antenna.

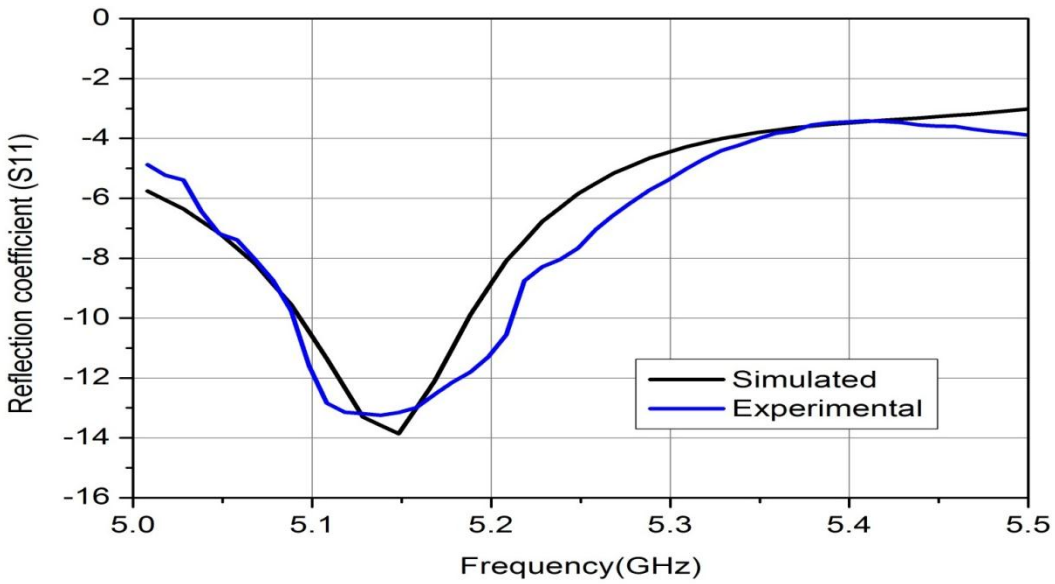


Fig. 6.27: Reflection Coefficient of RMPA with Gammadion Chiral Metamaterial Cover

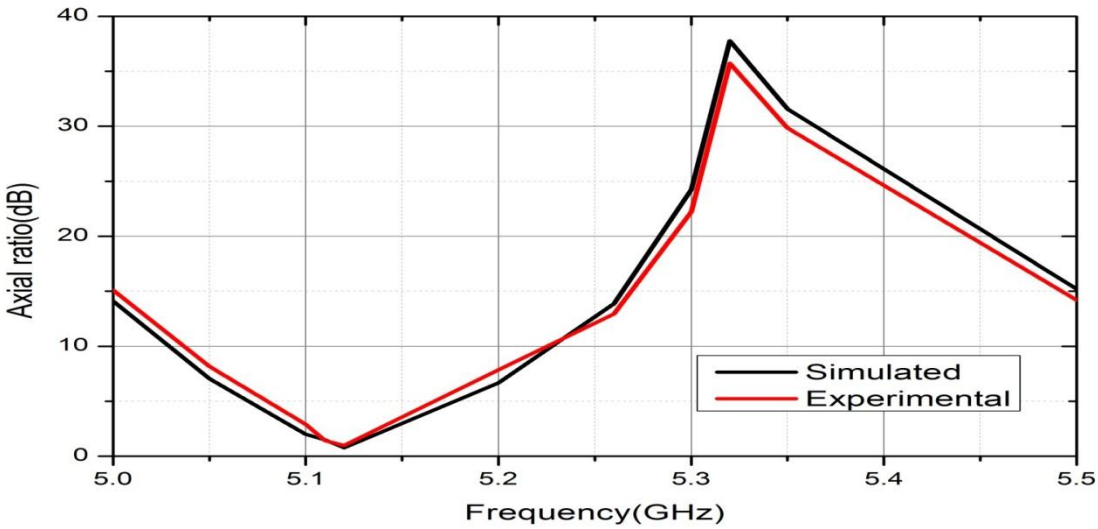


Fig. 6.28: Axial ratio of RMPA with Gammadion Chiral Metamaterial Cover

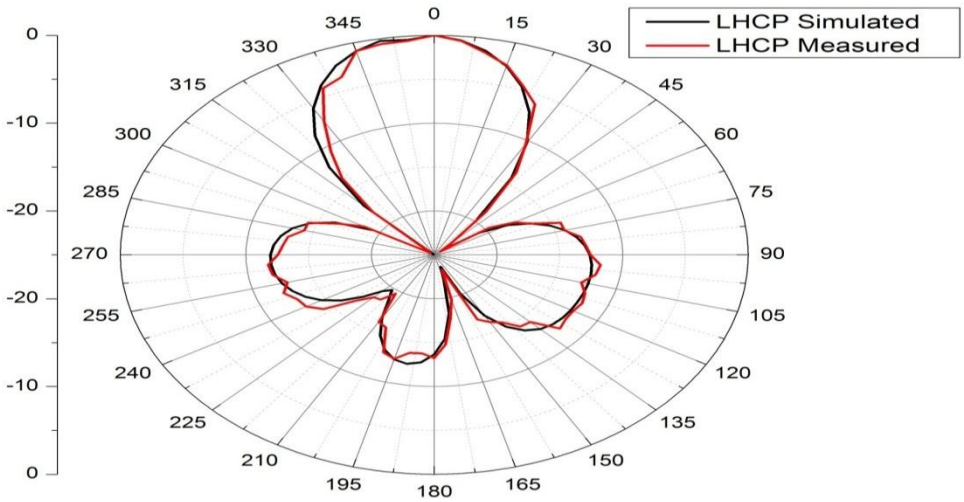


Fig. 6.29: Radiation Pattern of RMPA with Gammadion Chiral Metamaterial Cover

Parameter	Reference Antenna	Proposed Antenna with Gammadion chiral Metamaterial cover
Resonating Frequency	5. 15 GHz	5.14 GHz
Reflection Coefficient(S11)	-15.75dB	-13.93dB
Bandwidth	100 MHz	190 MHz
Axial ratio	45.75 dB	1.01 dB
LCP Gain	1.11 dB	1.93 dB
RCP Gain	1.11dB	-5. 16 dB

TABLE 6.1: Comparison of Various Performance Parameters of Reference and Proposed Antenna With Gammadion CM Cover

6.7. CONCLUDING REMARKS

In this chapter, a simple method for designing a circular polarized antenna using bilayer twisted cross wire and gammadion chiral metamaterial is presented. First antenna proposed in this chapter consists of conventional linear polarized Rectangular Microstrip Patch Antenna (RMPA) and cover of bilayer twisted cross wire Chiral Metamaterial (CM). The placement of CM cover over the linearly polarized RMPA changes its polarization from linear to circular and the antenna produces a left handed circularly polarized wave at resonant frequency of 6.24GHz with axial ratio of 0.46 dB.

Second proposed antenna uses gammadion chiral metamaterial to change the polarization of RMPA from linear to circular. This antenna radiates LCP wave at 5.15 GHz with 1.01 dB axial ratio. The designed antenna has advantage of simple structure, low cost and it is expected to benefit the application in wireless and satellite communication.

CHAPTER 7

DESIGN OF RECONFIGURABLE ANTENNAS USING PIN DIODES AND METAMATERIAL

In this chapter, reconfigurable fractal antenna, inverted circular patch antenna and polarizable reconfigurable patch antenna using pin diodes are proposed for wireless applications. Chiral Metamaterial is used for designing a polarizable reconfigurable patch antenna. All the three proposed antennas are fabricated and results are also verified experimentally.

7.1. INTRODUCTION

In the modern wireless communication systems, due to increased need to implement multiple systems on single platform need demand for tuneable and reconfigurable antenna has increased drastically. With the use of reconfiguration, single antenna can be used for multiple systems. The size of overall system and cost reduces considerably. In reconfigurable antenna, its aperture can be modified electronically using electromechanical switches (MEMS), field effect transistor, PIN diodes and varactor diodes. These switches are used to get selectivity in frequency, radiation pattern, and bandwidth and polarization characteristics. Reconfigurable antennas offer following advantages as compared to conventional antennas.

- Compact size
- Effective use of electromagnetic spectrum
- Similar radiation pattern and gain at all desired frequency bands
- Frequency selectivity useful for reducing adverse effect of co-site interference and jamming

The above mentioned advantages have made reconfigurable antennas very attractive in field of wireless and defence applications. Three reconfigurable antennas are proposed in this chapter. The first one is a reconfigurable multiband fractal antenna. Fractal antenna [51] is selected as it provides multi-band characteristic and miniaturization. The fractal antennas are composed of multiple iterations of a single elementary shape and are used to describe a family of complex shapes that possess an inherent self-similarity and self-affinity in their geometrical structure. Different types of fractal antennas [74] [105] [85] [75] [183] [139] [198] have been proposed by

researchers such as tree-shaped fractal antenna [75] [183], Sierpinski fractal antenna [74] [105] [85] and snowflake fractal antenna [139], Koch fractal antenna [198] etc. These fractal antennas provide the reduction in the cost and size, but a single antenna of this type cannot be used for modern wireless system as different communication applications work at different frequency bands. Therefore reconfiguration concept is introduce in fractal antenna to design multiband frequency selective antenna which has enhanced compactness and very beneficial for modern communication system. Thus a reconfigurable fractal antenna which has the advantages of both the antennas is proposed.

A frequency reconfigurable circular patch antenna with high gain is also presented in this chapter. Work is presented in literature which discusses the use of reconfiguration technique for designing dual band antennas [142-143] [219] [31] [124] [167] [148] for wireless applications. In these above works antenna gain which is the essential performance parameter is not considered or poor in different modes. The proposed antenna works in two modes and has high gain. In one mode, when switches are on it works in frequency band of 1.8-1.98 GHz and in other mode, it works in frequency band of 2.10 – 2.68 GHz when switches are off. Experimental and simulated results of radiation pattern, gain and return loss are presented and these results are in close agreement. The proposed inverted circular patch antenna is designed for personal communication (1.85 -1.99 GHz), wireless LAN (2.4 – 2.483 GHz) and Bluetooth (2.4 -2.5 GHz) applications.

In the third proposed antenna, reconfiguration concept is applied to metamaterial and a polarization reconfigurable antenna is presented. Bilayer split ring chiral metamaterial is used to convert the polarization of RMPA from linear to circular and then pin diodes are used in metamaterial to change the position of slots in ring. The change in position of slots changes the chiral metamaterial characteristics and it allows the LCP wave to pass in one state and stops the RCP wave. In other reconfiguration state this antenna passes the RCP wave and stops the LCP wave. Thus a polarization reconfigurable antenna is obtained by using pin diodes in chiral metamaterial.

7.2. DESIGN OF RECONFIGURABLE MULTIBAND FRACTAL ANTENNA

The basic RMPA is taken as reference antenna for designing the reconfigurable fractal antenna. Incorporation of reconfiguration technique in fractal antenna is very valuable for modern wireless system as it provides frequency selectivity and increased miniaturization of communication system. Thus in the proposed reconfigurable fractal antenna efforts are done to incorporate the advantages of both antennas. The geometry of proposed reconfigurable fractal antenna is shown in Figure 7.1.

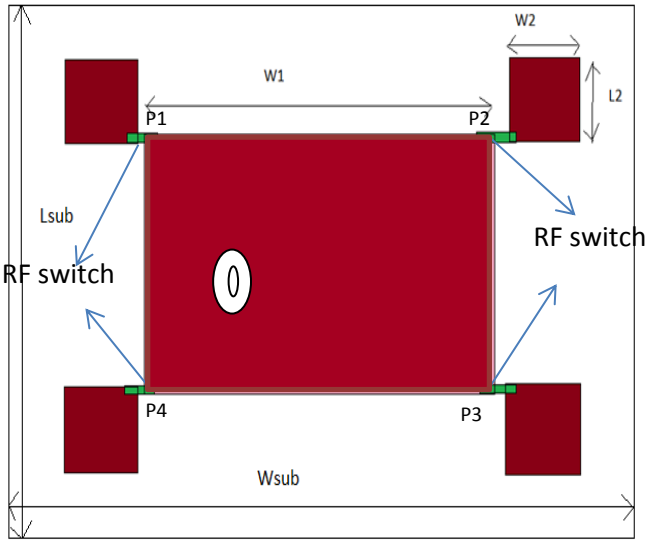


Fig. 7.1: Geometry of Proposed Reconfigurable Fractal Antenna

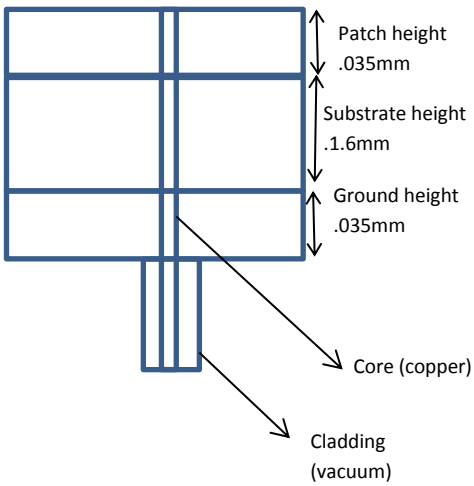


Fig. 7.2: Side View of Proposed Reconfigurable Fractal Antenna

For four RF switches P1-P4 are used for purpose of reconfiguration. Coaxial cable is used to feed the antenna. Side view of the proposed designed antenna is shown in Fig. 7.2.

Lithography technique is used to make prototype of proposed antenna. Fig. 7.3 and 7.4 show top and bottom view of fabricated antenna. Reconfigurable fractal antenna with pin diodes connections is shown in Fig. 7.5. Table 7.1 shows the design parameters of optimized reconfigurable fractal antenna.

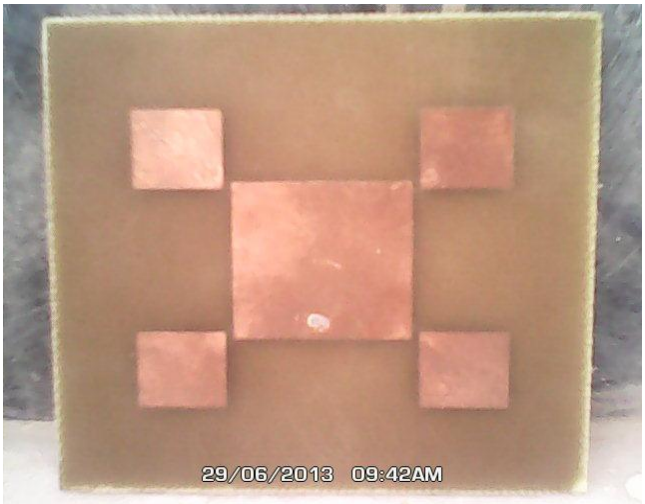


Fig. 7.3: Top view of Fabricated Reconfigurable Fractal Antenna

Fig. 7.4: Bottom view of Fabricated Reconfigurable Fractal Antenna

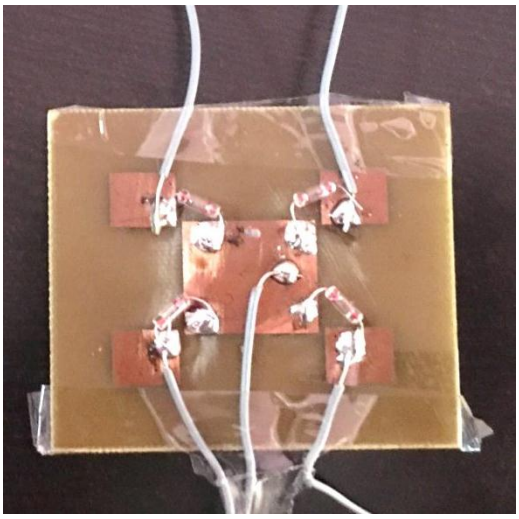


Fig. 7.5: Fabricated Reconfigurable Fractal Antenna with PIN Diodes

Antenna design parameter	Dimension(mm)	Antenna design parameter	Dimension(mm)
L1	20.02	H	1.6
Wsub	71.7	ε_r	4.4
W1	23.7	L2	9.87
W2	11.85	Lsub	60.02

Table 7.1: Design Parameters of Proposed Reconfigurable Fractal Antenna

7.3. RESULTS AND DISCUSSION OF MULTIBAND FRACTAL ANTENNA

The proposed antenna is optimized using HFSS software and ssimulated results are presented here.

S.NO.	MODES	Switch Position
1	Mode 1	P1=OFF ,P2=OFF P3=OFF ,P4=OFF
2	Mode 2	P1=ON, P2=ON, P3=ON, P4=ON
3	Mode 3	P1=ON, P2=OFF P3=ON, P4=OFF
4	Mode 4	P1=OFF, P2=OFF, P3=OFF, P4=ON

Table 7.2: Relationship between switch positions and different modes

Using different switch position antenna is optimized for four modes. Relationship between the operation modes and the states of switches of proposed antenna is shown in Table 7.2.

Modes of Reconfigurable Fractal Antenna

- **Mode 1**

All four switches are off in this mode. Fig. 7.6 presents the simulated and measured reflection coefficient of proposed reconfigurable fractal antenna. For this mode following conclusion can be drawn:

- When all the four switches are off the proposed antenna resonates approximately at same frequency of 5.74 GHz and 8.82 GHz as that of reference antenna.

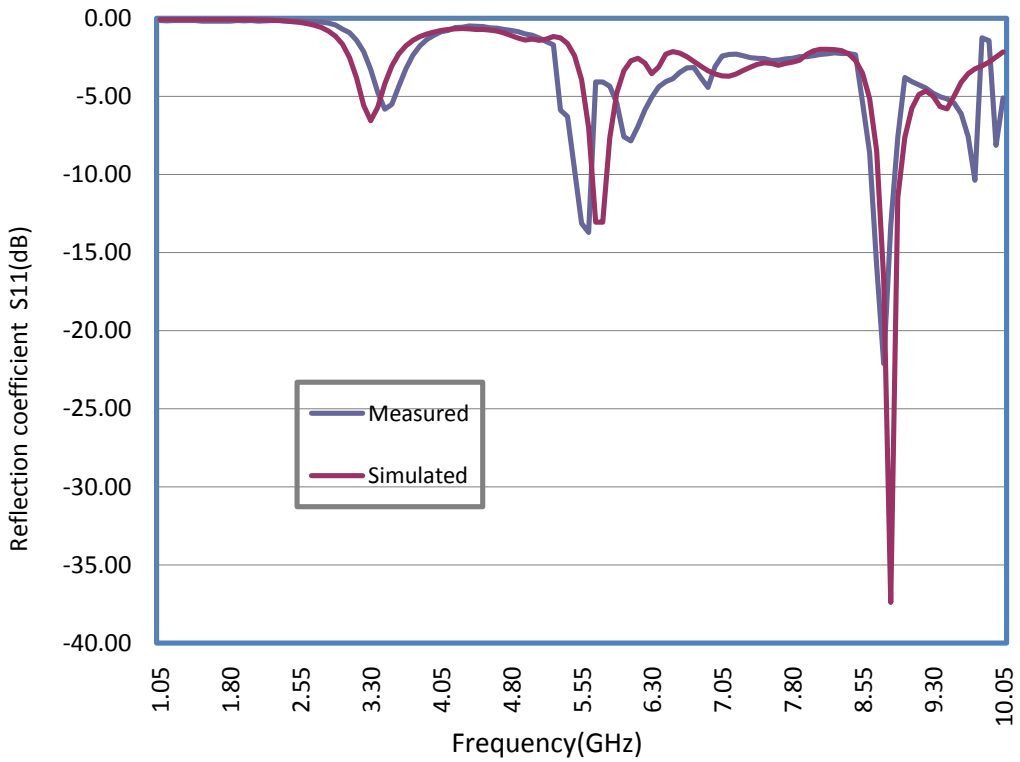


Fig. 7.6: Reflection coefficient of Proposed Antenna in Mode 1

- Antenna has gain of 2.488 dB & 4.93 dB at frequency of 5.74 GHz and 8.82 GHz respectively.
- The radiation efficiency of antenna is 36% and 38% at resonant frequency of 5.74 GHz and 8.82 GHz respectively.

- **Mode 2**

Fig. 7.7 shows the reflection coefficient of the proposed antenna in mode 2. In this mode all the switches are on. For this mode following points can be concluded.

- In this mode antenna resonates at the frequencies of 5.76 GHz, 6.35 GHz, 7.54 GHz and 9.80 GHz.
- Antenna has gain of 4.8 dB, 4.6dB, 2.20dB and 5.46dB at resonant frequency of 5.76 GHz, 6.35 GHz, 7.54 GHz and 9.80 GHz respectively.
- Radiation efficiency of proposed antenna in this mode is 87%, 43%, 45% and 62% at the resonant frequency of 5.76 GHz, 6.35 GHz, 7.54 GHz and 9.80 GHz respectively.

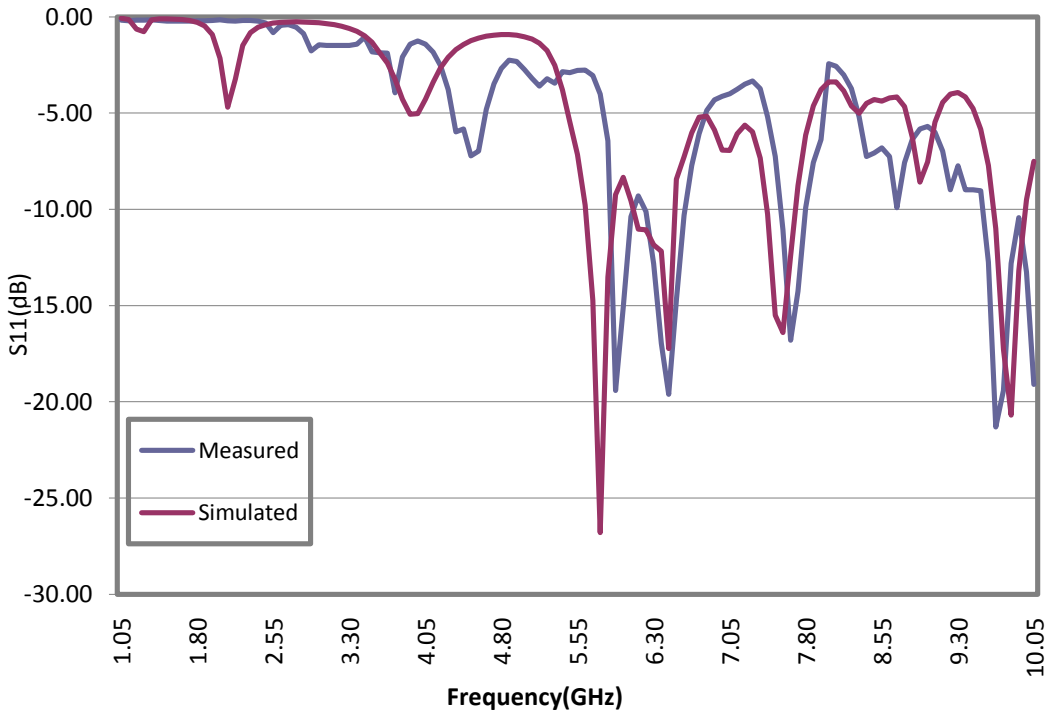


Fig. 7.7: Reflection Coefficient of Proposed Antenna in Mode 2

- **Mode 3**

The switches P1 and P3 are in on position, while switches P2 and P4 are in off position in this mode. Following points can concluded for this mode:

- Fig. 7.8 shows that reflection coefficient of antenna is -25.43 dB, -28.05 dB and -21.74 dB at resonant frequency of 5.70 GHz, 7.23 GHz and 9.52 GHz respectively.

- Gain of antenna is 3.62 dB, 5 dB and 5.02 dB at resonant frequency of 5.70 GHz, 7.23 GHz and 9.52 GHz respectively.
- Antenna has radiation efficiency of 56%, 47% and 52% at resonant frequency of 5.70 GHz, 7.23 GHz and 9.52 GHz respectively.
- Measured results are in close agreement with simulated results.

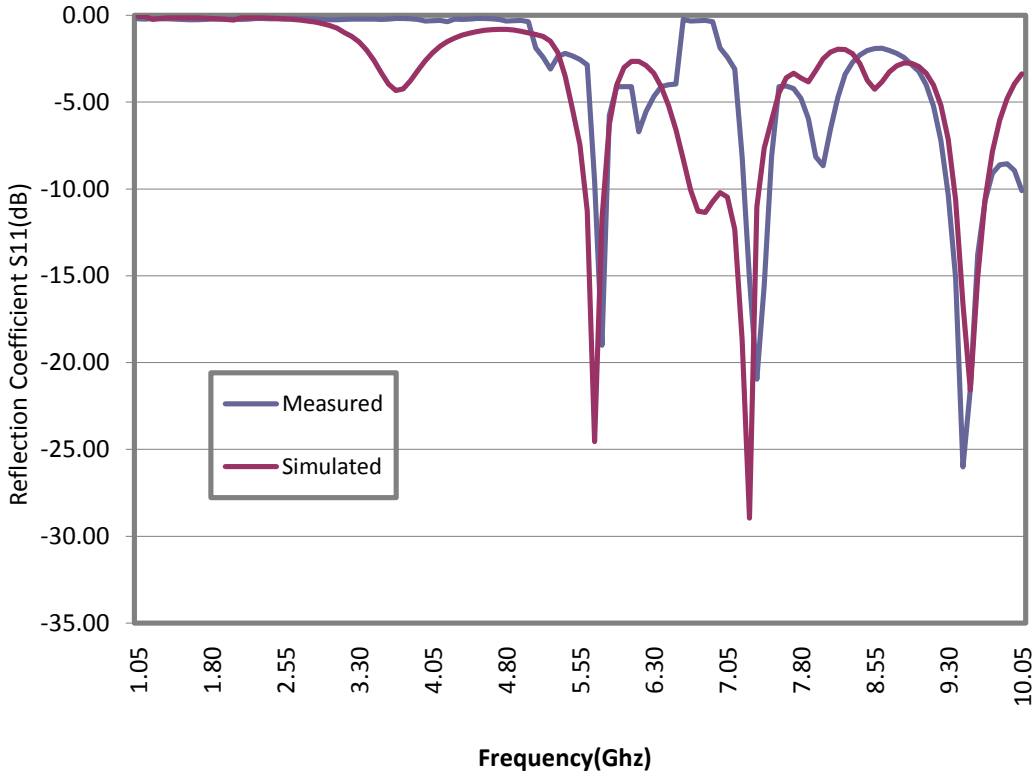


Fig. 7.8: Reflection Coefficient of Proposed Reconfigurable Antenna in Mode 3

- **Mode 4:**

In this mode, switches P1, P2 and P3 are turned off and switch P4 is turned on. Following points can be concluded for this mode.

- Antenna resonates at 3.436 GHz, 5.811 GHz, 6.51 GHz, 7.363 GHz and 8.915 GHz in this mode as shown in Fig. 7.9.
- In experimental results resonant frequencies of 3.436 GHz and 8.915 GHz shifted slightly to lower side in due to fabrication errors.
- Radiation efficiency of antenna is 80% at resonant frequency of 3.436 GHz.

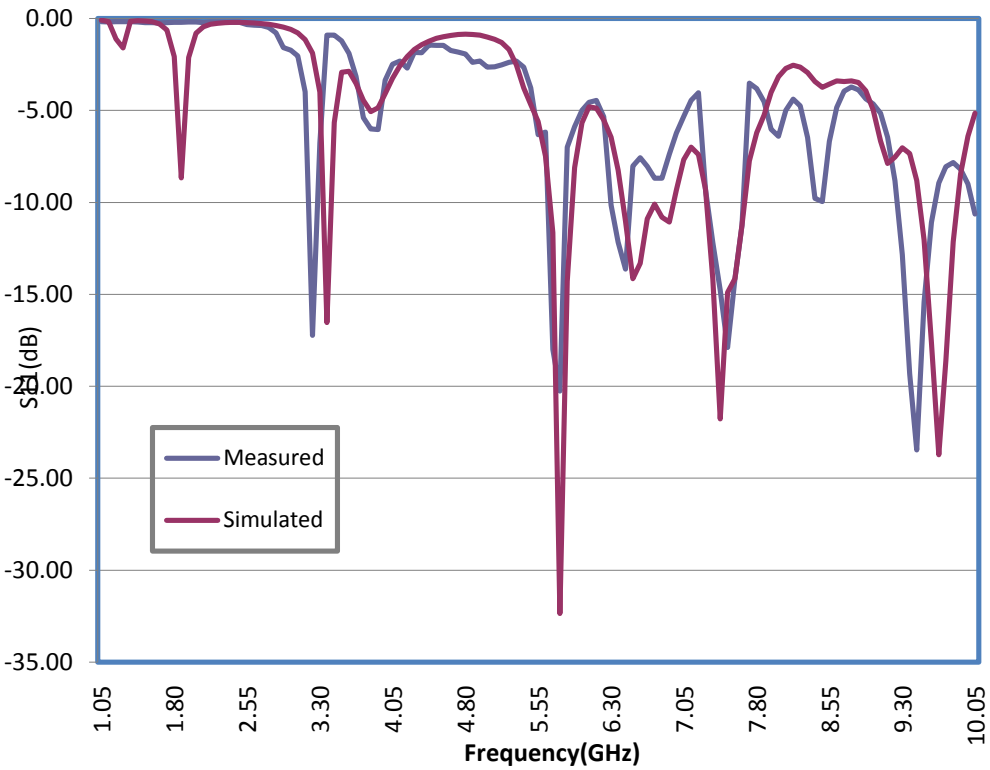


Fig. 7.9: Reflection Coefficient of Proposed Reconfigurable Fractal Antenna in Mode 4

A novel reconfigurable, simple, compact and multiband fractal antenna is proposed. Due to self-similarity geometry of fractal antenna, the proposed antenna is multiband in each reconfigurable mode. Non-reconfigurable fractal antenna in which small patches are connected to central patch permanently has three resonant frequencies. Advantage of introducing reconfiguration concept in fractal antenna is that now it can resonate at ten resonant frequencies in different modes. Power interference issues can also be circumvented by frequency switching in different modes. Proposed antenna works in four switchable modes and has very simple geometry. This antenna can be used for microwave imaging, medical imaging, radar and satellite communication.

The performance parameters of proposed antenna for various reconfigurable modes of reconfigurable fractal antenna for the 1nd iteration are shown in Table 7.3.

	Resonant Frequency (GHz)	**Reflection coefficient (dB)**	**Gain (dB)**	**Radiation Efficiency (magnitude)**
Mode 1	5.74	-14.97	2.488	.36
	8.822	-37.69	4.93	.38
Mode 2	5.76	-26.59	4.8	.87
	6.35	-12.35	4.6	.43
	7.54	-17.42	2.20	.45
	9.800	-22.35	5.46	.62
Mode 3	5.70	-25.43	3.62	.56
	7.23	-28.05	5	.47
	9.52	-21.74	5.02	.52
Mode 4	3.436	-16.03	5	.80
	5.811	-22.84	3.60	.60
	6.51	-27.00	3.03	.55
	7.363	-12.36	2.24	.39
	8.91	-14.60	3.02	.54

Table 7.3: Different Modes of Reconfigurable Antenna and its Performance Parameters

7.4. DESIGN OF RECONFIGURABLE INVERTED CIRCULAR PATCH ANTENNA

Reconfigurable inverted circular patch antenna is designed using two substrate layer that are separated by air gap. Arlon 25N is used as substrate material. The parameters of substrate are given below:

- Relative permittivity (ε_r) = 3.38
- Thickness (h) =1.52 mm
- Loss tangent (δ) =0.0025

Upper substrate of proposed antenna consists of a circular patch on bottom surface. Radius (a) of the patch is 28 mm with U-shape slot cut in it. Microstrip line is printed on bottom layer of lower substrate to feed the circular patch using aperture coupling technique. Bottom surface of upper layer is shown in Fig. 7.10. Top and bottom surface of lower substrate is shown in Fig. 7.11 and Fig. 7.12 respectively.

Firstly, the radius of circular patch is calculated mathematically for resonant frequency (f_r) =1.6 GHz as given below.

$$f_r = \frac{8.794}{a_e\sqrt{\varepsilon_r}} \tag{7.1}$$

$$a_e = a\left[1 + \frac{2h}{\pi\varepsilon_r a}\left\{ln\left(\frac{a}{2h}\right) + (1.41\varepsilon_r + 1.77) + \frac{h}{a}(.268\varepsilon_r + 1.65)\right\}\right]^{\frac{1}{2}} \tag{7.2}$$

Where $\mathbf{a_e}$ represents effective radius and **a** represents physical radius of circular patch. Due to effect of fringing fields at the periphery of circular patch conductor, it has effective radius a_e and $a_e > a$.

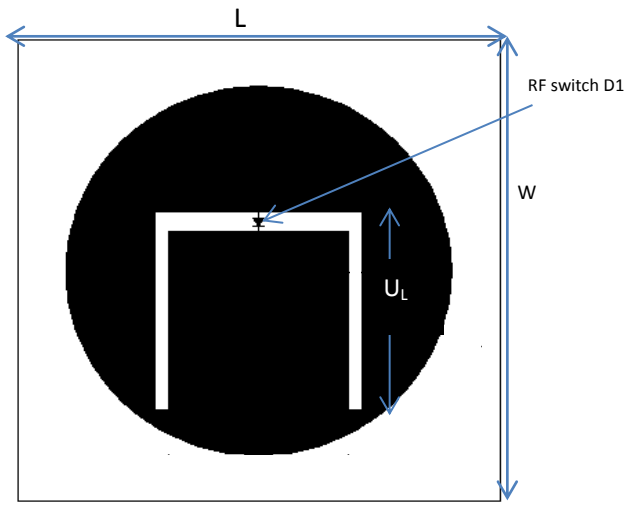


Fig 7.10: Bottom Surface of Top Layer of Antenna

High gain is achieved in proposed antenna due to proper impedance matching which is achieved by slot loading and due to thick air substrate. Effective permittivity of proposed antenna system gets reduced due to introduction of air gap between two layers of antenna substrate. Therefore antenna resonant frequency shifts towards the upper side and impedance bandwidth of proposed antenna system get improved. Bandwidth of antenna is further enhanced by U-slot that is etched in patch. Using HFSS software, air gap between two layers of substrate, length, width and position of U-slot is optimized such that the antenna resonates nearly at a frequency of 2.4 GHz with good gain and wide bandwidth.

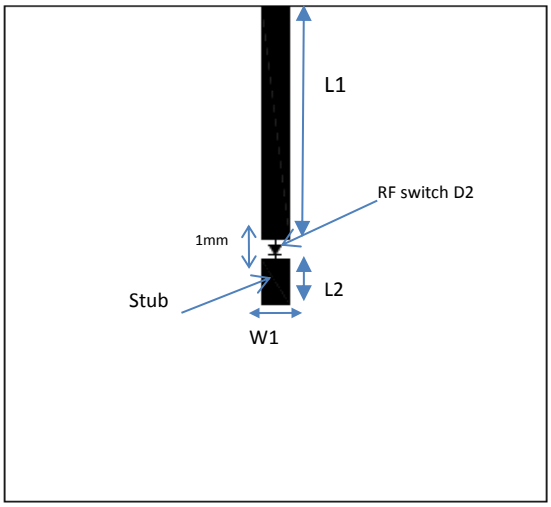


Fig 7.11: Bottom Surface of Bottom Layer of Antenna

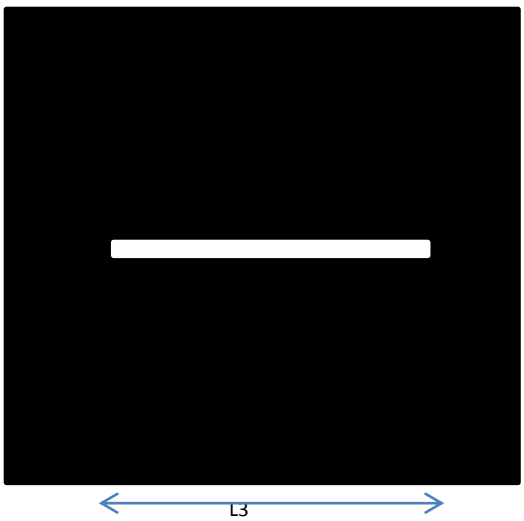


Fig 7.12: Top Surface of Bottom Layer of Antenna

As shown in Fig. 7.10 and Fig. 7.11 antenna is made reconfigurable using two pin diode switches. Table 7.4 shows the design parameters of proposed inverted circular patch antenna. Finally, the prototype of optimized antenna is fabricated and shown in Fig. 7.13.

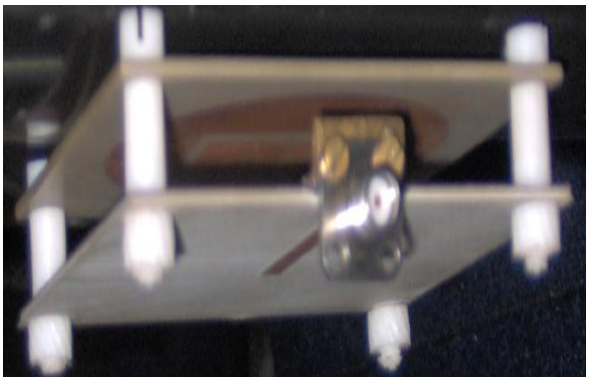


Fig 7.13: Photograph of Fabricated Antenna

Antenna Parameter	Dimension(mm)	Antenna Parameter	Dimension(mm)
Radius of circular patch	28	L1	40.2
L	70	L2	1.8
W	70	L3	42.1
Air gap between two layers	10	W1	3.616
Length of U-slot($U_{L)}$	30	Width of U-slot	2

Table 7.4: Critical Antenna Design Parameters of proposed Inverted Circular Patch Antenna

7.5. RESULTS AND DISCUSSION OF RECONFIGURABLE INVERTED CIRCULAR PATCH ANTENNA

The proposed reconfigurable inverted circular patch antenna works in two modes.

(i) U-slot mode

(ii) L-slot mode.

Table 7.5 shows the relationship between the states of switches and the different operating modes.

Mode	Switch Position
U-slot Mode	D1= off , D2=off
L-slot Mode	D1=on , D2=on

Table 7.5: Relationship between Switch Positions and Operating Modes

A common way to model the RF switch is that it is represented by metallic tape of dimension 1 mm×1mm, when switch is in on position and no metal tape is used to represent off position of switch. This modelling is used to achieve the results in simulation and measurement.

U-slot Mode

Pin diodes D1 and D2 are placed in off position in this mode. Fig. 7.14 shows the simulated and experimental reflection coefficient of proposed antenna.

Experimentally reflection coefficients are measured using the network analyzer. Fig. 7.15 shows both simulated and measured gain of antenna in this mode. Experimentally gain and radiation pattern of fabricated antenna are measured in anechoic chamber using a calibrated horn antenna. Fig. 7.16 and Fig. 7.17 show the simulated radiation pattern of proposed antenna in this mode at a frequency of 2.05 GHz and 2.5 GHz respectively. Fig. 7.18 and Fig. 7.19 show the measured radiation patterns. For U-slot mode following points can be concluded:

- Fig. 7.14 shows that proposed antenna resonates at frequency of 2.3 GHz in this mode and covers the 2.10 – 2.68 GHz frequency band.
- A broad impedance bandwidth of 24.2% is achieved due to U-slot in circular patch.
- Simulated and Measured reflection coefficient is in good agreement as can be seen 7.14.
- Both simulated and measured gain of the proposed antenna in this mode is 8 dB.
- Aperture coupling technique is used to feed the proposed antenna. Due to this in radiation pattern back lobe appears, but it is 16-20 dB lower than to the main lobe.

- Fig.7.18 and Fig.7.19 show more back lobe level in measured radiation pattern as compared to simulated radiation pattern due to effect of finite ground plane and losses.

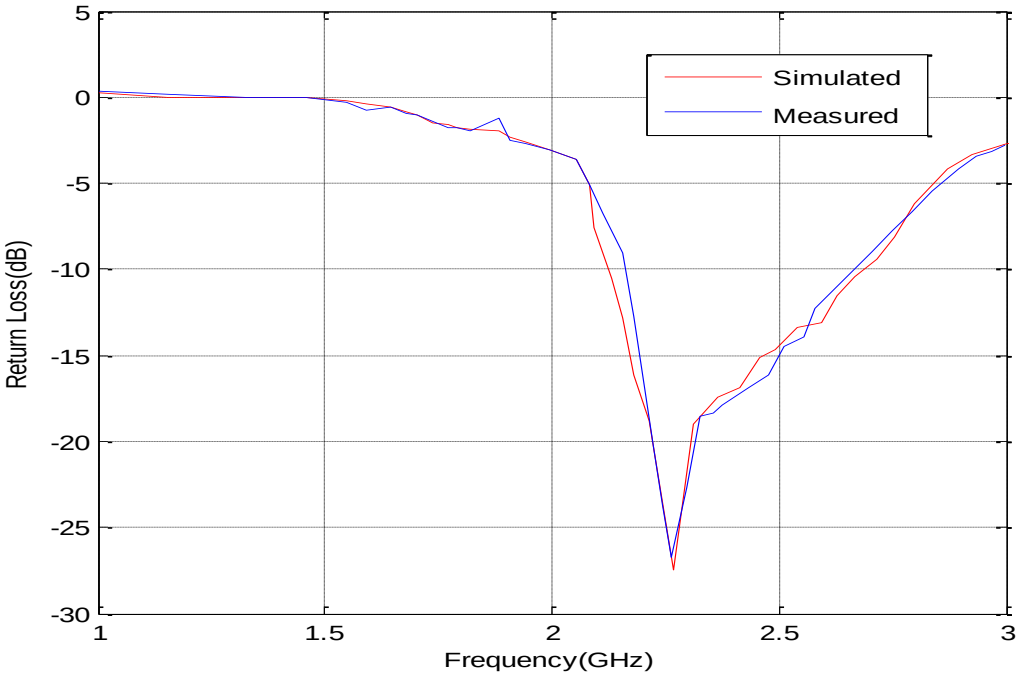


Fig. 7.14: Reflection Coefficient of Proposed Antenna in U-Slot Mode

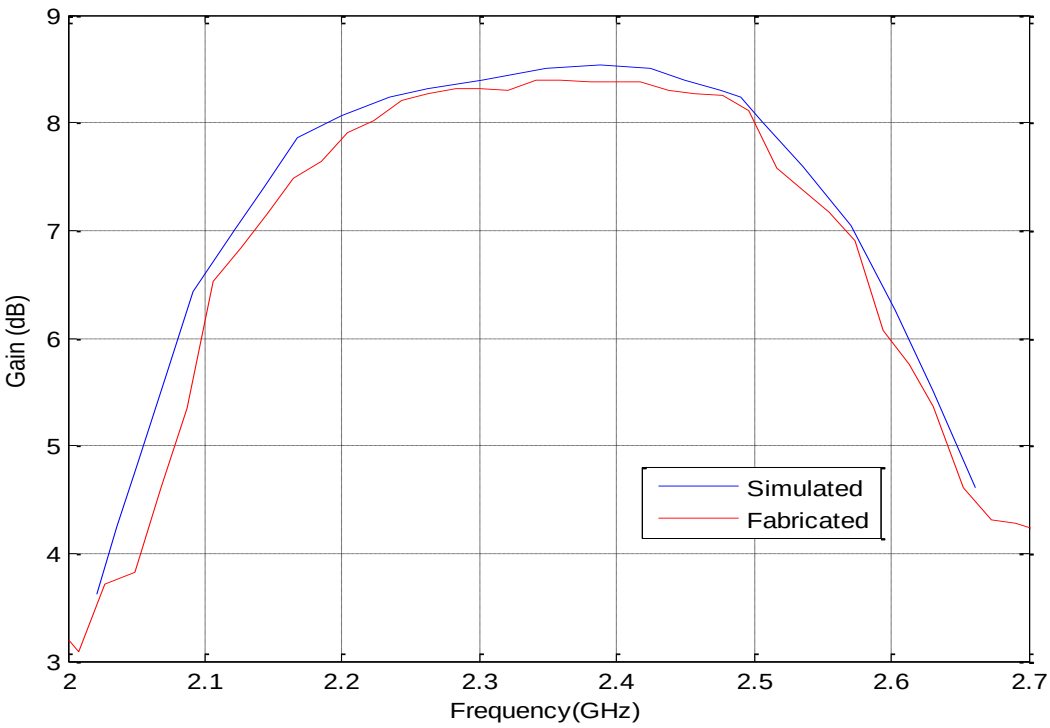


Fig. 7.15: Gain of Proposed Antenna in U-slot Mode

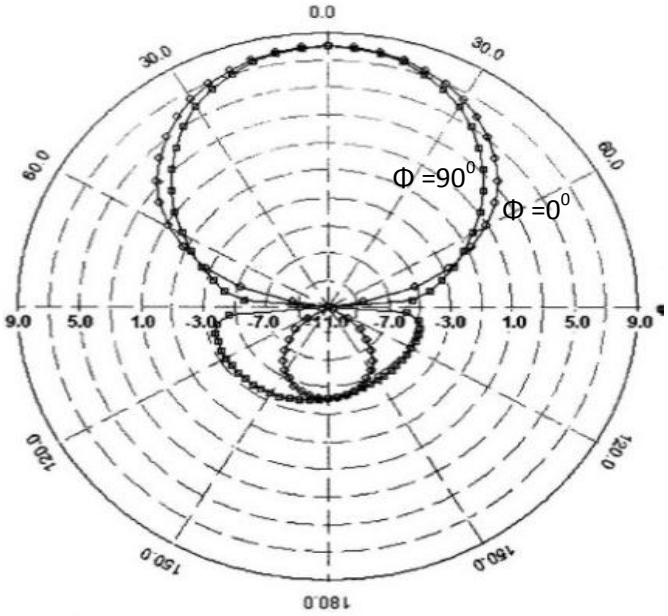


Fig.7.16: Simulated Radiation Pattern of U slot
Mode at 2.05 GHz for $\varphi=0^0$ and $\varphi=90^0$

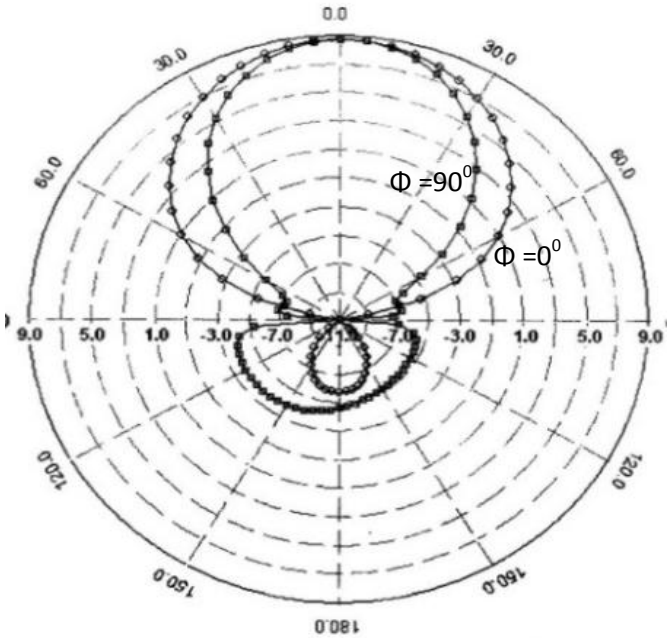


Fig. 7.17: Simulated Radiation Pattern of U slot
Mode at 2.5 GHz for $\varphi=0^0$ and $\varphi=90^0$

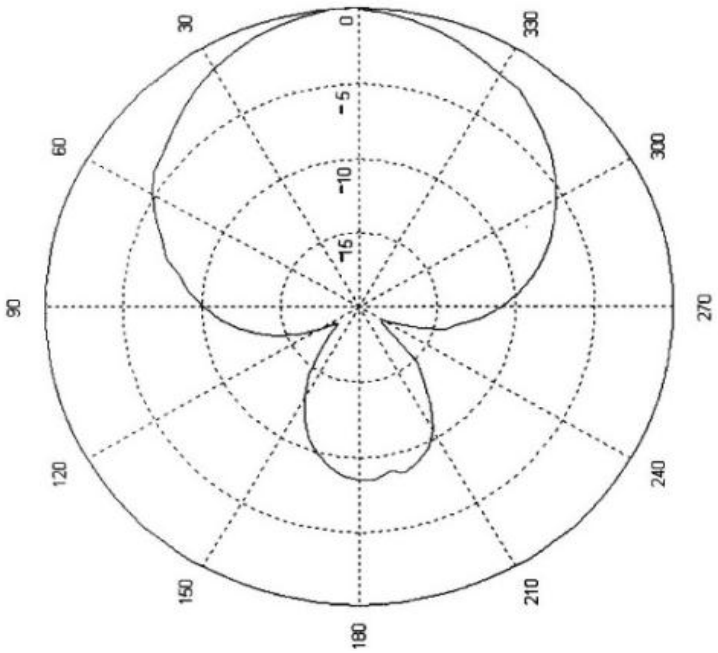


Fig.7.18: Measured Radiation Pattern of U slot Mode
at 2.05 GHz for $\varphi=0^0$

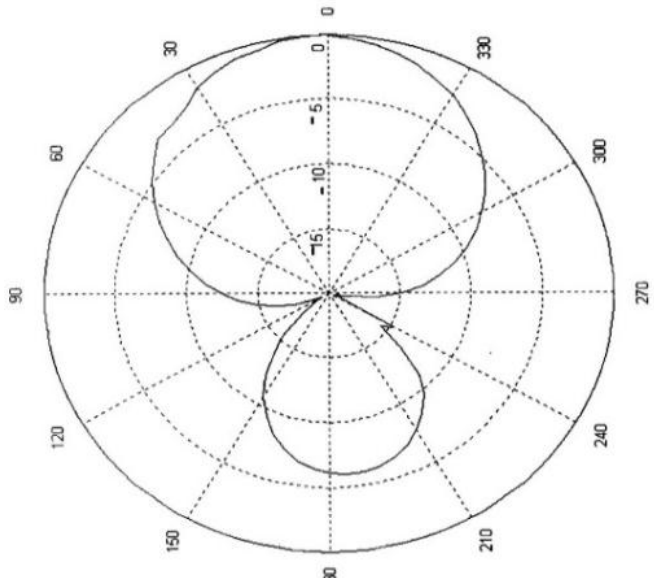


Fig. 7.19: Measured Radiation Pattern of U slot Mode
at 2.5 GHz for $\varphi=0^0$

L-Slot Mode

Antenna works in L-slot mode when both the pin diode switch D1 and D2 are placed in on position. Simulation is performed by positioning a copper strip of 1mm at the

center of U-slot. Through this copper strip current flow at the middle of U-slot and it appears that circular patch has two L-slot. As the current distribution in proposed antenna changes in this mode due to change in switch positions, hence resonant frequency of antenna get changed. To obtain proper impedance matching in this mode length of feed line is changed using the diode D2.

Fig. 7.20 shows the simulated and measured reflection coefficient of proposed antenna in this mode. For experimental purpose a copper strip of size 1 mm × 1 mm is connected at middle of U-slot to convert it to two L-slots. Same technique is used at the feed line and a copper strip of size 1 mm × 1 mm is used to connect it with stub. Fig. 7.21 shows the simulated and measured gain of antenna. Fig. 7.22 shows simulated radiation pattern and measured radiation pattern is shown in Fig. 7.23. For this mode, following points can be concluded:

- Antenna resonates at 1.88 GHz in this mode and covers 1.80 – 1.98 GHz bandwidth as shown in Fig. 7.20.
- From Fig. 7.20, it can be seen that measured reflection coefficient is in good agreement with simulated reflection coefficient.
- Gain of antenna is 7.8 dB at the resonant frequency of 1.88 GHz as shown in Fig. 7.21.

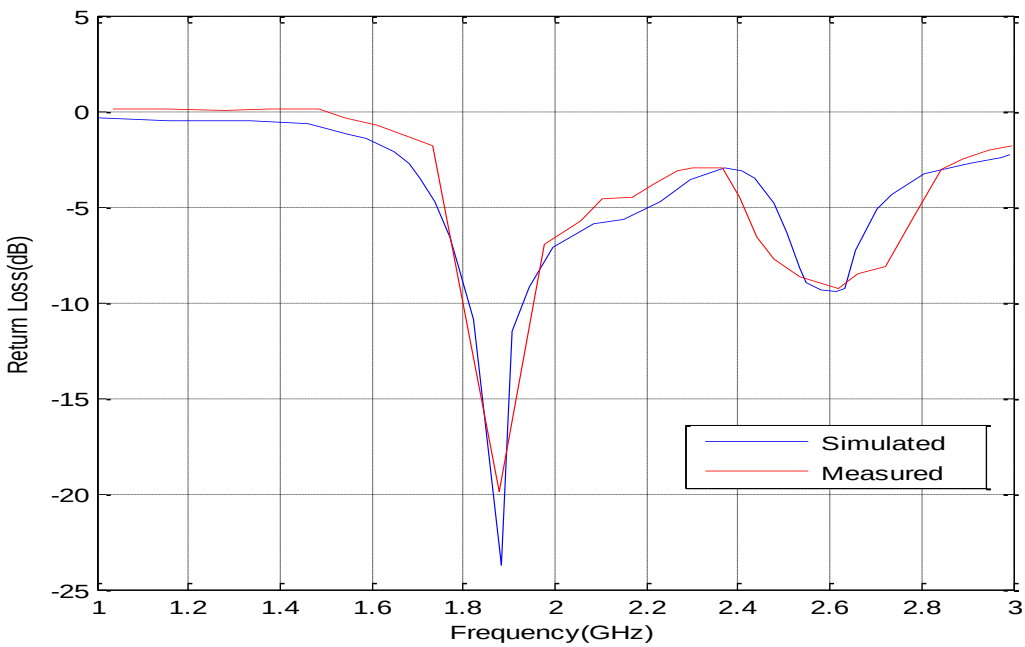


Fig. 7.20: Reflection Coefficient of Proposed Antenna in L-Slot Mode

- Impedance bandwidth of proposed antenna in this mode is 9.5%.
- Due to aperture coupling in radiation pattern back lobe appears, but it is 16 -20 dB lower than main lobe. Due to effect of finite ground plane, back lobe level is more in measured radiation pattern as compared to simulated one.

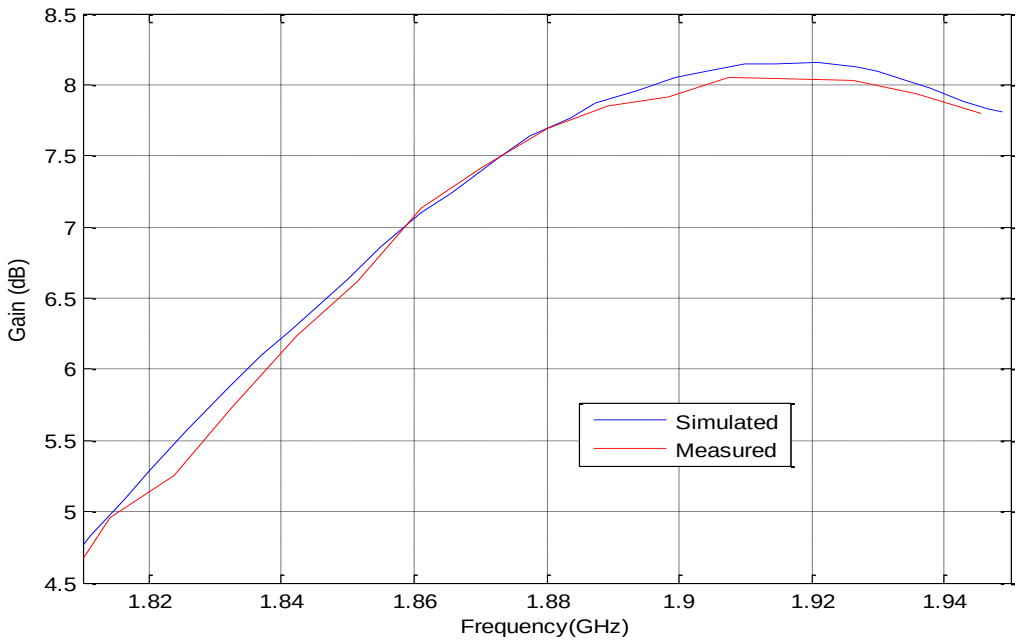


Fig. 7.21: Gain of Proposed Antenna In L-Slot Mode

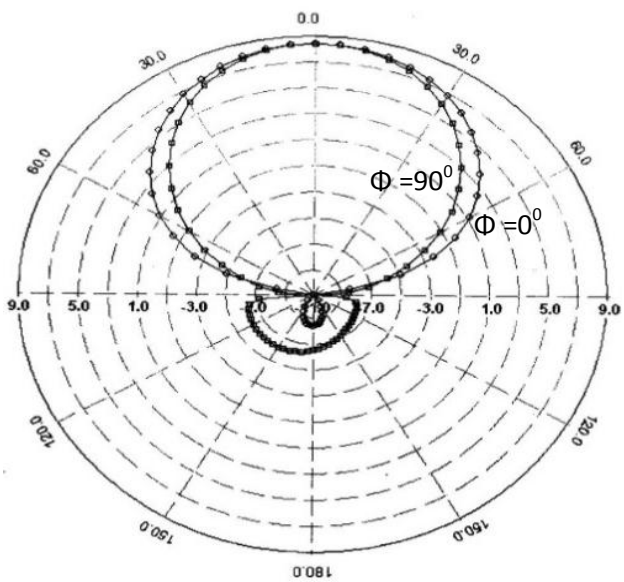


Fig.7.22: Simulated Radiation Pattern of L slot mode at 1.88 GHz for $\varphi=0^0$ and $\varphi=90^0$

In both the modes, gain and radiation pattern of proposed antenna are approximately same, only the change in frequency bands occurs when switching is done from one mode to another. This is the desired characteristic of reconfigurable antenna.

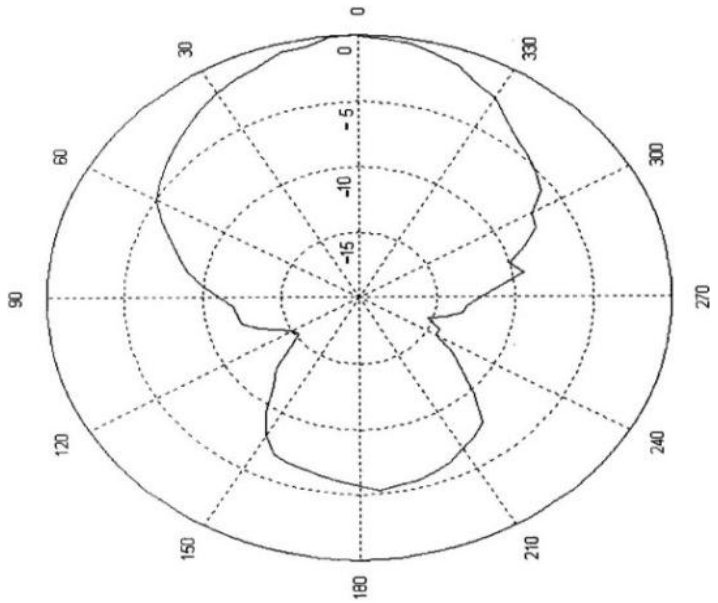


Fig.7.23: Measured Radiation Pattern of L-slot Mode at 1.88 GHz for $\varphi=0^0$

A frequency reconfigurable, high gain inverted circular patch antenna is presented. The proposed antenna is fed using aperture coupling by a microstrip line. By changing the distribution of current in patch, frequency reconfiguration is attained in antenna. It works in two modes i.e. U-slot mode and L-slot mode. In L-slot mode, antenna covers 1.80 – 1.98 GHz frequency band and in U-slot mode 2.10 – 2.68 GHz frequency band is covered. In both modes, gain of antenna is same and is approximately equal to 8 dB. In U-slot mode, antenna has impedance bandwidth of 24.2 % and in L-slot mode it is 9.5%. Due to aperture coupling back lobe appears in antenna radiation pattern which can be reduced using reflector. The proposed antenna can be used for WLAN and Bluetooth application in U-slot mode and can be used for PCS application in L-slot mode.

7.6. DESIGN OF POLARIZATION RECONFIGURABLE RMPA Polarization reconfigurable rectangular microstrip patch antenna (RMPA) is designed at 5.75 GHz using bilayer ring shaped chiral metamaterial and pin diodes.

7.6.1. Design of bilayer ring shaped chiral metamaterial

Bilayer ring shaped chiral metamaterial is designed using FR_4 epoxy substrate having dielectric constant ε_r = 4.4, loss tangent δ =.0025 and thickness h=1.6 mm. Unit cell of this metamaterial is modelled in HFSS and is shown in Fig. 7.24.

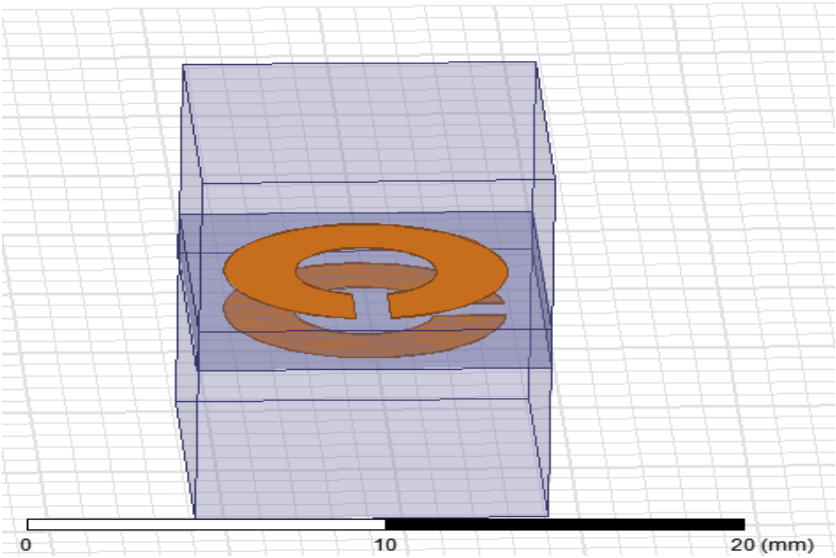


Fig. 7.24: Model of Unit Cell of Ring Shaped Chiral Metamaterial in Mode 1

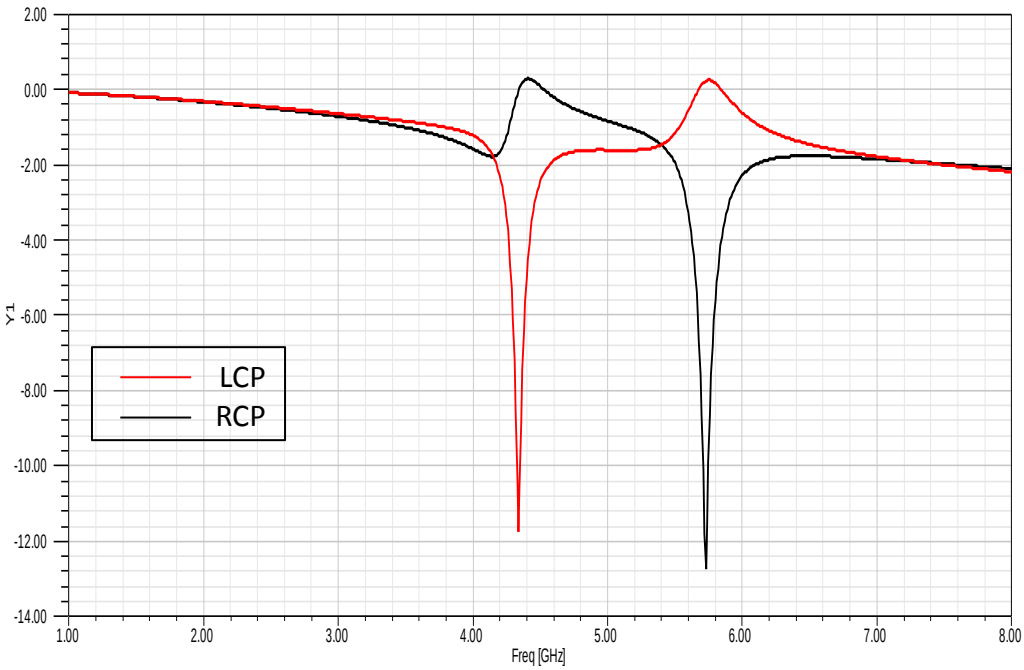


Fig. 7.25: Transmission Coefficient of LCP and RCP wave after passing through Chiral Metamaterial

Ring shaped chiral metamaterial works in two modes depending upon the cut in ring on lower layer of chiral metamaterial. In mode 1 the cut in the lower ring is on the left, while in mode 2 the cut on the lower ring is on right. Fig. 7.24 shows the designed bilayer ring shaped chiral metamaterial. Circular transmission coefficients of EMW waves after passing through the chiral metamaterial are obtained from linear transmission coefficient using the transformation given in equation (6.4) as shown in Fig. 7.25. From the transmission coefficient graph in Fig. 7.25 it can be seen that designed CM in mode 1 passes the LCP wave and stops the RCP wave at frequency of 5.75 GHz. Fig. 7.26 shows the geometric structure of unit cell of chiral metamaterial in mode 2.

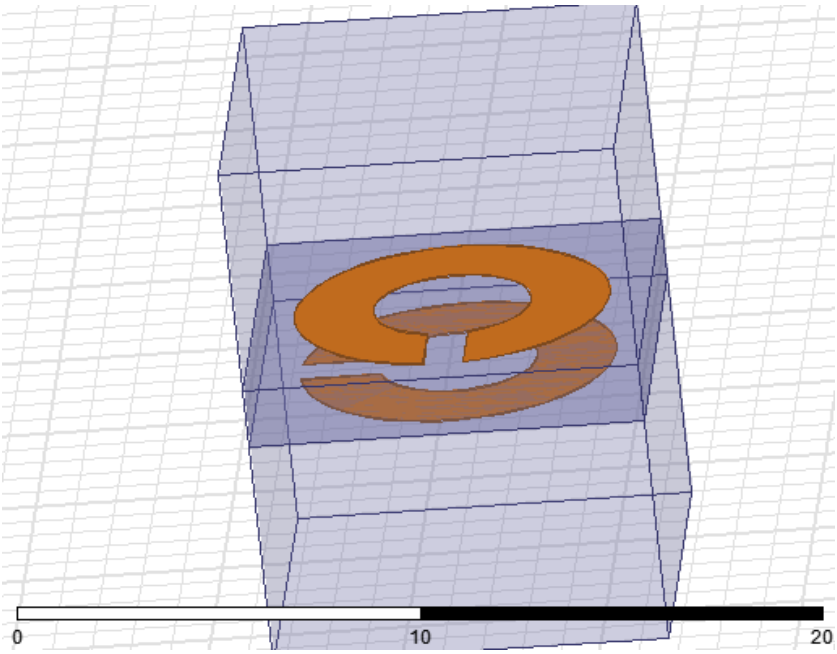


Fig. 7.26: Model of Unit cell of Ring Shaped Chiral Metamaterial in Mode 2

Fig. 7.27 shows the transmission coefficient of LCP and RCP wave after passing through CM in mode 2. From this graph it can be seen that in mode 2, CM passes the RCP and stops the LCP at the frequency of 5.75 GHz. Thus by changing the positon of cut in lower layer of ring shaped CM polarization reconfiguration can be achieved. For reconfiguration, two pin diodes can be used in lower ring as shown in Fig. 7.28

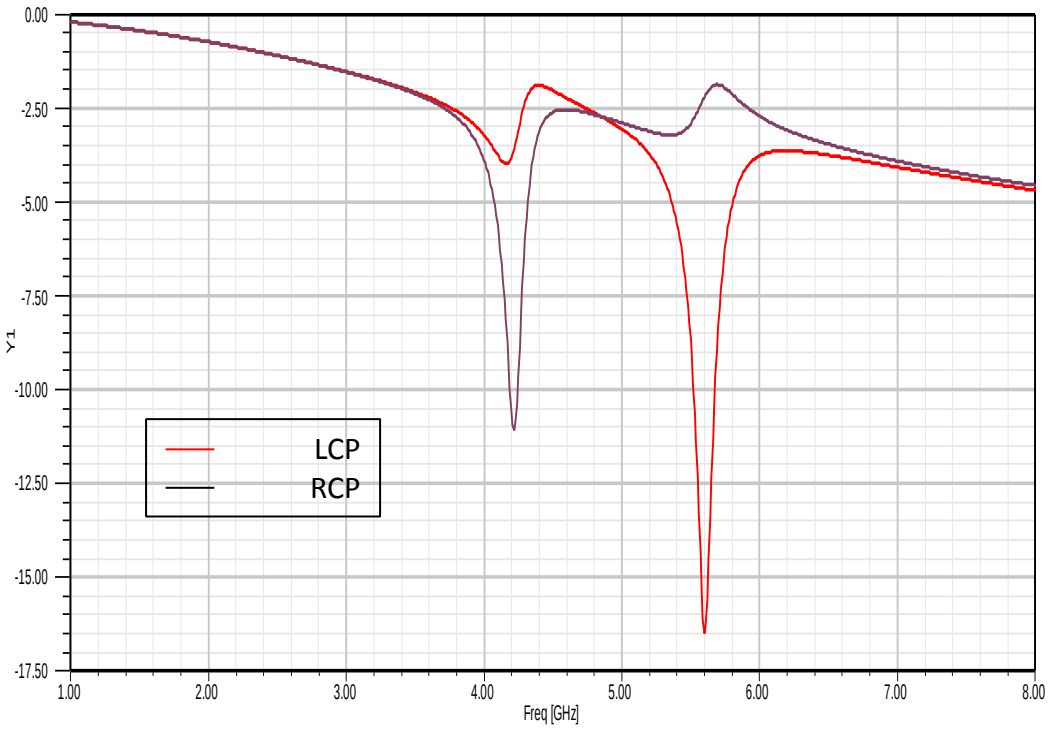


Fig. 7.27: Transmission Coefficient of LCP and RCP Wave after passing through Chiral Metamaterial

When the pin diode 2 is on and diode 1 is off, CM works in mode 1 and it passes the LCP wave and stops RCP. When pin diode 1 is off and 2 is on, this CM works in mode 2 and it passes RCP and stops LCP.

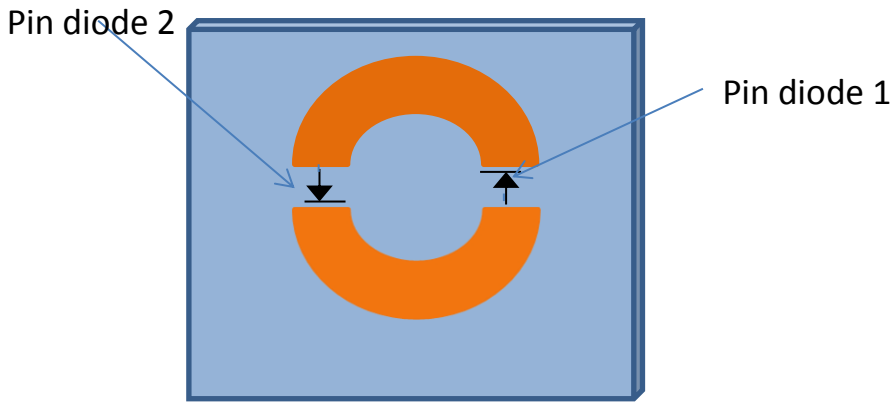


Fig. 7.28: Lower layer of Ring Shaped CM with Two Pin Diodes for Reconfiguration

7.6.2. Design and Results of Reference RMPA

Reference RMPA is designed on same FR_4 epoxy substrate as used for designing the chiral metamaterial as shown in Fig. 7.29. The length and width of the patch antenna are 16mm and 12.1 mm respectively.

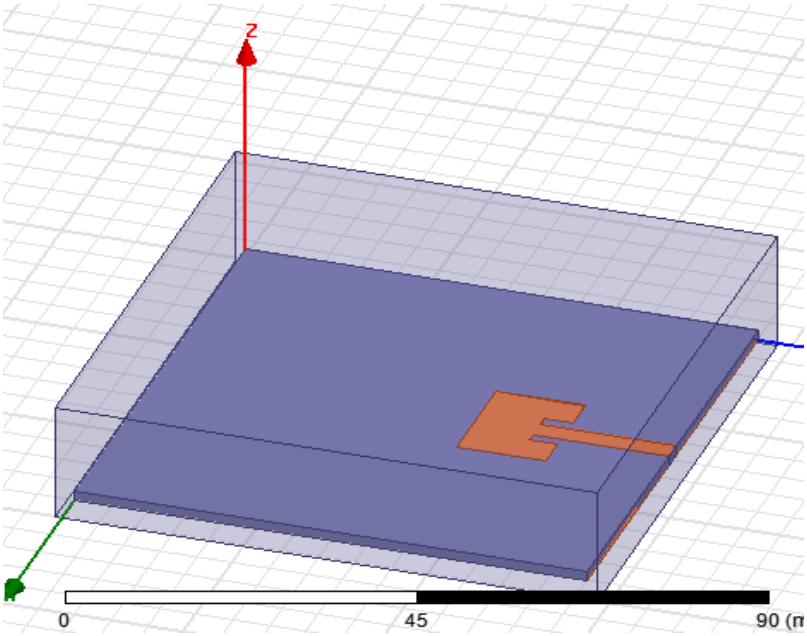


Fig.7.29: Simulation Model of Reference RMPA Resonating at 5.75 GHz

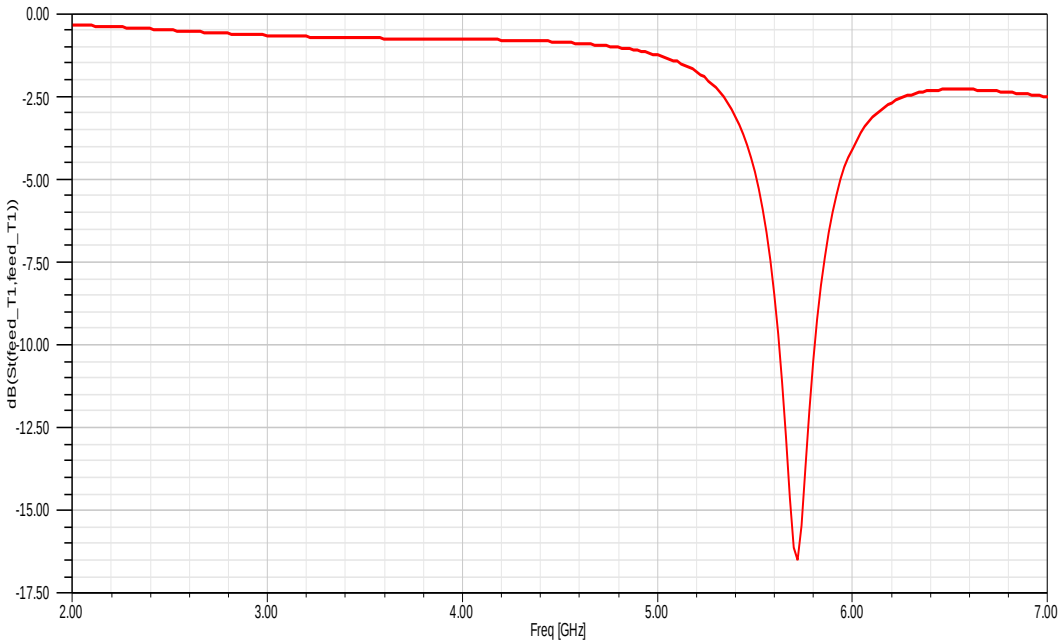


Fig. 7.30: Reflection Coefficient of Reference RMPA

From reflection coefficient graph of reference antenna in Fig. 7.30 shows that reference antenna resonates at 5.75 GHz and has an axial ratio of 45.74 dB at resonant frequency as shown in Fig. 7.31.

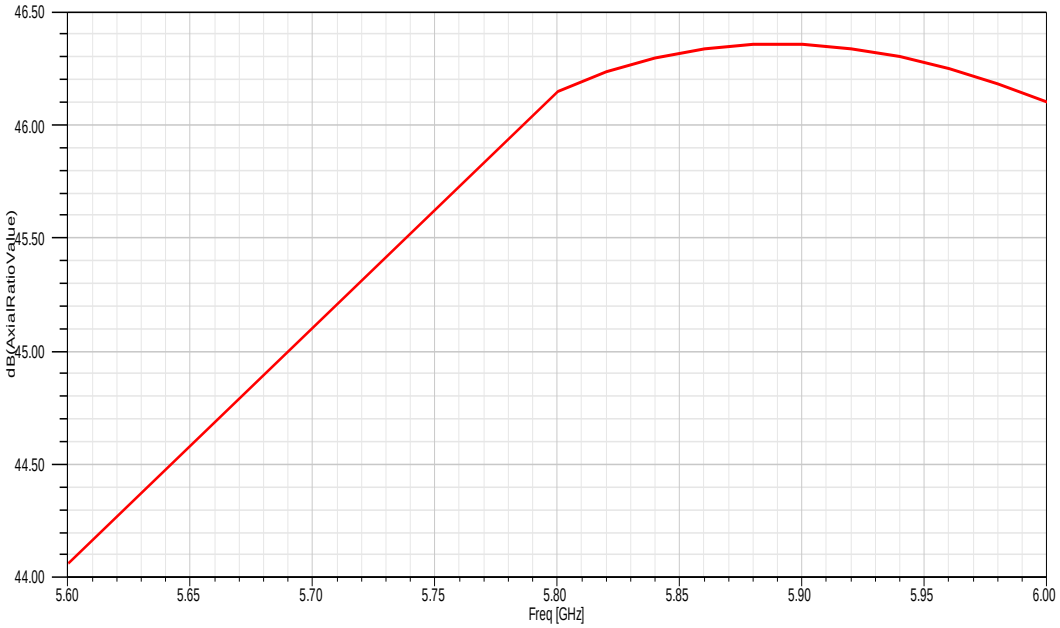


Fig. 7.31: Axial ratio of Reference RMPA

After designing the unit cell of bilayer ring chiral metamaterial in two modes, a 7×7 array of unit cells of this CM in mode 1 is applied over the RMPA at a spacing d as shown in Fig. 7.32.

Numerical simulation performed using HFSS in the range of 4 GHz to 6 GHz shows that optimum value of the spacing (d) between the RMPA and CM cover is 20 mm. The dimension of CM cover consisting of 7 ×7 unit cells is same as the size of substrate for RMPA. Fig. 7.32 shows the proposed reconfigurable antenna in Mode 1.

To design proposed antenna in mode 2, an array of 7 ×7 unit cell of ring shaped chiral metamaterial designed in mode 2 is placed over the reference antenna. The proposed antenna in mode 2 is shown in Fig. 7.33. Distance between the rectangular microstrip patch antenna and chiral metamaterial cover is 20 mm same as in the previous mode. In this case also numerical simulation is performed in the frequency range of 4 GHz to 6 GHz.

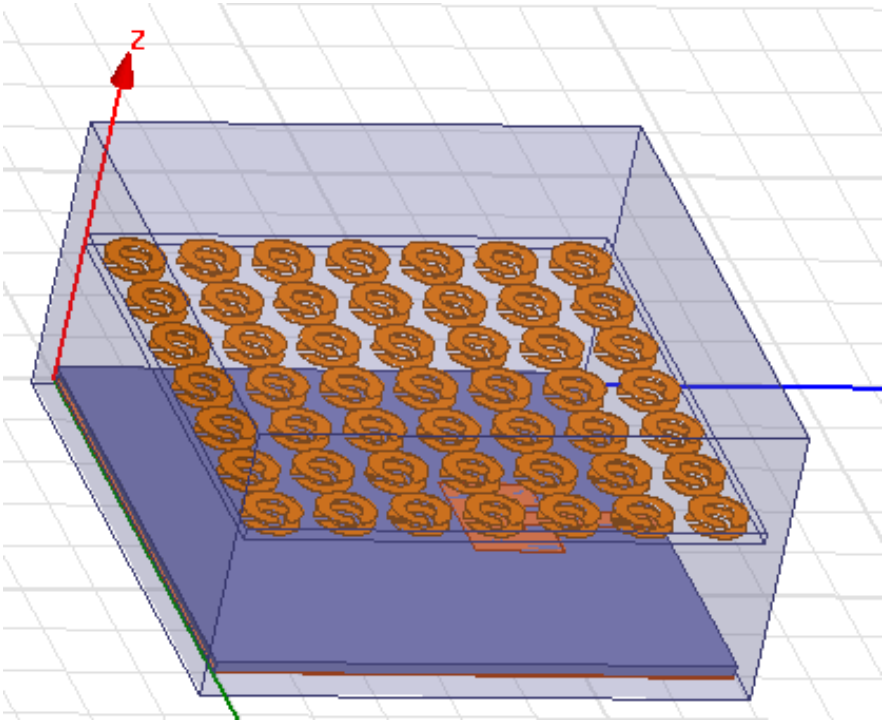


Fig.7.32: Simulation model of RMPA antenna with Chiral Metamaterial Cover in Mode 1

Direction of cut in lower layer of ring CM is different in mode 1 and mode 2 of proposed antenna.

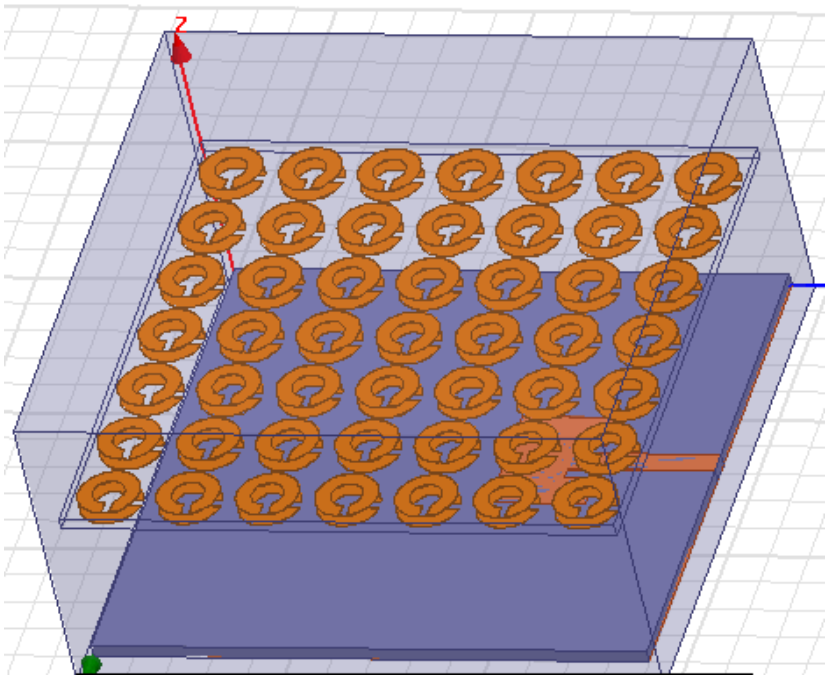


Fig. 7.33: Simulation Model of RMPA Antenna with Chiral Metamaterial Cover in Mode 2

7.7. RESULT AND DISCUSSION OF PROPOSED POLARIZATION RECONFIGURABLE ANTENNA

Optimized polarization reconfigurable antenna is simulated HFSS and results are obtained in mode 1 and mode 2. For reconfiguration pin diodes can be connected on lower layer of CM cover and switching between the two modes can be obtained.

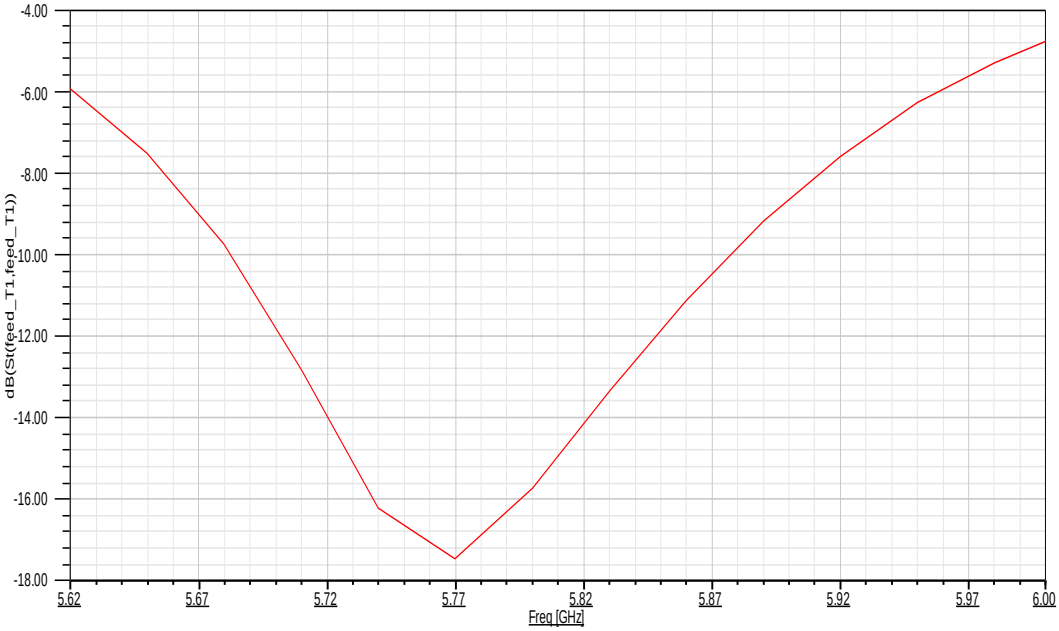


Fig. 7.34: Simulated Reflection Coefficient of RMPA Antenna with Chiral Metamaterial Cover in Mode 1

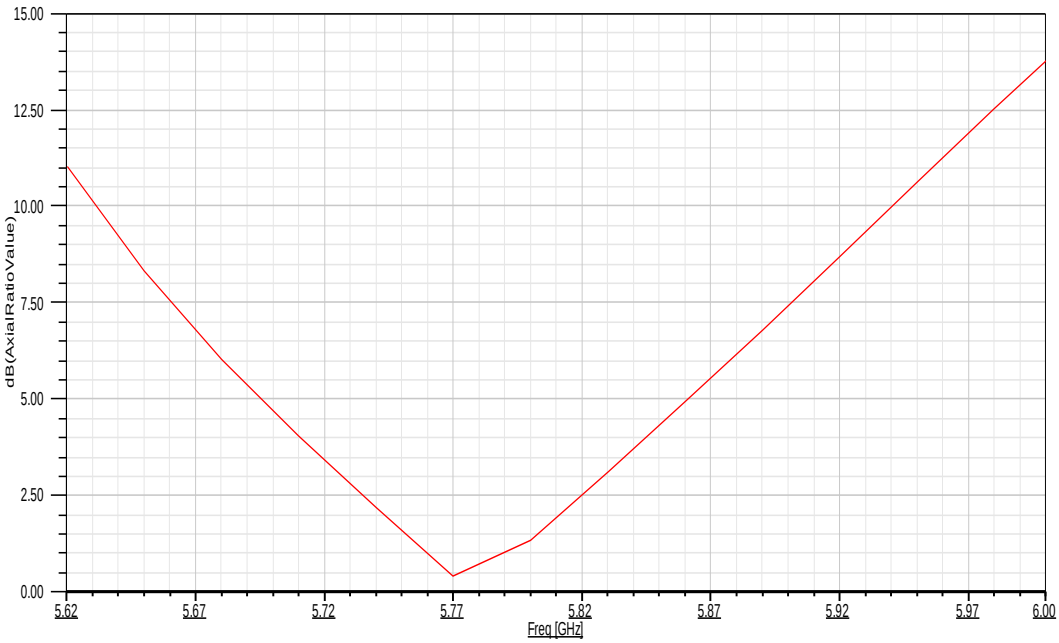


Fig. 7.35: Axial ratio of RMPA Antenna with Chiral Metamaterial Cover in Mode 1

Fig. 7.34 shows the reflection coefficient of proposed polarization reconfigurable antenna in mode 1. Antenna resonates at 5.77 GHz with axial ratio of 0.42 dB as shown in Fig. 7.35. Resonant frequency of RMPA has not changed with addition of CM cover, but the axial ratio has changed from 45.74 dB to 0.42 dB due to addition of CM cover in RMPA. Fig. 7.35 shows the LCP and RCP gain of proposed antenna. From the gain graph it is clearly seen that proposed antenna in mode 1 allows the LCP wave to pass and stops the RCP wave. So polarization of wave has changed from linear to circular and antenna radiates LCP wave in mode 1.

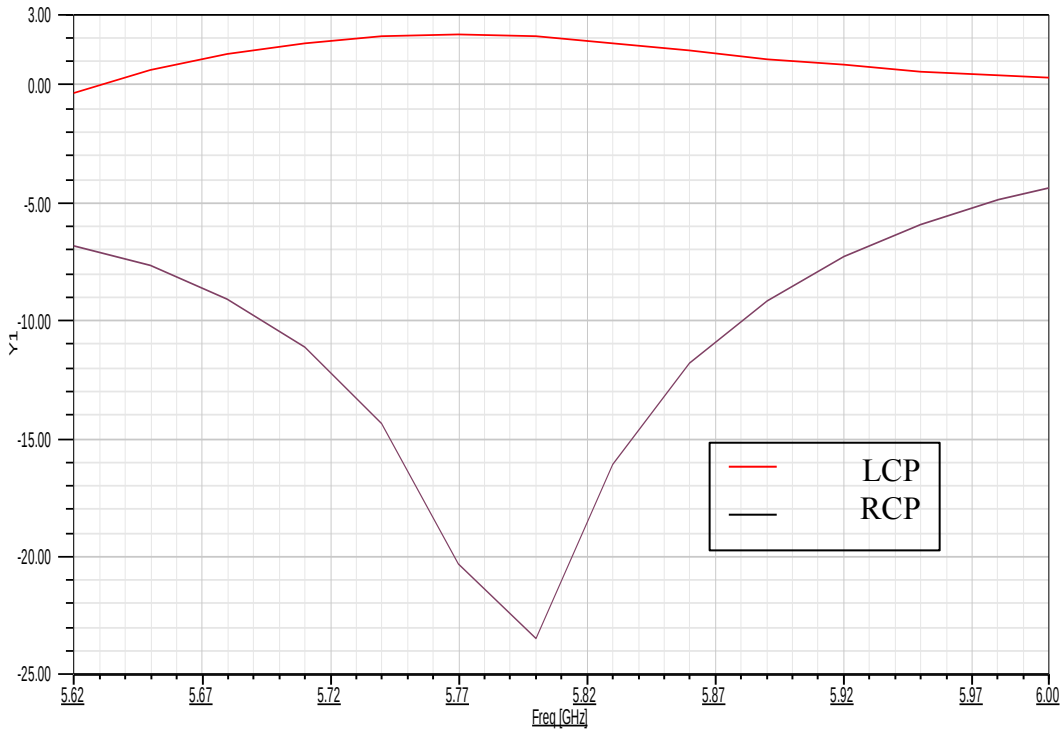


Fig.7.36: Gain of Rectangular patch antenna (RMPA) with Chiral Metamaterial Cover in Mode 1

For mode 2, reflection coefficient of proposed antenna is shown in Fig. 7.37. In this mode also, resonant frequency of rectangular patch antenna does not change and it resonates at same frequency of 5.77 GHz as in mode 1. Fig. 7.38 shows the simulated axial ratio of proposed antenna in mode 2 and at resonant frequency, axial ratio is 0.40 dB. As the axial ratio of proposed antenna is less than 3 dB in operating frequency range of antenna, so in this mode also antenna is circularly polarized. Fig. 7.39 shows the gain of proposed antenna in mode 2.

Gain graph shows that in mode 2, proposed antenna passes RCP wave and stops LCP wave. RCP gain of antenna is 2.28 dB and LCP gain is -19.49 dB in this mode at the resonant frequency.

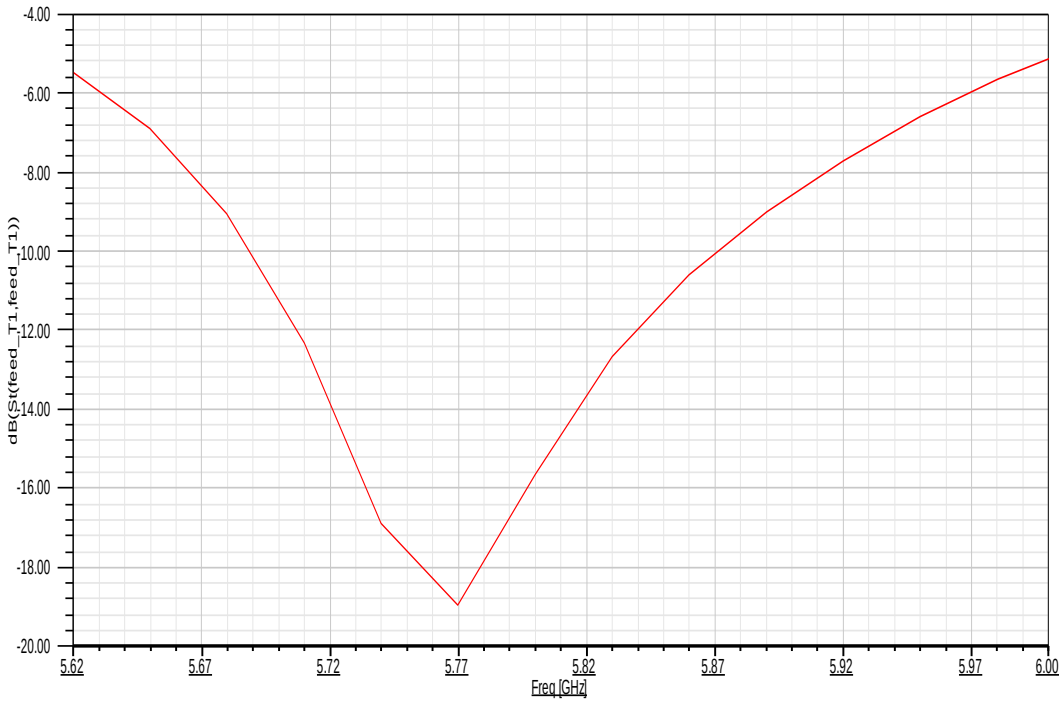


Fig. 7.37: Simulated Reflection Coefficient of RMPA Antenna with Chiral Metamaterial Cover in Mode 2

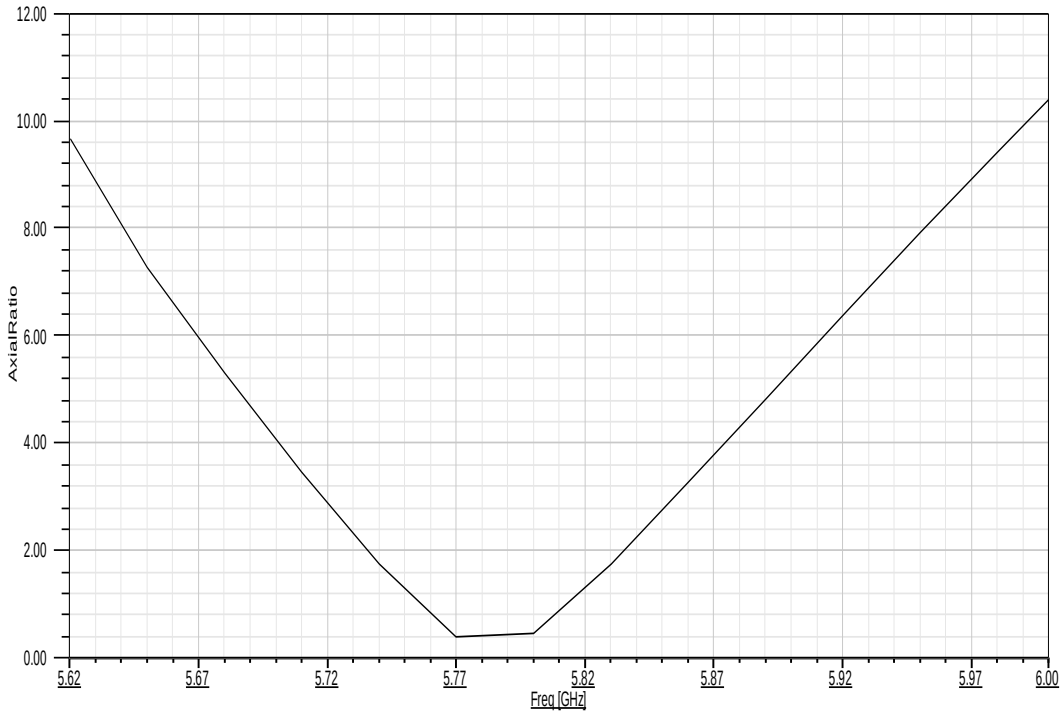


Fig. 7.38: Axial ratio of RMPA Antenna with Chiral Metamaterial Cover in Mode 2

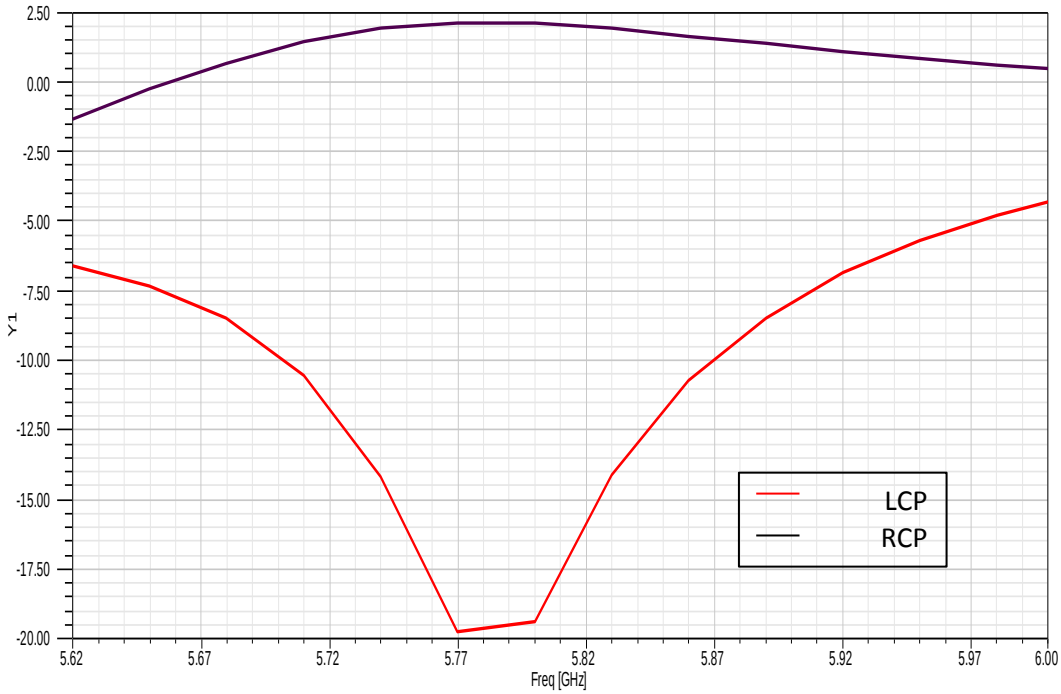


Fig. 7.39: Gain of RMPA Antenna with Chiral Metamaterial Cover in Mode 2

7.8. FABRICATED POLARIZATION RECONFIGURABLE ANTENNA AND ITS RESULTS

The optimized proposed polarization reconfigurable antenna is fabricated. Number of pin diodes required for switching of CM cover is ninety eight, so for measurement purpose CM cover is made separately for two modes and applied over the reference antenna. Fig. 7.39 shows top and bottom layer of fabricated CM cover in mode 1.

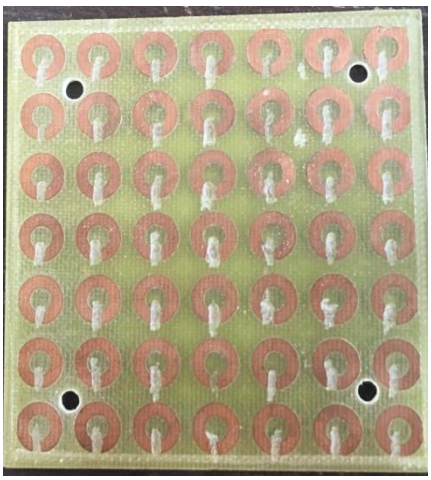


Fig. 7.40(a): Top Layer of CM cover in Mode 1

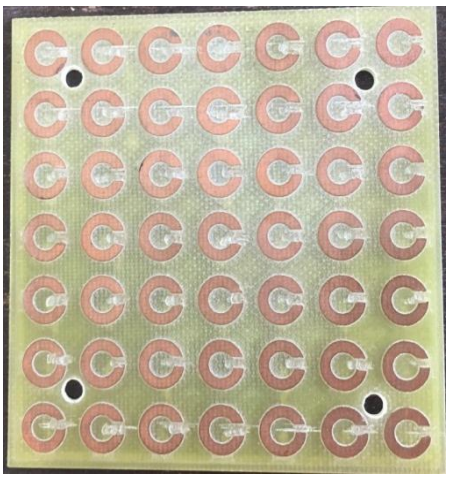


Fig. 7.40(b): Bottom Layer of CM Cover in Mode 1

Fig. 7.41 shows the fabricated RMPA with CM cover in mode 1. This fabricated antenna is tested using VNA and its axial ratio and radiation pattern is measured in anechoic chamber. Fig. 7.42 shows the simulated and measured reflection coefficient of proposed antenna in mode 1. Both the results are in close agreement.

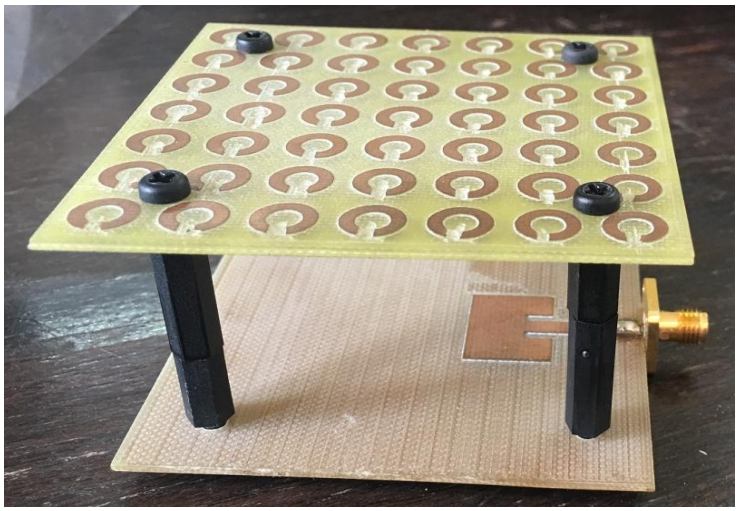


Fig. 7.41: Fabricated RMPA with CM Cover in Mode 1

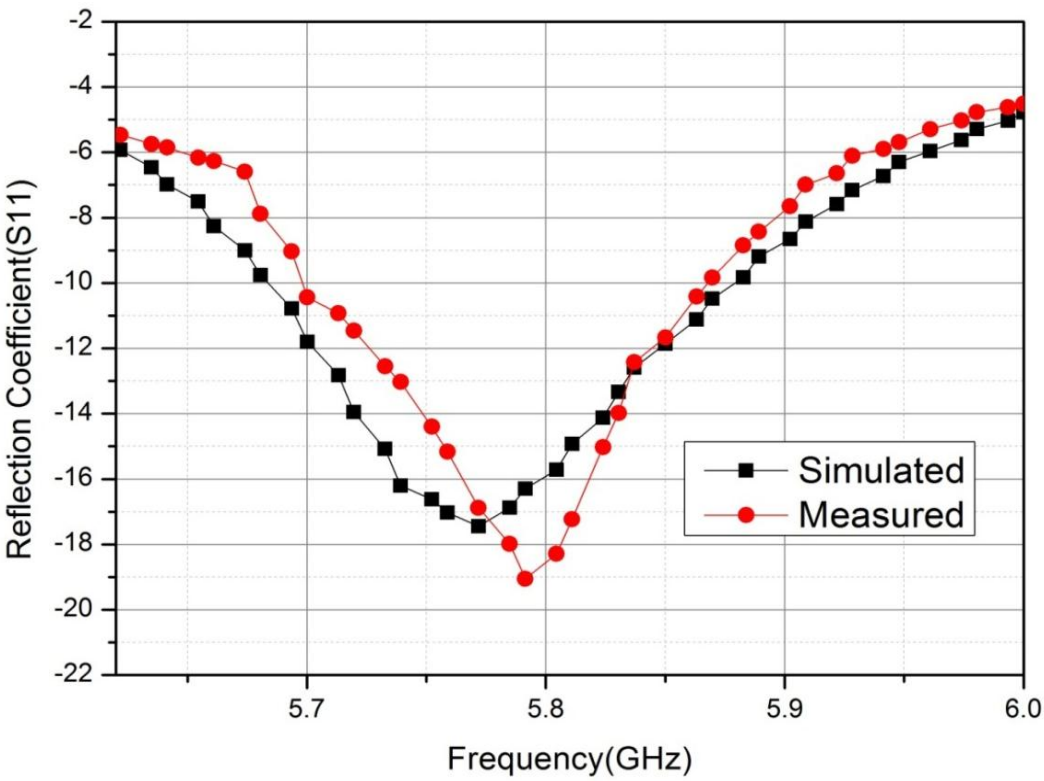


Fig.7.42: Simulated and Measured Reflection Coefficient of Proposed Antenna in Mode 1

Fig. 7.43 shows the measured axial ratio of proposed polarization reconfigurable antenna in mode 1 and Fig. 7.44 shows the LCP and RCP radiation pattern of proposed antenna in mode 1. Simulated and measured results are compared in these graphs and both the results are approximately same. Fig. 7.45 shows the top and bottom layer of fabricated CM cover in mode2 and Fig. 7.46 shows the prototype of fabricated RMPA with CM cover in mode 2.

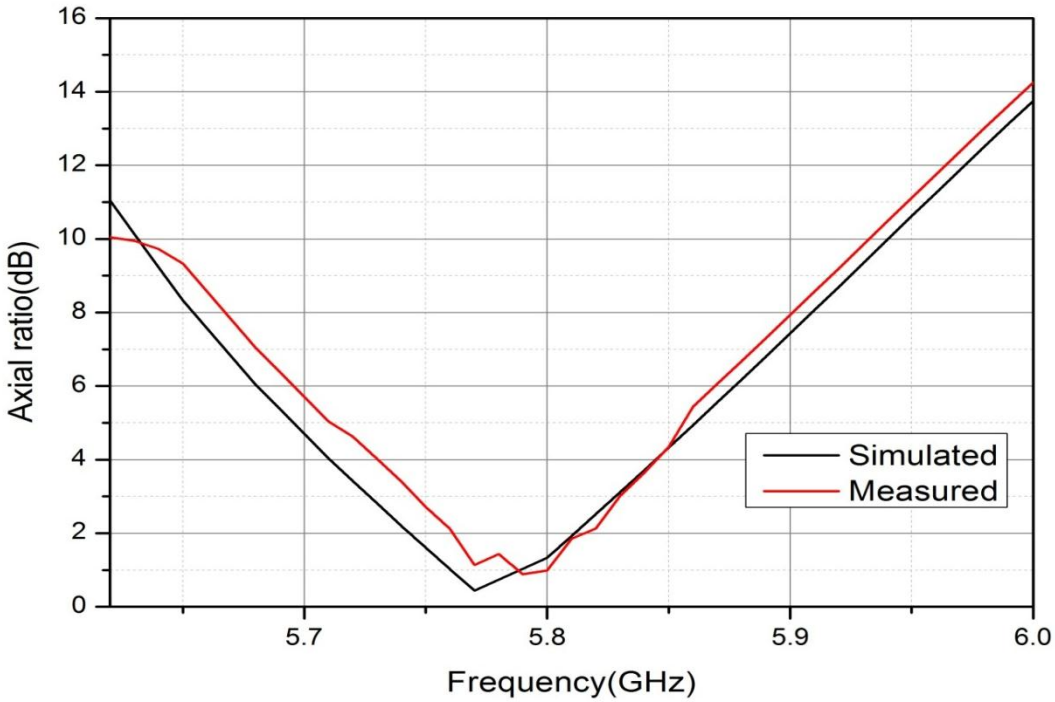


Fig.7.43: Axial ratio of Proposed Antenna in Mode 1

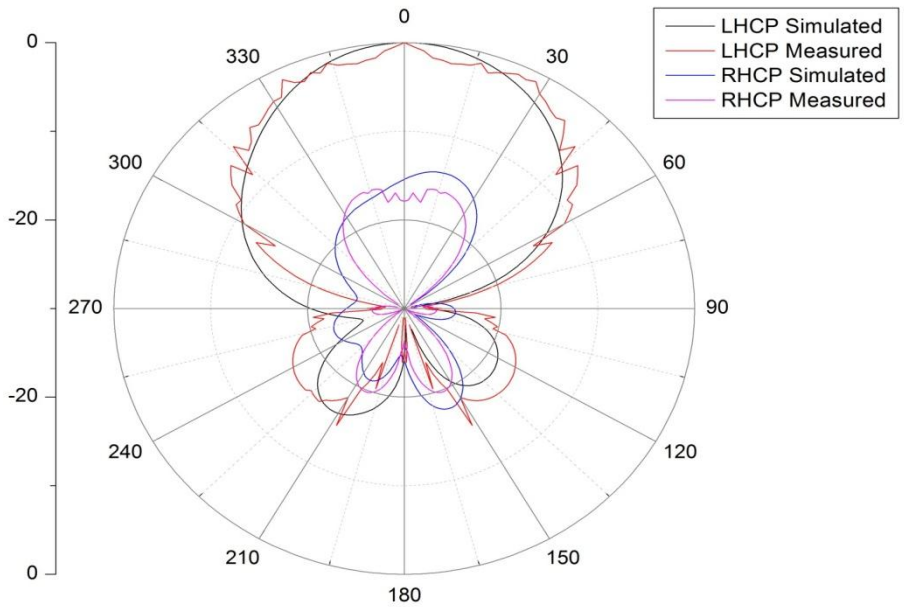


Fig.7.44: Radiation Pattern of Proposed Antenna in Mode 1

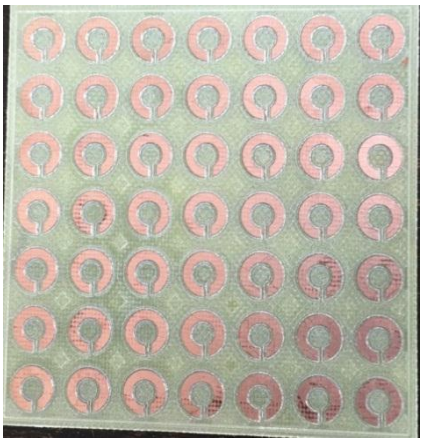


Fig. 7.45(a): Top Layer of CM Cover in Mode 2

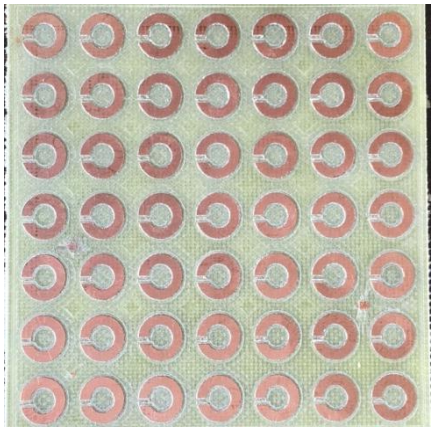


Fig. 7.45(b): Bottom Layer of CM Cover in Mode 2

Fig. 7.46: Fabricated RMPA with CM Cover in Mode 2

The measured and simulated reflection coefficient of proposed antenna in mode 2 is shown in Fig. 7.47. Fig. 7.48 shows the axial ratio of proposed antenna in mode 2 and it is less than 3 dB in operating range of proposed antenna as can be seen from this graph. Fig. 7.49 shows the simulated and measured radiation pattern of proposed antenna in mode 2. From graph it can be seen that antenna passes RCP wave and stops the LCP wave. Hence the proposed antenna excites LCP wave in mode1 and RCP wave in mode 2.

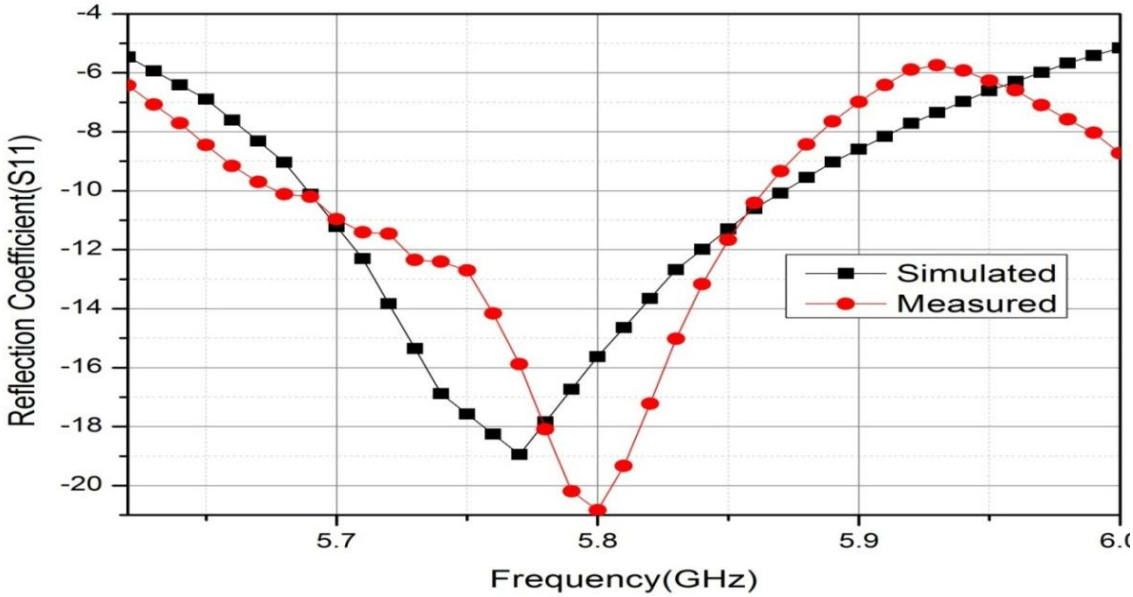


Fig.7.47: Reflection Coefficient of Proposed Antenna in Mode 2

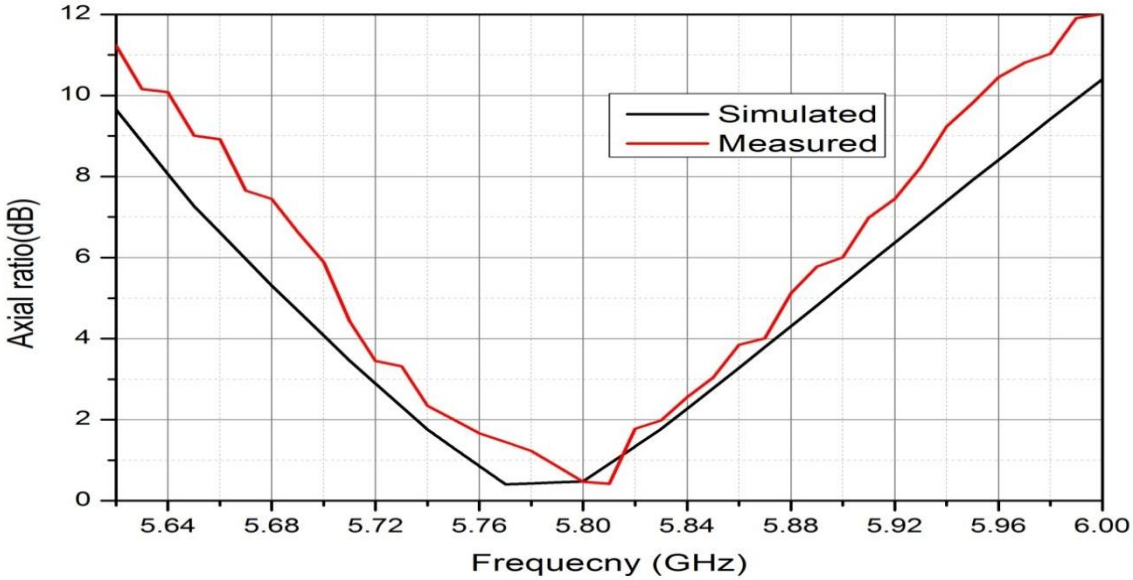


Fig. 7.48: Axial Ratio of Proposed Antenna in Mode 2

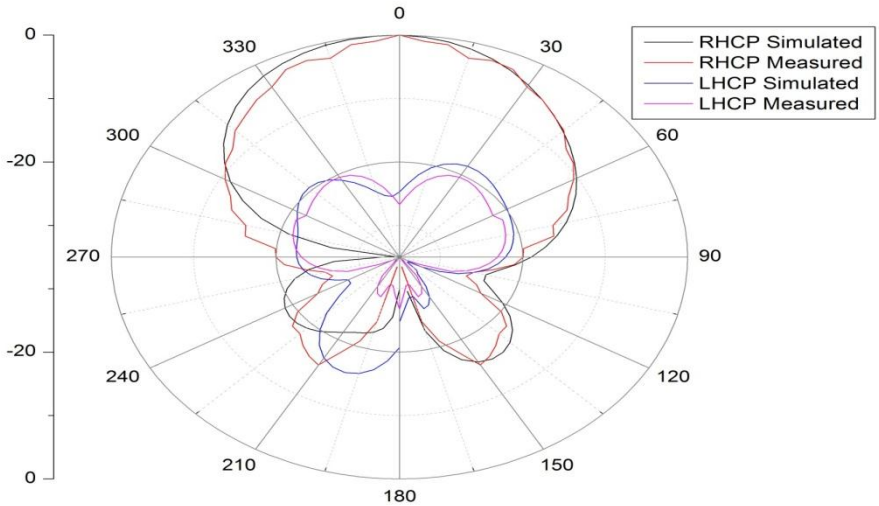


Fig. 7.49: Radiation Pattern of Proposed Antenna in Mode 2

Parameter	Reference Antenna	Proposed Antenna with chiral metamaterial cover Mode 1	Proposed Antenna with chiral metamaterial cover Mode 2
Resonating Frequency	5.72 GHz	5.77 GHz	5.77 GHz
Reflection Coefficient(S11)	-16.36 dB	-17.48 dB	-18.92 dB
Bandwidth	120 MHz	190 MHz	190 MHz
Axial ratio	45.74 dB	0.42dB	0.40 dB
LCP Gain	1.56 dB	2.52 dB	-19.49 dB
RCP Gain	1.56 dB	-23 dB	2.28 dB

Table 7.6: Comparison of Performance Parameters Of Reference Antenna and Proposed Reconfigurable Antenna with CM Cover

Table 7.5 compares the results of reference RMPA and proposed polarization reconfigurable antenna. LCP and RCP gain of reference antenna is 1.56 dB, which shows antenna is linearly polarized. The proposed antenna has 2.52 dB LCP gain and -23 dB RCP gain in mode 1 and in mode 2, LCP gain of proposed antenna is -19.49 dB and RCP gain is 2.28 dB. Thus the proposed antenna is circularly polarized and provides polarization reconfiguration by switching between two states.

7.9. CONCLUDING REMARKS

Design and analysis of three novel reconfigurable antennas is presented. First antenna presented is multiband reconfigurable fractal antenna and it works in four modes. The optimized reconfigurable fractal antenna is fabricated and experimental results are obtained. Measured results of fabricated antenna are in close agreement with simulated one. The proposed reconfigurable fractal antenna can be used for microwave and medical imaging application, satellite communication, radar and wireless communication applications.

A frequency reconfigurable, high gain inverted circular patch antenna is the second antenna proposed in this chapter. U-slot is etched in circular patch in this proposed antenna. Introduction of U-slot in circular patch helps to attain a broad impedance bandwidth than traditional patch antenna. By incorporating shorts at suitable position in feed and U-slot, this antenna is made resonant at two frequency bands. In L-slot mode, it works in frequency bands of 1.80 -1.98 GHz and in U-slot mode it covers the 2.10 -2.68 GHz frequency band. Advantages of this reconfigurable antenna is that it circumvent the problem of interference that is faced in fixed antenna, works in two frequency bands and provides a good gain of 8 dB. The proposed antenna system can be used for Bluetooth, WLAN and PCS applications.

Design of a polarization reconfigurable antenna using chiral metamaterial and pin diode is also presented in this chapter. Linearly polarized RMPA is taken as reference antenna. Addition of chiral metamaterial over the RMPA not only converts the polarization of antenna from linear to circular, but it also provides polarization reconfiguration by switching between two modes of proposed antenna. In mode 1, proposed antenna has left hand circular polarization and in mode 2, it has right hand circular polarization. A simple technique is presented to design a circular polarized antenna without using complex feeding. And another advantage is reconfiguration among this circularly polarization states.

CHAPTER 8

CONCLUSION AND FUTURE SCOPE

8.1. CONTRIBUTION OF THE THESIS

In this thesis investigations on patch antennas with the metamaterial and pin diodes have been presented. The main objective behind this work is to miniaturize and improve the performance of patch antenna. Different ENG, MNG and LH metamaterial structures are designed and investigated to improve the performance parameters of patch antenna. This thesis also explored the use of Chiral metamaterial to design circularly polarized patch antenna without using complex feed. Design of reconfigurable antenna using the pin diodes is also presented in this thesis. Design of polarization reconfigurable patch antenna is also proposed in this work.

The major contributions of this thesis are listed below:

- A state of art overview on the use of metamaterial to the performance improvement of antennas is presented. In the review, first the limitation of patch antenna and description of conventional techniques for performance enhancement of patch antenna is presented. It was found that although a number of methods had reported to miniaturize and improve the performance of microstrip antennas, still there is need of technique which provides cost-effective solution and overcome the constraint of conventional techniques. These facts prompted us to use the metamaterial in design of patch antenna. As per the need of today's communication system design of reconfigurable antenna using metamaterial and pin diode is also presented.
- Cylindrical rods artificial dielectric metamaterial is investigated to reduce the size and improve performance of microstrip antenna. It is found that rods when embedded in patch antenna its resonant frequency does not depends on length of patch antenna, which is major constraint for size reduction of patch antenna. Embedding of rods in patch antenna provides the size reduction, improves its return loss and bandwidth. A general procedure for designing of patch antenna at a desired subwavelength frequency is also proposed in this work. Embedding of rods in patch antenna substrate improves all the performance characteristic of antenna except gain. To improve the gain a

superstrate of properly designed rodded medium can be applied over the patch antenna. Multiband antenna can also be designed by embedding properly designed rodded medium in patch antenna.

- Metamaterial enhance the performance of patch antenna and reduce its size. To compare the different types of metamaterial in regards to improvement of the performance of patch antenna, double folded I shaped ENG metamaterial, C shaped and split ring MNG metamaterial are compared. It is found that ENG metamaterial provides the better size reduction as compared to MNG metamaterial, but at the cost of gain. MNG metamaterial provides an optimum solution for performance improvement of microstrip antenna. Design of broad bandwidth patch antenna is also presented in this research work by combining the two modes of patch antenna using split ring resonator.
- A size reduction technique is presented by cutting slots in patch antenna and embedding the left handed H shaped metamaterial in it. By this method a compact patch antenna can be designed which is easy to fabricate. The antenna designed this technique provides 37% miniaturization and has improved bandwidth as compared to reference antenna.
- Design of high performance RMPA is also presented by embedding and using a superstrate of left handed double h shaped metamaterial. The proposed antenna has improved return loss, efficiency, bandwidth and gain as compared to reference antenna. Results of high performance patch antenna are also verified experimentally.
- Circularly polarized antennas have attained consideration in wireless communication systems as compared to linearly polarized antennas. To design circular polarized patch antenna using conventional method complex feed is used. In this work, design of circular polarized patch antenna is presented using chiral metamaterial without using the complex feed. Bilayer twisted cross wires and bilayer gammadion chiral structures are used to design the circular polarized antenna. The placement of CM cover over the linearly polarized RMPA changes its polarization from linear to circular. Antenna designed using bilayer twisted cross wires produces a left handed circularly polarized wave at resonant frequency of 6.24GHz and has an axial ratio of 0.46 dB. Second circularly polarized antenna designed using gammadion chiral

metamaterial radiates LCP wave at 5.15 GHz with 1.01 dB axial ratio. The proposed technique to design CP antenna using chiral metamaterial is very simple and designed antenna is easy to fabricate. The designed antennas have advantages of simple structure, low cost and are expected to benefit the application in wireless and satellite communication.

- In modern wireless communication need of reconfigurable antennas has increased as many systems are integrated on single platform. This motivated us to design a reconfigurable multiband fractal antenna. The antenna has simple structure and has multiband characteristics due to fractal geometry. It works in four different reconfigurable modes and can be used for wireless communication
- A reconfigurable high gain inverted circular patch antenna is designed for PCS, Bluetooth and WLAN applications. This proposed antenna works in two switchable modes. In one mode, it resonates at 1.88 GHz and has a gain of 7.8 dB. In other mode, antenna resonates at 2.3 GHz and has broad impedance bandwidth of 24.2%. In this mode gain of presented antenna is 8 dB.
- Design of polarization reconfigurable patch antenna is presented using chiral metamaterial and pin diodes. According to our knowledge, polarization reconfiguration using chiral metamaterial is proposed for first time. Bilayer split rings are used as chiral metamaterial to design a CP antenna. The proposed antenna provides the polarization reconfiguration by switching between two modes. In one mode, antenna has left hand circular polarization and right hand circular polarization in other mode.

8.2. FUTURE WORK

The following aspects may appropriately be explored for the future scope of this work to give more understanding of the applications of metamaterial and active devices for patch antenna.

- The use of metamaterial show tremendous potential for designing and performance enhancement of antennas for various applications. There still many numbers of metamaterial geometries whose hidden potential is still to be explored.

- Though the metamaterial has been studied in variety of microwave components, still, there is a scope to investigate the metamaterial behavior on microstrip filters, dividers, couplers, combiners etc. for their improved performance.
- Many techniques are available for parameter extraction of metamaterials, but still, there is scope of development of parameter extraction method for different geometries of metamaterial.
- There is tremendous scope of use of metamaterial and active devices for designing the multifunctional antennas according to the current need of wireless and communication industry.

REFERENCES

[1]. A. Alu and N. Engheta, "Guided modes in a waveguide filled with a pair of single-negative (SNG), double-negative (DNG), and/or double –positive (DPS) metamaterial layers," *IEEE Transaction on Microwave Theory and Techniques*, vol. MTT-52, No. 1, Jan. 2004, pp. 199–210.

[2]. A. Alu and N. Engheta, "Polarizabilities and effective parameters for collections of spherical nano-particles formed by pairs of concentric double-negative (DNG), single-negative (SNG) and/or double-positive (DPS) metamaterial layers," *Journal of applied Physics.*, vol. 97, 2005, pp. 1-33.

[3]. A. Alu, F. Bilotti, N. Engheta, and L. Vegni, "Subwavelength, compact, resonant patch antennas loaded with metamaterials," *IEEE Transaction on Antennas and Propag*ation, vol. 55, no. 1, 2007, pp. 13–25.

[4]. A. Alu, F. Bilotti, N. Engheta, and L. Vegni,"Radiation properties of sub-wavelength resonant patch antennas filled with a pair of DPS, DNG, and/or SNG metamaterial blocks," *Dig.USNC/CNC/URSI National Radio Science Meeting, Washington, DC, USA*, July 3-8, 2005, pp. 113.

[5]. A. Mishra, P.Singh, N.P.Yadav, J.A. Ansari, "Compact shorted microstrip patch antenna for dual band operation", *Progress in Electromagnetic Research C*, vol. 9, 2009, pp. 171-182.

[6]. A. Vallecchi, G. B. Gentili, and M. Calamia, "Dual-band dual polarization microstrip antenna," *IEEE Antenna and Propagation Society International Symposium*, 2002, pp. 64-67.

[7]. A.Sharma and G.Singh, "Design of single pin shorted three dielectric layered substrates rectangular patch microstrip antenna for communication systems," *Progress in Electromagnetic Research Letters*, vol. 2, 2008, pp. 157-165.

[8]. Agarwall, N. P., G. Kumar, and K. P. Ray, ''Wideband Planar Monopole Antennas,'' *IEEE Transaction on Antennas and Propagation*, vol. 46, no. 2, 1998, pp. 294–295.

[9]. Ali A. Saleh, Abdulkareem S. Abdullah, "A Novel Design of Patch Antenna Loaded with Complementary Split-Ring Resonator and L- Shape Slot for (WiMAX/WLAN) Applications," *International Journal of Wireless and Microwave Technologies(IJWMT)*, vol. 4, no. 3, 2014, pp.16-25.

[10]. Amir Jafargholi; Mohammad Hossein Mazaheri, “Broadband microstrip antenna using epsilon near zero metamaterials,” *IET Microwaves, Antennas & Propagation*, vol. 9, issue 14, 2015, pp.1612-1617.

[11]. Ammar Nadal Shareef, Amer Basim Shaalanb, “Fractal Peano Antenna Covered by Two Layers of Modified Ring Resonator,” *International Journal of Wireless and Microwave Technologies (IJWMT)*, vol.2, 2015, pp. 1-11.

[12]. Anamika Singh, Aadesh Arya & Sanjay Sharma “High Gain of C Shape Slotted Microstrip Patch Antenna for Wireless System,” *International Journal of Applied Engineering Research*, vol. 7, no.11, 2012, pp.1343-1346.

[13]. Andrea Alù, Student, Filiberto Bilotti, Nader Engheta, and Lucio Vegni, “Subwavelength, Compact, Resonant Patch Antennas Loaded With Metamaterials,” *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 1, 2007, pp. 13-25.

[14]. Anuja A Odhekar, Amit A Deshmukh, “Microstrip Antenna optimization using split ring and complementary split ring resonator”, *International Conference on Information Communication and Embedded Systems (ICICES)*, 2016, pp.1-7.

[15]. Anwer Sabah Mekki, Mohd Nizar Hamidon, Alyani Ismail, and Adam R. H. Alhawari “Gain Enhancement of a Micro strip Patch Antenna Using a Reflecting Layer” *Hindawi Publishing Corporation International Journal of Antennas and Propagation*, 2015.

[16]. Arcyan Erentok,Richard,“Metamaterial-inspired efficient electrically small antennas,” *IEEE Transaction on Antenna and Propagation*, vol. 56, no. 3, 2008, pp.691, 707.

[17]. Arycan Erentok, Richard w. ziolkowski, “A summary of recent development on metamaterial based and metamaterial inspired efficient electrically small antennas,” *Turk. J. of Elec. Engineering*, vol. 16, no. 1, 2008, pp.21-32.

[18]. Attia, H. and O. M. Ramahi, "EBG superstrate for gain and bandwidth enhancement of microstrip array antennas," *Proceeding of IEEE Antennas and Propag. Society International Symposium*, 2008, pp.1-4..

[19]. Aycan Erentok and Richard W. Ziolkowski, “A Dual-band Efficient Metamaterial-inspired Electrically-Small Magnetic-based Antenna”, *IEEE*

Antennas and Propagation Society International Symposium, 2007, pp. 1877-1880.

[20]. B.-I. Wu, W. Wang, J. Pacheco, X. Chen, T. Grzegorczyk and J. A. Kong, "A study of using Metamaterials as antenna substrate to enhance gain," *Progress in Electromagnetics Research, (PIER)* , 2005, pp.295-328.

[21]. B.wang, J.Zhou, T.Koschny, M.Kasesaki and C.M. Soukoulis, "Chiral metamaterials: Simulations and experiments," *Journal of opt. and pure appl. Opt.*, vol.11, 2009, 114003.

[22]. Bae-Lan, Hongsheng Chen and Jin Kong, "Surface wave suppression in antenna systems using magnetic metamaterial," *Journal of Applied Physics*, vol. 101, no. 3, 2007, pp. 225–232.

[23]. Barun Mazumdar, *Design of Microstrip Antenna in Wireless Communication:* Lambert Academic Publishing, 2012.

[24]. Baumer, C., ''Analysis of Slot Coupled Circular Microstrip Patch Antennas,'' *Electronics Letters*, vol. 28, no. 15, 1992, pp. 1454–1455.

[25]. Bimal Garg, Ankit Samadhiya and Rahul Dev,"Analysis and design of microstrip antenna loaded with innovative metamaterial structure", *Research Journal of Physics and Applied Science*, vol. 1, no. 1, 2012, pp.13-19.

[26]. Bimal Garg, Nitin Agrawal, Vijay Sharma, Ankita Tomar, Prashant Dubey, "Rectangular Microstrip Patch Antenna with "Pentagonal Rings" Shaped Metamaterial Cover," *IEEE International Conference on Communication System and Network Technologies*, 2012, pp. 40-44.

[27]. BingnanWang, Jiangfeng Zhou, Thomas Koschny, Maria Kafesaki, and Costas M Soukoulis,"Chiral metamaterials: simulations and experiments," *Journal of Opt., Pure Appl. Opt.* , 2009, 114003.

[28]. BoraUng, "Metamaterials:a metareview, 2009, https://www.researchgate.net /publication/22870625.

[29]. Bushra Farooq, Tahira Parveen Imad Ali, Sadiq Ullah, "Antenna design for advance wireless systems using metamaterial surfaces," *13th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*,2016, pp. 641 – 646.

[30]. C. Caloz, H. Okabe, H. Iwai, and T. Itoh "Transmission line approach of left-handed metamaterials." *Proc. USNC/URSI Nat. Radio Sci. Meeting, San Antonio, TX*, 2002, pp. 39-40.

[31]. C.T.P.Song, Z.H.Hu, J.Kelly and P.Gardner, "Wide tuneable dual-band reconfigurable antenna for future wireless devices", *Loughborough Antenna and Propagation Conference, UK, 2009*, pp.601-604.

[32]. Chen,C.C. and J.L.Volakis, "Bandwidth broadening of patch antenna using nonuniform substrates" , *Microwave and Optical Technology Letter*, vol. 47, no. 5, 1995, pp. 421-423.

[33]. Chen. W. and K.F.Lee, "Input impedance of coaxially fed rectangular microstrip antenna on electrically thick substrate," *Microwave and Optical Technology Letter*, vol. 6, 1993, pp. 387-390.

[34]. Chew, W. C., ''A Broadband Annular Ring Microstrip Antennas,'' *IEEE Trans. Antennas Propagation*, vol. 30, 1982, pp. 918–922.

[35]. Choo,H., A. Hutani, L.C.Traintinalia and H.ling, " Shape optimization of broadband microstrip antenna using genetic algorithm," *Electronic letter*, vol. 36, no. 25,2000, pp.2057-2058.

[36]. Christina F. Jou, Jin-Wei Wu, Chien-Jen Wang, "Novel Broadband Monopole Antennas with Dual-Band Circular Polarization", *IEEE Transaction on Antennas and Propagat*ion, vol. 57, 2009, pp. 1027-1034.

[37]. Christophe Caloz, Tatsuo Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications:* Wiley Interscience, A John wiley & sons, inc., publication, 2006.

[38]. Colan G. M. Ryan; George V. Eleftheriades, "Single and Dual-Band Transparent Circularly Polarized Patch Antennas with Metamaterial Loading," *IEEE Antennas and Wireless Propagation Letters*, vol.14, 2015, pp.470-473.

[39]. Constantine A. Balanis, *Antenna Design and Theory*: Wiley India, 1982.

[40]. D. R. Smith, W.J. Padilla, D.C. Vier, et al, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Letters*, vol. 84, 2000, pp. 4184-4187.

[41]. D. Tataranikov, "Enhanced Bandwidth patch antennas with artificial dielectric substrates for high precision satellite positioning," *IEEE International Conference on Antenna Technology*, 2009, pp. 1-4.

[42]. D.M. Pozar, “A microstrip antenna aperture coupled to a microstrip line,” *Electronics Letters*, vol. 21, 1987, pp. 49-50.

[43]. D.M. Pozar, B. Kaufman, “Increasing bandwidth of a microstrip antenna by proximity coupling,” *Electronics Letters*, vol. 23, 1985, pp. 368-369.

[44]. D.M.Pozar and D.H.Schaubert, *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*: NewYork: IEEE Press, 1995.

[45]. D.r. smith, W.J.Padilla, D.C.vier, Nemat-naseer, S. Schultz , “ Composite medium with simultaneously negative permeability and permittivity,” *phys. Rev. letters*, vol.84, 2000, pp. 4184-87.

[46]. D.R.Smith, D.C. Vier, Th. Koschny and C.M.Soulouis, “Electromagnetic parameter retrieval from inhomogeneous metamaterials”, *Physics review letter*, vol. 71, 2005, 036617.

[47]. Das, N., S. K. Chowdhury, and J. S. Chatterjee, ‘‘Circular Microstrip Antenna on Ferrimagnetic Substrate,’’ *IEEE Transaction on Antennas and Propagation*, 1983, pp. 188–190.

[48]. Davoud Zarifi, Mohammad Soleimani, and Vahid Nayyeri, “Dual- and Multiband Chiral Metamaterial Structures with Strong Optical Activity and Negative Refraction Index”, *IEEE Antennas and Wireless Propagation Letters*, vol. 11, 2012, pp.334-337.

[49]. Davoud Zarifi, Mohammad, Soleimani, Vahid Nayyeri, and Jalil Rashed-Mohassel, “On the Miniaturization of Semiplanar Chiral Metamaterial Structures,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 12, 2012, pp. 5768-5775.

[50]. Dimitrios K. Rongas, Stamatios A. Amanatiadis, Alexandros I. Dimitriadis, and Nikolaos V. Kantartzis, “Directivity-Enhanced Log-Spiral Antenna through a Chiral Metamaterial Superstrate” ,*7th European Conference on Antenna and Propagation*, 2013, pp.2079-2083.

[51]. Douglas H. Werner and Suman Ganguly, “An Overview of Fractal Antenna Engineering Research”, *IEEE Antenna and wave Propagation Magazine*, vol. 45, no.1, 2003, pp. 38-57.

[52]. E. Lee, P. S. Hall, and P. Gardner, “Compact dual-band dual-polarization microstrip patch antennas,” *Electronics Letters*, vol. 35, 1999, pp. 1034-1036.

[53]. El Yazidi, M., ‘‘Analysis of Aperture-Coupled Circular Microstrip Antenna,’’ *Electronics Letters*, vol. 29, no. 11, 1993, pp. 1021–1022.

[54]. F. Bilotti, A. Alù, and L. Vegni, “Design of miniaturized metamaterial patch antennas with μ-negative loading,” *IEEE Transaction on Antennas and Propagation*, vol. 56, no. 6, 2008, pp. 1640–1647.

[55]. F.Yang and Y.Rahmat Samii, “Patch antenna with switchable slot (PASS) for dual frequency operation”, *Microwave and Optical Technology Letter*, vol.31, 2001, pp. 165-168.

[56]. F.Yang and Y.Rahmat Samii, “Switchable dual band circularly polarized Patch antenna with single feed”, *Electronics Letter*, vol.37, 2001, pp. 1002-1003.

[57]. Fayyaz, N. and S.S.Naeini, “Bandwidth enhancement of a rectangular patch antenna by integrated reactive loading,” *IEEE antenna and propagation symposium digest*, 1998, pp.1100-1103.

[58]. Filiberto Bilotti, Andrea Alú, Member and Lucio Vegni, “Design of Miniaturized Metamaterial Patch Antennas With μ -Negative Loading,” *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 6, 2008, pp.1640-1647.

[59]. Filiberto Bilotti, Andrea Alù, Nader Engheta, and Lucio Vegni, " Miniaturized Circular Patch Antenna with Metamaterial loading," *IEEE First European Conference on Antenna and Propagation*, 2006, pp. 1-4.

[60]. Furkan Dincer, Cumali Sabah, Muharrem Karaaslan, Emin Unal, Mehmet Bakir, and Utku Erdiven, “Asymmetric transmission of linearly polarized waves and dynamically wave rotation using chiral metamaterial,” *Progress in Electromagnetic Research*, vol.140, 2013, pp.227-239.

[61]. G. Kumar, and K.C. Gupta, “Directly coupled multiple resonator wideband microstrip antennas,” *IEEE Transaction on Antennas and Propagation*, vol. AP-33, 1985, pp. 588- 593.

[62]. G.H.Huff, J.feng, J.T.Bernhard, “A novel radiation pattern and frequency reconfigurable single turn square spiral microstrip antenna,” *IEEE Microwave and Wireless Component Letters*, vol. 13, no.2, 2003,pp. 57-59.

[63]. Galaba Sai Rajesh, K Venkata Kishore, Vijay Kumar, “Multiband microstrip patch antenna design using metamaterial for airborne SAR system,” *IEEE*

International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES), 2015, pp. 1-3.

[64]. Girish Kumar, K.P.Ray, *Broadband Microstrip antenna:* Artech house, Boston, London, 2003.

[65]. Gitin, M. M., et al., ‘‘Broadband Characterization of Millimeter-Wave Log-Periodic Antennas by Photoconductive Sampling,’’ *IEEE Transaction on Antennas and Propagation*, vol. AP-42, no. 3, 1994, pp. 335–339.

[66]. Gregorio J. Molina-Cuberos, Ángel J. García-Collado, Ismael Barba, and José Margineda, “Chiral Metamaterials With Negative Refractive Index composed by an Eight-Cranks Molecule,” *IEEE Antennas and Wireless Propagation Letters*, vol. 10, 2011, pp. 1488-1490.

[67]. H.Attia, O.Siddiqui and O.M.Ramahi, “Artificial Magneto-superstrates for gain and efficiency improvement of microstrip antenna arrays,” *PIERS online*, vol. 6, no. 6, 2010, pp. 555–558.

[68]. Hall, P. S., ‘‘Multi-Octave Bandwidth Log-Periodic Microstrip Antenna Array,’’ *IEE Proc. Microwaves, Antennas Propagation*, Pt. H, Vol. 133, No. 2, April 1986, pp. 127–138.

[69]. Hall, P.S., “Probe compensation in thick microstrip patches,” *Electronic letters*, vol.23, no.1, 1987, pp. 606-607.

[70]. Hammoud, M., P. Poey, and F. Colombel, ‘‘Matching the Input Impedance of a Broadband Disc Monopole,’’ *Electronics Letters*, vol. 29, 1993, pp. 406–407.

[71]. Han Xiong , Jing-Song Hong , Yue-Hong Peng, “Impedance Bandwidth and Gain Improvement for Microstrip Antenna Using Metamaterials,” *Radio Engineering*, vol. 21, no. 4, 2012, pp. 993-998.

[72]. Hattan F. Abutarboush,R. Nilavalan, S. W. Cheung,Karim M. Nasr,Thomas Peter and Djuradj Budimir, “A Reconfigurable Wideband and Multiband Antenna Using Dual-Patch Elements for Compact Wireless Devices,” *IEEE Transaction on Antenna and Propagation,* vol. 60, no. 1, 2012, pp.36-43.

[73]. Honda, S., et al., ‘‘A Disc Monopole Antenna with 1:8 Impedance BW and Omnidirectional Radiation Pattern,’’ *Proc. ISAP, Sapporo, Japan*, 1992, pp. 1145–1148.

[74]. Hwang, K.C., “A Modified Sierpinski Fractal Antenna for Multiband Application,” *IEEE Antennas and Wireless Propagation Letters*, vol.6, 2007, pp.357 – 360.

[75]. Hyo-Won Song, Hee-Soon An, Jung-Nam Lee,et al., “Design of the Tree-Shaped UWB Antenna Using Fractal Concept,” *Korea-Japan Microwave Conference*, 2007, pp. 73 – 76.

[76]. I. Wu, W. Wang, J. Pacheco, X. Chen, T. Grzegorczyk, and J. A. Kong, "A study of using metamaterials as antenna substrate to enhance gain," *Progress in Electromagnetics Research, PIER*, 2005, pp. 295-328.

[77]. Iraj Arghand, Pejman Rezaei “Miniaturized rectangular patch antenna loaded with spiral/wires metamaterial,” *European Journal of Scientific Research*, vol. 65, no. 1, 2011, pp.121-130.

[78]. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart , “Low frequency plasmons in thin wire structures”, *Journal of physics: Condensed matter*, vol.10, 1998, pp.4789-4809.

[79]. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart “Magnetism from conductors and enhanced nonlinear phenomena.” *IEEE Transaction on Microwave Theory and Techniques*, vol. 47, 1999, pp.2075–2084.

[80]. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Extremely Low frequency plasmons in metallic mesostructures”, *Physics rev. letters*, vol.76, 1996, pp.4773.

[81]. J. B. Pendry, D. Schurig and D. R. Smith, "Controlling Electromagnetic Fields," *Science* (312.5781), 2006, pp. 1780-1782.

[82]. J. K. Gansel, M. Thiel, M. S. Rill, M. Decker, K. Bade, V. Saile, G. Freymann, S. Linden, and M. Wegener, “Gold helix photonic metamaterial as broadband circular polarizer,” *Science*, vol. 325, 2009, pp. 1513–1515.

[83]. J. Liang, C. C. Chiau, X. Chen and C. G. Parini, "Printed circular disc monopole antenna for ultra-wideband applications," Electronic Letters, vol. 40, issue. 20, 2004, pp. 1246-1247.

[84]. J. S. Lim, C. B. Kim, J. S. Jang, H. S. Lee, Y. H. Jung, J. H. Kim, S. B. Park, B. H. Lee, and M. S. Lee, “Design of a Subwavelength Patch Antenna Using Metamaterials,” *Proceedings of the 38th European Microwave Conference*, 2008, pp.1246-1249.

[85]. J. Vemagiri, M. Balachandran, M. Agarwal et al., “Development of compact half-Sierpinski fractal antenna for RFID applications,” *Electronics Letters*, vol. 43, no.22, 2007, 1.

[86]. J. Zhu. G. V. Eleftheriades, "Dual-band metamaterial-inspired small monopole antenna for WiFi applications," *Electronic Letters*, vol.45, issue.22, 2009, pp. 1104-1106.

[87]. J.G.Joshi, S.S.Pattnaik and S.Devi, “Metamaterial embedded wearable rectangular microstrip patch antenna,” *International Journal of Antenna and propagation*, 2012, pp. 1–9.

[88]. J.R. James and P.S. Hall, *Handbook of Microstrip Antennas*, London, U.K., Peter Peregrinus, 1989.

[89]. J.S. Row, “A simple impedance-matching technique for patch antennas fed by coplanar microstrip line,” *IEEE Trans. Antennas and Propag.*, vol. 53, no. 10, 2005, pp. 3389-3391.

[90]. J. Zhou, J. Dong, B.Wang, T. Koschny, M. kafesaki and C.M. Soukoulis, “Negative refractive index due to chirality,” *Phys. Rev. B*, Vol. 79,2009, 121104.

[91]. Jaegeun Ha, Kyeol Kwon, Youngki Lee, and Jaehoon Choi, "Hybrid Mode Wideband Patch Antenna Loaded With a Planar Metamaterial Unit Cell," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, 2012, pp.1143-1147.

[92]. Jaypal Baviskar, Afshan Mulla, Amol Baviskar, Sandeep Pawar, “Metamaterial lens incorporated enhanced gain omnidirectional conformal patch antenna,” *2016 IEEE Aerospace Conference*, 2016, pp. 1 – 7.

[93]. JB Pendry, “Negative refraction makes perfect lens,” *Physics review letters*, vol.85, issue 18, 2000,3966.

[94]. Jiangfeng Zhou, Jianfeng Dong, Bingnan Wang,Thomas Koschny, Maria Kafesaki, and Costas M. Soukoulis, “Negative refractive index due to chirality”, *Physical Review B*, 2009, 121104.

[95]. Jiun-Peng Chen, and Powen Hsu, “A Compact Strip Dipole Coupled Split-Ring Resonator Antenna for RFID Tags,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 11, 2013, pp. 5372-5376.

[96]. K. L. Wong and W. S. Chen, “Compact microstrip antenna with dual-frequency operation,” *Electronics Letters*, vol. 33, no. 8, 1997, pp. 646-647.

[97]. K. L. Wong, *Compact and Broadband Microstrip Antennas*: New York: Wiley, 2002.

[98]. K.C.Gupta, Abdelaziz Benalla, *Microstip Antenna Design*: Artech house publisher, 1988.

[99]. K.C.Gupta, J.Li, R.Ramadoss, C.wang, Y.C.Lee and V.M.Bright, “Design of frequency reconfigurable slot ring antennas”, *IEEE International symposium on Antennas and Propagation, Salt Lake city, UT*, 2000, pp. 326.

[100]. K.E.Golden, “A Study of Artificial Dielectric”, *Plasma research lab., California, Rep. SSD-TDR 64-9C*, 1964.

[101]. K.F. Tong and J.J.Huang, “New proximity coupled feeding method for reconfigurable circularly polarized microstrip ring antennas,” *IEEE Trans. Antennas Propagation*, vol. 56, no.7, 2008, pp. 1860-1866.

[102]. K.M. Mak and K.M.Luk, “ A shorted cross bowtie patch antenns with a cross dipole for circular polarization,” *IEEE International Symposium on Antennas Propagation*, 2007, pp. 2702-2705.

[103]. Kakkar, R., and G. Kumar, ‘‘Stagger Tuned Microstrip Log-Periodic Antennas,’’ *IEEE AP-S Int. Symposium Digest*, 1996, pp.1262–1265.

[104]. Kin Fai Tong, Kai Fong Lee and Kwai Man Luk, “On the effect of ground plane size to wideband shorting wall probe-fed patch antennas,” *IEEE conference on Antennas and Propagation in Wireless Communication*, 2011, pp. 486.

[105]. Kingsley, N., Anagnostou, D.E. ,Tentzeris, M. , Papapolymerou, J.,“RF MEMS Sequentially Reconfigurable Sierpinski Antenna on a Flexible Organic Substrate With Novel DC-Biasing Technique,” *Microelectromechanical Systems*, vol. 16, 2007, pp. 1185 – 1192).

[106]. Kock, W.P., Metal-lens antennas, *Proceedings of the I.R.E and Wave and Electrons*, vol.34, 1946, pp. 828-836.

[107]. Kumar, G., and K. C. Gupta, ‘‘Broadband Microstrip Antennas Using Additional Resonators Gap-Coupled to the Radiating Edges,’’ *IEEE Trans. Antennas Propagation*, vol. AP-32, 1984, pp. 1375–1379.

[108]. Kumar, G., and K. C. Gupta, ‘‘Nonradiating Edges and Four Edges Gap-Coupled Multiple Resonator, Broadband Microstrip Antennas,’’ *IEEE Trans. Antennas Propagation*, Vol. AP-33, 1985, pp. 173–178.

[109]. L. D. Landau, E. M. Lifshitz, and L. P. Pitaevskii, *Electrodynamics of Continuous Media*: Pergamon press, New York, 1984.

[110]. L.N.Prongle, P.G.Friederich, T.L.Fountain and G.S.Smith, “GTRI reconfigurable aperture design,” *IEEE International symposium on Antennas Propagation*, 2002, pp.473-476.

[111]. Lang Wang, Long Wang, and Joshua Le-Wei Li, "A Series-Fed Metamaterial Microstrip Antenna Array of Broadband and High-Gain," *IEEE Iinternational Workshop on Electromagnetics; Applications and Student Innovation*, 2012, pp. 1-2.

[112]. Lee R.Q., K.F.Lee, and J. Bobinchak, “Characteristics of a two layer electromagnetically coupled rectangular microstrip antenna,” *Electronic letters*, vol. 23, no. 20, 1987, pp. 1070-1072.

[113]. Lee, Y. J., J. Yeo, R. Mittra, and W.S. Park, "Application of electromagnetic bandgap (EBG) superstrates with controllable defects for a class of patch antennas as spatial angular filters," *IEEE Trans. Antennas Propagation*, vol. 53, no. 1, 2005, 224-235.

[114]. Lei Bian, Yong-Xin Guo, L. C. Ong, Xiang-Quanb Shi, “Wideband Circularly-Polarized Patch Antenna”, *IEEE Trans. Antennas Propagation*, vol.54, 2006, pp. 2682-2686.

[115]. Lei Xing, Qian Xu, Jing Li Zhixia Wei, Jun Ding and Chenjiang Guo, “Broaden the bandwidth of patch antenna by using inhomogeneous metamaterial substrate,” *Progress in Electromagnetic research Symposium Proceedings, China*, 2010, pp. 155-159.

[116]. Le-Wei Li , Ya-Nan Li, Tat Soon Yeo, Juan R. Mosig, and Olivier J.F. Martin, "A broadband and high-gain metamaterial microstrip antenna," *Applied Phys. Letters*, 2010, http://dx.doi.org/10.1063/1.3396984.

[117]. Le-Wei Li and Ke Xiao, "Broadband and High-Gain Metamaterial Microstrip Arrays," (Invited Paper), *Proc. of European Conference on Antennas and Propagation (EuCAP), Barcelona, Spain*, 2010, pp 1-4.

[118]. Le-Wei Li, Ya-Nan Li, and Juan R. Mosig, "Design of a Novel Rectangular Patch Antenna with Planar Metamaterial Patterned Substrate," (Invited Paper), *International Workshop on Antennas Technology, Chiba, Japan*, 2008, pp. 123-126.

[119]. Le-Wei Li, Ya-Nan Li, Tat-Soon, Yeo, Juan R. Mosig and Olivier J.F. Martin, "Addendum: 'A Broadband and High-gain Metamaterial Microstrip Antenna' [Appl. Phys. Lett. 96, 164101(2010)]," *Appl. Phys. Lett*ers, vol. 99, 2011, http://dx.doi.org/10.1063/1.3396984.

[120]. Lin Wang, Meng Qing Yuan, and Qing Huo Liu, "A Dual-Band Printed Electrically Small Antenna Covered by Two Capacitive Split-Ring Resonators," *IEEE Antennas And Wireless Propagation Letters*, vol. 10, 2011, pp. 824-826.

[121]. Lindell, I. V., A. H. Sihvola, S. A. Tretyakov, and A. J. Viitanen, *Electromagnetic Waves in Chiral and Bi-isotropic Media*: Artech House, Boston, 1994.

[122]. Luk, K. M., K. F. Lee, and W. L. Tam, ''Circular U-Slot Patch with Dielectric Superstrate,'' *Electronics Letters*, vol. 33, no. 12, 1997, pp. 1001–1002.

[123]. Luk, K. M., K. F. Tong, and T. M. Au, ''Offset Dual Patch Microstrip Antenna,'' *Electronics Letters*, vol. 29, no. 18, 1993, pp. 1635–1636.

[124]. Luo Xiaowu, Zhang Min, Cai Linji and Yu Feiqun, "Design of a on board dual frequency reconfigurable antenna", *6th IEEE International Conference on ITS Telecommunications Proceedings*, 2006, pp. 394-396.

[125]. M. Barakat, C. Delaveaud, F. Ndagijimana, "Circularly Polarized Antenna on SOI for the 60 GHz band", *IEEE Second European conference on antenna and propagation, 2007*, pp. 1-6.

[126]. M. Mutlu, A. E. Akosman, A. E. Serebryannikov, and E. Ozbay, "Asymmetric chiral metamaterial circular polarizer based on four U-shaped split ring resonators," *Optical Letters*, vol. 36, 2011, pp. 1653–1655.

[127]. M. Sanad, "Effect of the shorting posts on short circuit microstrip antennas," Proceedings," *IEEE Antennas and Propagation Society International Symposium*, 1994, pp. 794-797.

[128]. M.M. Gitin, F.W. Wise, G. Arjavalingam, Y. Pastol, and R.C. Compton, "Broadband characterization of millimeter-wave log-periodic antennas by

photoconductive sampling," *IEEE Trans. Antennas and Propag.*, vol. AP-42, no. 3, 1994, pp. 335-339.

[129]. M.M. Sharma, , Sanjeev Yadav, Ashok Kumar, Y.Ranga,, Deepak Bhatnagar, "Compact Elliptical Microstrip Patch Antenna with Slotted Ground for Ku-Band Applications" , *IEEE Applied Electromagnetic conference*, 2011, pp. 1-3.

[130]. M.Malathong, A. Sonsilphong, W. Panpradit and N. Wongkasem, "Chiral Metamaterial Based Circularly Polarized Microstrip Antennas," *IEEE conference on Antenna and propagation in wireless communiation*,2011, pp.898-901.

[131]. M.T Ali, N.Nordin, Norsuzila Ya'acob and M.N.Md Tan , "Design of Wideband Microstrip Patch Antenna Using L-Probe Fed at 2.6 GHz," *International Conference on Computer and Communication Engineering*, 2012, pp.961-965.

[132]. M.T.Oswald, S.C.Hagness, B.D.Van Veen and Z.Popovie, "Tuneable slot antenna using varactor," *IEEE International Symposium Antennas and Propagation*, vol.2, 2004, pp.1839.

[133]. Mahmoud Abdalla, Usama Abdelnaby, and Abdelazez A. Mitkees, "Compact and Triple Band Meta-material Antenna for All WiMAX Applications," *IEEE international symposium on antenna and propagation*, 2012, pp. 1176-1179.

[134]. Marco A. Antoniades and George V. Eleftheriades, "A Broadband Dual-Mode Moopole Antenna using NRI-TL Metamaterial Loading," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, 2009, pp. 258-261.

[135]. Merih Palandoken, Andre Grede, and Heino Henke, "Broadband Microstrip Antenna with Left-Handed Metamaterials," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 2, 2009, pp.331-338.

[136]. Metra Nageswara Pavan, Neela Chattoraj, "Design and analysis of a frequency reconfigurable antenna using metasurface for wireless applications," *IEEE International Conference on Innovations in Information, Embedded and Communication Systems*, pp.1-5, 2015.

[137]. Michael Selvanayagam, and George V. Eleftheriades, "A Compact Printed Antenna With an Embedded Double-Tuned Metamaterial Matching Network," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 7, 2010, pp.2354-2361.

[138]. Michal Blaha and Jan Machac, "Planar resonator for metamaterials," *Radio Engineering*, vol.21, no.3, 2012, pp. 852-859.

[139]. Mirzapour, B., Hassani, H.R., "Size reduction and bandwidth enhancement of snowflake fractal antenna," *IET Microwaves, Antennas & Propagation*, vol. 2, 2008, pp.180 – 187.

[140]. Mishra, R. K., S. S. Patnaik, and N. Das, ''Tuning of Microstrip Antenna on Ferrite Substrate,'' *IEEE Trans. Antennas Propagation*, vol. AP-41, no. 2, 1993, pp. 230–233.

[141]. Mouhouche Faiza, A. Azrar; Djafri Kahina, "Study of Microstrip antenna using complimentary metamaterial etched in ground plane" ,*4th International Conference on Electrical Engineering (ICEE)*, 2015, pp.1-4.

[142]. N. Behdad and K. Sarabandi, "A varactor tuned dual-band slot antenna," *IEEE Transaction on Antennas and propagation*, vol. 54, no. 1, 2006, pp. 401–408.

[143]. N. Behdad and K. Sarabandi, "Dual-Band Reconfigurable Antenna With a Very Wide Tunability Range," *IEEE Transaction on Antennas and Propagation*, vol. 54, no. 2, 2006, pp. 406–419.

[144]. N. Engheta, "An idea for thin subwavelength cavity resonator using metamaterials with negative permittivity and permeability," *IEEE Antennas Wireless Propag. Letter*, vol. 1, no. 1, 2002, pp. 10–13.

[145]. N.Engheta and R.W.Ziokowski , Special issue on Metamaterials, *IEEE trans. on Antennas propagation*, vol. 51, 2003, pp.2256-2750.

[146]. N.Engheta and R.W.Ziokowski, *Metamaterials: physics and engineering explorations*: Wiley, IEEE press, Piscataway, NJ,2006

[147]. N.Engheta and R.W.Ziokowski, "A positive future for double negative metamaterials," *IEEE transaction on Microwave theory technology*, vol.5.no. 4. 2005, pp. 1553-1556.

[148]. Nadar Behdad and Kamal Sarabandhi, " A varactor tuned dual band slot antenna," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, 2006, pp.401-407.

[149]. Nadar Engheta, Richard W. Ziolkowski, *Metamaterial Physics & Engineering Explorations:* Wiley-IEEE Press, 2006.

[150]. Najla Mohammed Sali, Binu Paul, “ A 2.4 GHz Polarization Reconfigurable Metasurface Antenna,” *Fifth International Conference on Advances in Computing and Communications (ICACC)*, 2015, pp.254-257.

[151]. Nathan Burford, Yumin Zhang, Jai N. Dahiya, “Polarization Rotation by Helix Metamaterial,” *IEEE International Symposium on Antennas and Propagation,* 2011, pp. 1163-1165.

[152]. Neeraj Rao and Dinesh Kumar V. “Gain and Bandwidth Enhancement of a Microstrip Antenna Using Partial Substrate Removal in Multiple-layer Dielectric Substrate” *Progress in Electromagnetic Research Symposium Proceedings, Suzhou, China*, 2011, pp 1285-1288.

[153]. Osama M. Haraz and Abdel-Razik Sebak, "Gain enhancement in Ultra-Wideband Antennas backed by a suspended ground or covered with metamaterial superstrates," *IEEE Canadian Conference Electrical and Computer Engineering*, 2012, pp.1-4 .

[154]. P. A. Belov, R. Marque´s, S. I. Maslowski, I. S. Nefedov, M. Silveirinha, C. R. Simovski, and S. A. Tretyakov, “Strong spatial dispersion in wire media in the very large wavelength limit.” *Physics Review Lett*ers, vol. 67, 2003,113103.

[155]. P. Kumar and G. Singh, “Computation of mutual coupling for gap-coupled circular patch antennas loaded with shorting post,” *International Journal of Electronics Engineering*, vol. 1, no. 1, 2009, pp. 99-102.

[156]. P. Kumar, G. Singh, and S. Bhooshan, “Pin shorted rectangular patch microstrip antenna for mobile communication,” *Proceedings of National Conference on Wireless and Optical Communication*, 2007, pp. 77-79.

[157]. P. Kumar, V. K. Dwevidi, G. Singh and S. Bhooshan, “Miniaturization of gap-coupled microstrip antennas,” *International Conference on Recent Advances in Microwave and Applications (Microwave-08), India*, 2008, pp. 489-491.

[158]. P. Kumar, V. K. Dwivedi, G. Singh and S. Bhooshan, “Input impedance of gap-coupled circular microstrip antennas loaded with shorting post,” *Progress in Electromagnetics Research Symposium, Beijing, China*, 2009, pp. 1634-1638.

[159]. Pai Yen Chen and Andrea Alu, “Sub-Wavelength Elliptical Patch Antenna Loaded With μ-Negative Metamaterials,” *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 9, 2010, pp.2909-2919.

[160]. Palanisamy, V., and R. Garg, ‘‘Rectangular Ring and H-Shaped Microstrip Antennas Alternative to Rectangular Patch Antennas,’’ *Electronics Letters*, vol. 21, no. 19, 1985, pp. 874–876.

[161]. Popovic, B. D., et al., ‘‘Broadband Quasi-Microstrip Antenna,’’ *IEEE Trans. Antennas Propagation*, vol. AP-43, no. 10, 1995, pp. 1148–1152.

[162]. Pozar, D. M., ‘‘Microstrip Antenna Aperture-Coupled to a Microstrip Line,’’ *Electronics Letters*, vol. 21, no. 2, 1985, pp. 49–50.

[163]. Pozar, D. M., and V. Sanchez, ‘‘Magnetic Tuning of a Microstrip Antenna on a Ferrite Substrate,’’ *Electronics Letters*, Vol. 24, 1988, pp. 729–731.

[164]. Pozar, M., and S. D. Targonski, ‘‘Improved Coupling for Aperture-Coupled Microstrip Antennas,’’ *Electronics Letters*, vol. 27, no. 13, 1991, pp. 1129–1131.

[165]. Prathaban Mookiah, and Kapil R. Dandekar, “Metamaterial-Substrate Antenna Array for MIMO Communication System”, *IEEE Transactions On Antennas and Propagation*, vol. 57, no. 10, 2009, pp. 2383-2392.

[166]. Preet Kaur, S. K. aggarwal and Asok De, “ Design of compact rectangular patch antenna using square grid and I shaped metamaterial,” IEEE International conference on signal processing and communication(ICSC), 2015, pp. 132-135.

[167]. Preet kaur,”A reconfigurable square ring slot antenna for operation in GSM and WLAN frequency bands,” *International Journal of Microwave and Optical technology*, vol.7, no.1, 2012, pp. 49-54.

[168]. Pues H.F. , and A.R. Vande Capelle, “ An impedance matching technique for increasing the bandwidth of microstrip antennas,” *IEEE transaction on Antenna and Wave propagation*, vol. AP-37, 1989, pp. 1345-1354.

[169]. R. A. Shelby, D. R. Smith, and S. Schultz, “Experimental verification of negative index of refraction,” *Science*, vol. 292, 2001, pp. 77.

[170]. R. E. Collin, *Field Theory of Guided Waves*: New York: McGraw-Hill, 1960, chapter 12.

[171]. R. Khajeh Mohammad Lou, T. Aribi, and Ch. Ghobadi, "Improvement of Characteristics of Microstrip Antenna Using of Metamaterial Superstrate," *International Conference on Communication Engineering*, 2010, pp. 126-129.

[172]. R. Marques, F. Martin, and M. Sorolla, *Metamaterials with Negative Parameters: theory, Design and Microwave Applications*: Wiley Series in Microwave and Optical Engineering (Wiley-Blackwell), 2008.

[173]. R. Pandeeswari, Dr. S. Raghavan, Pravin A Bagde, and Ananda Kumar chittipothul, "A Compact Multi-Split Ring Resonator Loaded Antenna," *IEEE International Conference on Communication and Signal Processing*, 2013.

[174]. R.B. Waterhouse. "Small microstrip patch antennas," *Electron. Letter*, vol.31, 1995, pp. 604-605.

[175]. R.Chair, K.F.Lee, and K.M. Luk, "Bandwidth and cross polarization characteristics of quaterwave shorted patch antennas," *Microwave Optical Technology Letters*, vol. 22, 1999, pp. 101-103.

[176]. R.K. Mishra, S.S. Patnaik, and N. Das, "Tuning of microstrip antenna on ferrite substrate," *IEEE Trans. Antennas and Propagation*, vol. AP-41, no. 2, 1993, pp. 230-233.

[177]. R.W.Ziolkowski and A. Erentok, "Metamaterial-based efficient electrically small antennas," *IEEE Trans. Antenna Propagation*, vol. 54, no. 7, 2006, pp.4111-4121.

[178]. Rajesh Saha, Santanu Maity, "Design of O-shape metamaterial structure on rectangular patch antenna for RFID application," *International Conference on Electrical, Electronics, Signals, Communication and Optimization (EESCO)*, 2015, pp. 1-5.

[179]. Ramesh Garg, Prakash Bhartia, Inder bahl, Apisak ittopiboon, *Microstrip Antenna Design Handbook* : Artech house,Boston, London, 2001.

[180]. Rathi, V., G. Kumar, and K. P. Ray, ''Improved Coupling for Aperture-Coupled Microstrip Antennas,'' *IEEE Trans. Antennas Propagation*, vol. AP-44, no. 8, 1996, pp. 1196–1198.

[181]. Ray, K. P., et al., ''Broadband Planar Rectangular Monopole Antennas,'' *Microwave Optical Tech. Letters*, vol. 28, no. 1, 2001, pp. 55–59.

[182]. Ricardo marques, Ferran Martin, Mario Sorolla, *Metamaterials with Negative Parameters Theory, Design, and Microwave Application:* Wiley interscience, A John wiley & sons, inc., publication, 2007.

[183]. Rmili, H., Mrabet, O.E., Floc'h, J.-M., Miane, J.-L., "Study of an Electrochemically-Deposited 3-D Random Fractal Tree-Monopole Antenna,"

IEEE Transactions on Antennas and Propagation, vol55, 2007, pp.1045 – 1050.

[184]. Robert S. Salama, Ranjith Liyana-Pathirana, “Analyzing the Effect of Metamaterials on a Cylindrical-rectangular Microstrip Patch Antenna Using the Electric Surface Current Method,” *IEEE International Conference on Signal Processing and Communications*,2010, pp. 1-5.

[185]. Rodney B. Waterhouse, *Microstrip Patch Antennas: Designer’s Guide:* Springer Sciences and Business media, 2003.

[186]. Rongkuo Zhao, Thomas Koschny and Costas M. Soukoulis, “Chiral metamaterials: retrieval of the effective parameters with and without substrate,” *Optics Express*, vol. 18, no. 14, 2010, pp. 14553-67.

[187]. RongLin Li, G.DeJean, M.M.Tentzeris, “Development and analysis of a folded shorted-patch antenna with reduced size,” *IEEE transaction on Antenna and Propagation*, vol. 52, issue 2, 2004, pp. 555-562.

[188]. S. Enoch, G. Tayeb, P. Sabouroux, N. Guerin, and P. Vincent, "A metamaterial for directive emission," *Physics Review Letters*, vol. 89, no. 21, 2002, http://dx.doi.org/10.1103/PhysRevLett.89.213902.

[189]. S.Pinhas and S. Shtrikman, “Comparison between computed and measured bandwidth of quaterwave microstrip radiators,” *IEEE Transaction on Antenna and Propagation*, vol. 36, 1988, pp. 1615-1616.

[190]. S.Zhang, G.H.Hiff, J.Fengand, J.T. Bernhard, “A pattern reconfigurable microstrip patch antenna array,” *IEEE transaction on Antenna and propagation*, vol.52, no. 10, 2004, pp.1440-1441.

[191]. Saber Dakhli, Jean-marie Floch, Kourosh Mahdjoubi, Hatem Rmili and Fethi Choubani, “Superdirective and Low Profile Metamaterial-Inspired Antenna,” *IEEE Loughborough Antennas & Propagation Conference*, 2013, pp. 337-340.

[192]. Saimmom Ferdous, Ababil Hossain, Shah Mahmud Hasan Chowdhury, Mahdy Rahman Chowdhury Mahdy, Matin Abdul, "Reduced and conventional size multi-band circular patch antennas loaded with metamaterials," *IET Microwave, Antennas & Propagation*, 2013, pp. 768-776.

[193]. Serdyukov, A., I. Semchenko, S. Tretyakov, and A. Sihvola, *Electromagnetics of Bi-anisotropic Materials Theory and Applications:* Gordon and Breach Science Publishers, 2001.

[194]. Shyh-Yeong Ke, “Single-feed Microstrip Antenna with Two-layer Substrate for Circular Polarization”, *ISCOM*, 2005, pp. 103-105.

[195]. Sivaranjan Goswami, Kumaresh Sarmah, Angana Sarma, Kandarpa Kumar Sarma, Sunandan Baruah, “Slot loaded square patch antenna with CSRR at ground plane” , *International Conference on Microelectronics, Computing and Communications (MicroCom*), 2016, pp. 1-5.

[196]. Son Xuat Ta, Ikmo Park, “Low-Profile Broadband Circularly Polarized Patch Antenna Using Metasurface,” *IEEE Transactions on Antennas and Propagation*, vol.63, issue 12, 2015, pp. 5929-5934.

[197]. Sridhar Pattanaik, “A study on the engineering techniques adopted for microstrip antenna for achieving some specific performance for commercial personal communication,” *European Journal of Applied Engineering and Scientific Research*, 2012, pp. 50-56.

[198]. Sundaram, A., Maddela, M., Ramadoss, R., “Koch-Fractal Folded-S.lot Antenna Characteristics,” *IEEE Antennas and Wireless Propagation Letters*, vol. 6, 2007, pp.219 – 222.

[199]. Surbhi Dwivedi, Vivekanand Mishra, and Yogesh Kosta, "Metamaterial inspired patch antenna miniaturization technique for satellite," 1st IEEE *International Conference on Emerging Technology Trends in Electronics, Communication and Networking*, 2012, pp. 1-6.

[200]. T. Chakravarty and A. De, “Design of tunable modes and dual-band circular patch antenna using shorting posts,” *IEE Proceedings on Microwave, Antennas and Propagation*, vol. 146, no. 3, 1999, pp. 224-228.

[201]. T. Chakravarty and A. De, “Investigation of modes tunable circular patch radiator with arbitrarily located shorting posts,” *IETE Technical Review*, vol. 16, no.1, 1999, pp. 109-111.

[202]. T.Shanmuganantham, S.Raghavan,“Design of a compact broadband microstrip patch antenna with probe feeding for wireless applications,” *International Journal of Electronics and Communication*, vol.63, 2009, pp.653–659.

[203]. Taufal Hidayat, Fitri Yuli Zulkifli, Basari, Eko Tjipto Rahardjo “Bandwidth and Gain Enhancement of Proximity Coupled Microstrip Antenna Using Side Parasitic Patch” *ICRAMET, Surabaya – Indonesia*, 2013, P-95.

[204]. Tzung-Wern Chiou and Kin-Lu Wong, “Broad-Band Dual-Polarized Single Microstrip Patch Antenna With High Isolation and Low Cross Polarization”, *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 3, 2002, pp.399-401.

[205]. V. G. Veselago, "The Electrodynamics of substances with simultaneously negative values of epsilon and mu," *Soviet Phys. Usp*., vol. 10, no. 4, 1968, pp. 509-514.

[206]. V.K.Kundu and M.Ali, “ Reconfigurable stacked patch antenna for satellite and tersstial applications,” *IEEE topical conference on wireless communication technology*, 2003, pp. 152-153.

[207]. Wenquan Cao, Yang Xiang, Bangning Zhang, Aijun Liu, Tongbin Yu, and Daosheng Guo, “A Low-Cost Compact Patch Antenna With Beam Steering Based on CSRR-Loaded Ground, ” *IEEE Antennas and Wireless Propagation Letters*, vol. 10, 2011, pp.1520-1523.

[208]. Wen-Shyang Chen, Chun-KunWu, Kin-LuWong, “Novel Compact Circularly Polarized Square microstrip Antenna”, IEEE Trans. Antennas Propagation, vol. 49, 2001, pp. 340-342.

[209]. Wong ,K.L. and Y.F.Lin, “ Small broadband microstrip antenna with chip-resistor loading,” *Electronic letters*, vol.33, 1997, pp. 1593-1594.

[210]. Wong ,K.L. and Y.F.Lin, “Microstrip-line fed compact microstrip antenna with broadband operation,” *IEEE Antennas and Propagation symposium Diges*t, 1998, pp.1120-1123.

[211]. Wong, K. L., and Hsu W. H., ‘‘Broadband Triangular Microstrip Antenna with U-Shaped Slot,’’ *Electronics Letters*, vol. 33, no. 25, 1997, pp. 2085–2087.

[212]. Wood, C., ‘‘Improved Bandwidth of Microstrip Antennas Using Parasitic Elements,’’ IEE Proceedings Microwaves, Optics and Antennas, 1980, pp. 231–234.

[213]. X. L. Ma, C. Huang, M. B. Pu, W. B. Pan, Y. Q.Wang, and X. G. Luo, “Circular dichroism and optical rotation in twisted Y-shaped chiral metamaterial, ”*Applied Physics Expr*ess, vol. 6, 2013, 022001.

[214]. X. L. Ma, C. Huang, M. Pu, Y. Wang, Z. Zhao, C. Wang, and X. Luo, “Dual-band asymmetry chiral metamaterial based on planar spiral structure,” *Applied Physics Letters*, vol. 101, 2012, 4756901.

[215]. X.L.Bao and M.J.Ammann, “ Comparision of several novel annular ring microstrip patch antennas for circular polarization,” *Journal of Electromagnetic Waves Appl.*, vol. 20, no. 11, 2006, pp. 1427-1438.

[216]. Xiaoliang Ma, Cheng Huang, Wenbo Pan, Bo Zhao, Jianhua Cui, and Xiangang Luo, “A Dual Circularly Polarized Horn Antenna in Ku-Band Based on Chiral Metamaterial,” *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 4, 2014, pp. 2307-2310.

[217]. Xue-Hua Song, Wen-Yun Wu, Ting-Gen Shen and Yue-Qun Zhou, “Investigation of a patch antenna based on I-shaped left-handed material,” *International Journal for Light and Electron Optic*s, vol. 122, no. 16, 2011, pp.1426-1429.

[218]. Y. G. Ma, P. Wang, X. Chen, and C. K. Ong, "Near-field plane-wave-like beam emitting antenna fabricated by anisotropic metamaterial," *Applied Physics Letters*, vol.94, 2009, http://dx.doi.org/10.1063/1.3077128.

[219]. Y. K. Park and Y. Sung, “A reconfigurable antenna for quad-band mobile handset applications,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 6, 2012, pp.3003-3006.

[220]. Y.F.Lin, H.M. Chen and S.C.Lin, “A new coupling mechanism for circularly polarized annular-ring patch antenna,” *IEEE Transaction on Antenna and Propagation*, vol. 56, 2013, pp. 305-308.

[221]. Y.Ye , X.Li, F. Zhuang and S.W.Chang, “ Homogenous Circular Polarizer using a bilayered chiral metamaterial,” *Applied Physics Letter* , vol.99, 2011, http://dx.doi.org/10.1063/1.3615054.

[222]. Yahong Liu, Kun Sang, Ying Qi, Shuai Gu and Xiaopeng Zhao, “Investigation of Circularly polarized patch Antenna with Chiral Metamaterial,” *IEEE antennas and Wireless propagation letters*, vol.12, 2013, pp. 1359-1362.

[223]. Yuchu He, Geroge. V. Eleftheriades, "Metamaterial-Inspired Wideband Circular Monopole Antenna," *IEEE International Symposium on Antennas and Propagation*, 2012, pp. 1-2.

[224]. Zaid, L., et.al., “ Dual-frequency and broadband antennas with stacked quarter wavelength elements,” *IEEE transaction antennas and propagation*, vol. AP-47, 1999, pp. 654-660.

[225]. Zeeshan Qamar, Umair Naeem, Shahid A. Khan, Mitchai Chongcheawchamnan, M. Farhan Shafique, “Mutual Coupling Reduction for High-Performance Densely Packed Patch Antenna Arrays on Finite Substrate,” *IEEE Transactions on Antennas and Propagation*, vol. 64, Issue. 5, 2016, pp. 1653 - 1660.

[226]. Zhaofeng Li, Rongkuo Zhao, Thomas Koschny, Maria Kafesaki,Kamil Boratay Alici, Evrim Colak, Humeyra Caglayan, Ekmel Ozbay and C. M. Soukoulis, “Chiral metamaterials with negative refractive index based on four “U” split ring resonators”, *Applied Physics Letters*, vol. 97, issue 8, 2010, http://dx.doi.org/10.1063/1.3457448.

[227]. Zhi Hao Jiang, Donovan E. Brocker, Peter E. Sieber, Douglas H. Werner, “ A Compact, Low-Profile Metasurface-Enabled Antenna for Wearable Medical Body-Area Network Devices,” *IEEE Transactions on Antennas and Propagation*, vol. 62, issue 8, 2014, pp.4021-4030.

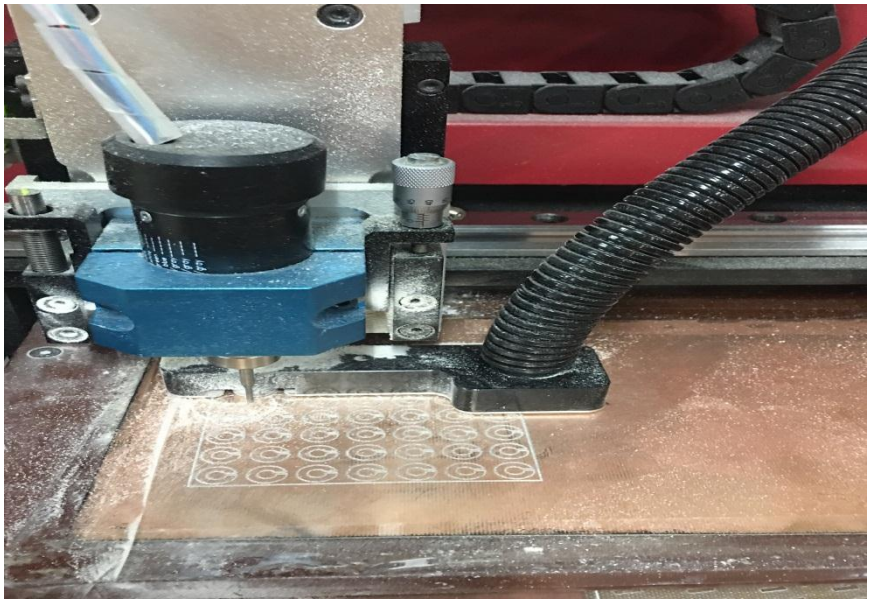
[228]. Zhi Ning Chen, Yong Sun, Pui Yi Lau, Xianming Qing and Yewen Zhang, “Metamaterial-based high gain planar antennas”, *IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, 2012, pp. 1-4.

[229]. Zhongqing Wang, Bao Li, Lidan Peng, "Application of Novel Left-handed Metamaterial Structure in Antenna Cover," *IEEE International Workshop on Electromagnetics; Applications and Student Innovation*, 2012, pp 1-2.

APPENDIX

TOOLS AND SOFTWARE USED:

1. **HIGH FREQUENCY STRUCTURE SIMULATOR (HFSS)**: For modelling and simulation of antennas and metamaterial HFSS 15.0 software is used. Optimization of antenna and metamaterial is done using the optimetric tool of this software.
2. **PCB PROTOTYPE MACHINE**: For fabrication of metamaterial and antennas PCB prototype Machine Caddo 71 as shown below is used.



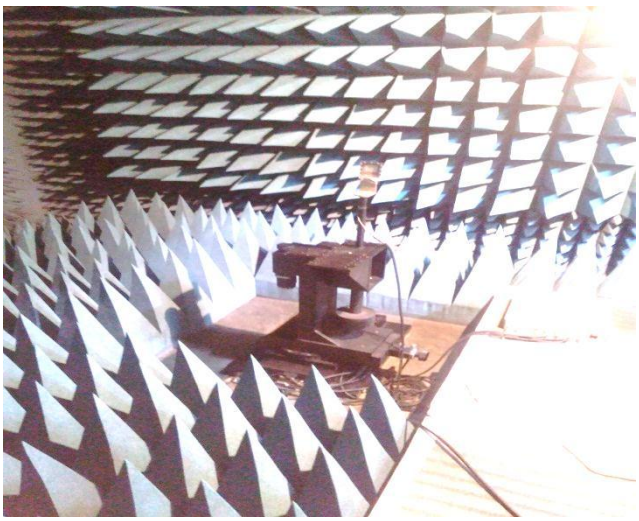
PCB Prototype Machine (Caddo 71)

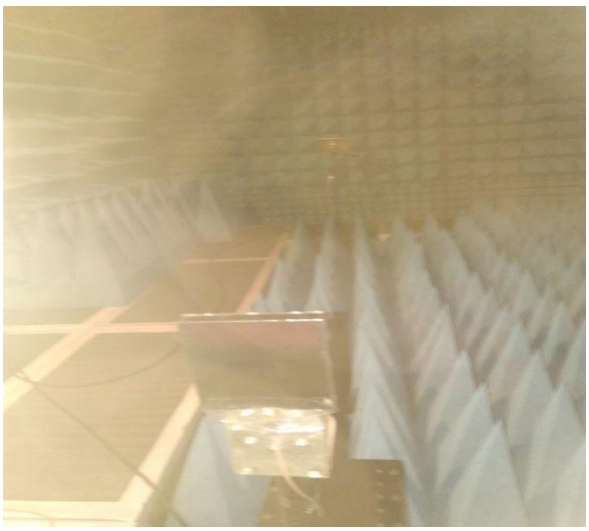
3. TOOLS FOR MEASUREMENT OF PERFORMANCE PARAMETERS OF ANTENNAS:

(i) Vector Network Analyzer (VNA): For calculating reflection coefficient of fabricated antenna Anritsuu VNA Master MS2027C as shown in picture below is used.

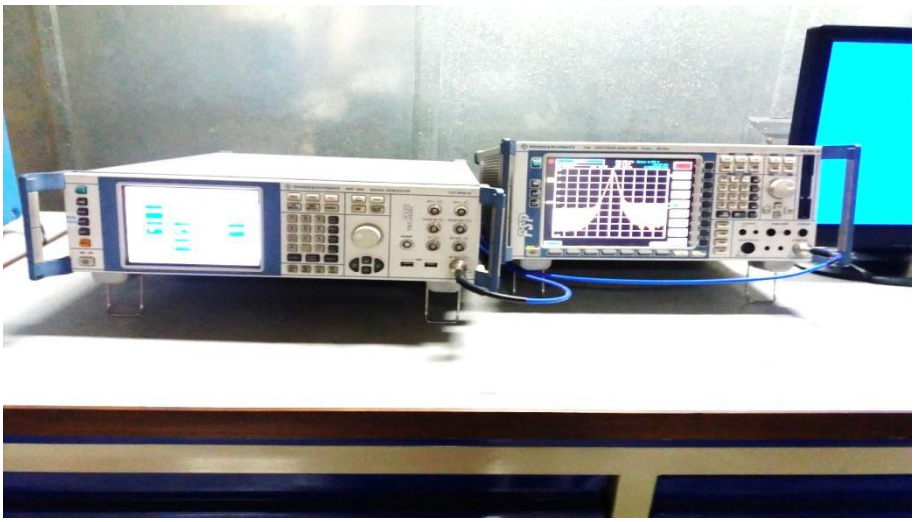
Vector Network Analyzer (Anritsu MS2027C)

(ii) Anechoic chamber: Measurement of gain, radiation pattern and axial ratio of fabricated antenna is done in anechoic chamber of GB Pant Govt. Engg. College, Delhi as shown in picture below.





Anechoic chamber



Rodhe & Schwarz Signal Generator and
Rodhe & Schwarz Spectrum Analyzer (9 KHz -30 GHz)

4. **MATLAB AND ORIGIN SOFTWARE**: MATLAB software is used for extracting the permittivity and permeability of metamaterial from S parameter data and origin software is used for plotting the graph from measured data.

BRIEF PROFILE OF THE RESEARCH SCHOLAR

Preet Kaur (preetmoar@gmail.com) received the M.Tech Degree in RF and Microwave Engineering form Indian Institute of Technology (IIT), Roorkee (Uttarakhand) and B.E Degree in Electronics and Communication Engineering from DCRUST, Murthal (Haryana) in 2006, 2002 respectively. She started her carrier as Design Engineer, ST Microelectronics in 2006. She is working as Assistant Professor in YMCA University of Science and Technology in the Department of Electronics Engineering, since 2008. She is pursuing Ph.D. in the field of Antenna design. Her research interests include metamaterials, antenna design, microwave engineering and electromagnetic wave theory.

LIST OF PUBLICATIONS

Paper Published in International Journals: 7

International IEEE Conference: 3

Accepted Papers: 2

Communicated Papers: 1

List of Published Papers

Sl. No.	Title of Paper	Name of Journal where published	ISBN /ISSN No.	Volume & Issue	Year	Pages
1.	Design of A Novel Reconfigurable Fractal Antenna for Multi-Band Application	International Journal of Advanced Science and Technology	2005-4238	62	2014	103-112
2.	Reconfigurable Inverted Circular Patch Antenna for Wireless Applications	International Journal of Advanced Science and Technology	2005-4238	70	2014	55-64
3.	Performance Comparison of Micro-strip Antennas with Different Shape of the Patch	International Journal of u- and e- Service, Science and Technology	2005-4246	6 & 3	2013	13-22
4.	Double H Shaped Metamaterial Embedded Compact RMPA	IEEE International conference on advances in computing, communicatio n and informatics	978-1-4799-3080-7		2014	483-486
5.	Design of compact rectangular patch	IEEE International	978-1-4799-		2015	132-135

	antenna using square grid and I shaped metamaterial	conference on signal processing and communicatio n	6761-2			
6.	Design and Parametric Analysis of Circular Shaped Split Ring resonator,	International Journal on Advanced Research in Electrical and Electronic Engineering	2349-5812	2 & 7	2015	44-47
7.	Metamaterial and their application in patch antenna: A Review	International Journal of Hybrid Information Technology	1738-9968	8 & 11	2015	199-212
8.	A survey of techniques for performance enhancement of patch antenna using metamaterial,	IOSR journal of Electronics and Communicatio n Engineering	2278-2834	10 & 6	2015	98-109
9.	Design and Investigation of Circularly Polarized RMPA with Chiral Metamaterial Cover	International Journal of Wireless and Microwave Technologies	2076-9539	6 & 3	2016	61-70

List of Accepted Papers

Sl. No.	Title of Paper	Name of Journal where accepted	No.	Volume/ IssuePresent Status	Year
1	Performance Enhancement of RMPA using Double H shaped Metamaterial	Springer, Radio Electronics and Communication Systems	1934 - 8061	Accepted	2016
2	Design and Analysis of Subwavelength RMPA using Double Folded I Shaped ENG Metamaterial	IEEE conference on power electronics, intelligent control and energy system (ICPEICES), DTU 2016		Paper presented	2016

List of Communicated Papers

Sl. No.	Title of the Paper	Name of Journal	Present Status	Year
1	Design of Sub-wavelength, Directive & Multiband RMPA using Cylindrical Rods	Taylor& Francis, IETE Journal of Research	Submitted with minor modification as suggested by reviewers	2014 Resubmitted in February 2016