# High gain, Circularly Polarized 1 x 4 Antenna Array with Circular Slots for Wireless Power Transmission Applications

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# ABSTRACT

## High Gain, Circularly Polarized 1 x 4 Antenna Array with Circular Slots for Wireless Power Transmission

Wireless Power Transmission is asubstitute solution to supply power to the electrical and electronics components without wired association. In this paper we present amicrostrip patch array antenna design which is the vitalcomponent of a Rectenna (rectifier + antenna) system. The developed design consists of a 1 x 4 antennaarrays having an operating frequency of 2.45 GHz, which is central frequency of ISM band. An inclined rectangular slot has been introduced at the center of each antenna element to improve the circular polarization by decreasing axial ratio. Furthermore, circularnotches to enhance the gain of single patch antenna have been introduced at the cornersof antenna.Final array antenna delivers a high gain of 11.3 dBi and return loss of -38 dB. Results of simulations in CST software and that of measured on VNA in theMicrowave labof Military College of Signals depicts that this antenna is suitable for use in Wireless Power Transmission applications.

## ENDORSEMENT OF CORRECTNESS AND APPROVAL

It is affirmed thatdatapresented in this thesis "**High Gain, Circularly Polarized 1 x 4 Antenna Array with Circular Slots for Wireless Power Transmission**" carried out by 1) Capt. Azmat Jamil 2) Capt. MuhammadZeeshan 3) Capt. Hassan Khurshid 4) Capt. Abdus Salam under the direction of Assoc. Prof. Dr. Farooq Ahmed Bhatti is in complete satisfaction of our level of Bachelor of Telecommunication Engineering is right and endorsed. Percentage of plagiarism found in document as per software Turnitin available on LMS NUST comes out to be **____**

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# DECLARATION

We herewith declare that no content and variety of work bestowed during this thesis has been submitted in support of another award of qualification or degree either during this course or anyplace else

# DEDICATION

This proposition is devoted in thanks to ALLAH ALMIGHTY our Creator who has blessed us with wisdom, knowledge and understanding then to our parents for their direction and their endless support. Then to our Faculty for their guidance and supervision. Without their help and supervision this project would not have been made possible.

# ACKNOWLEDGEMENT

The accomplishment of this projectwould not have been possible without the contribution of different people the names of which cannot be reckoned with. Their assistances are sincerely respected and thankfully recognized. We would like to thank following:

To Allah Almighty who is the most Powerful and Merciful and everything is in His obedience.

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# ABBREVIATIONS

1. **WPT** > WIRELESS POWER TRANSMISSION
2. **CST** > COMPUTER SIMULATION TECHNOLOGY
3. **IEEE** > INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS
4. **EM** > ELECTROMAGNETIC
5. **CP** > CIRCULARLY POLARIZED
6. **dB** > DECIBEL
7. **BW** > Bandwidth
8. **Tx** > Transmitting
9. **Rx** > Reception

# CHAPTER 1

## 1. INTRODUCTION

An antenna is a device (usually metallic) for Tx or RxEM waves. Theantenna is an imperative component ofany communication equipment.An antenna array consists of two or more patch antennas arranged together to act as single antenna . The signals fromthe multiple antennas are combined or processed together so to achieve increased performance as compared to individual element antenna.

An antenna array is a set of individual antennas used for Tx & Rx EM waves, arranged in such a way that their indl current & voltage are in a definite phase & amplitude association. This arrangement permits the resulting array to behave as a single antenna, generally with significantly enhanced directive properties (which is directly proportional to the gain of antenna ) than would be possible as compared to indl patch element .

## 1.1 PROJECT OVERVIEW

We have selected **"Circularly Polarized Array antenna for WPT applications"** as our project. Project envisages on the design and fabrication microstrip patch array antenna with circular slots. This antenna forms an essential part of rectenna (Antenna + Rectifier) systems.

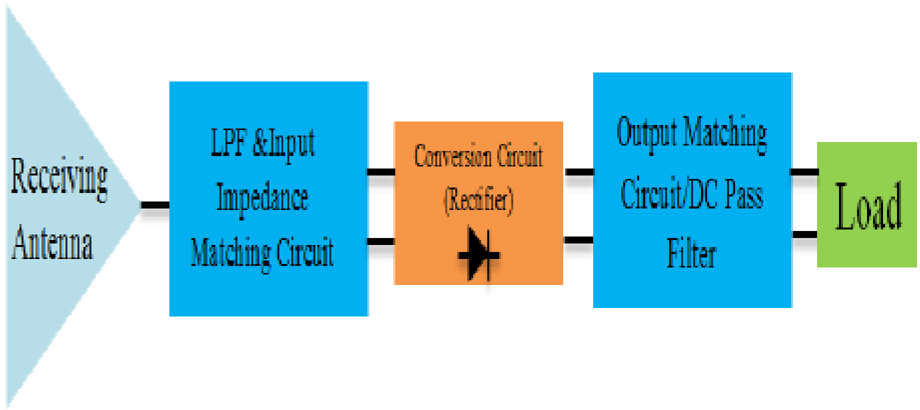



FIGURE 1: RECTENNA SYSTEM BLOCK DIAGRAM

**Why CP ANTENNA?**

To decrease the Tx loss as signal traverses between Tx antenna and Rx antenna it is essential that polarization between two antennas must be matched.Linearly polarized antennas suffer more frequently from out of phase issues. The utilization of CP antennas presents an alternative solution to this problem and hence reduces the harmful effects of multipath reflections.

**Why ARRAY ANTENNA?**

The array antenna increases the gain of patch antenna. As depicted from figure 3 and figure 4 power received at Rx antenna is directly proportional to the gain of receiving antenna hence performance of system increases. Also, free space path loss is inversely proportional to gain of receiving antenna

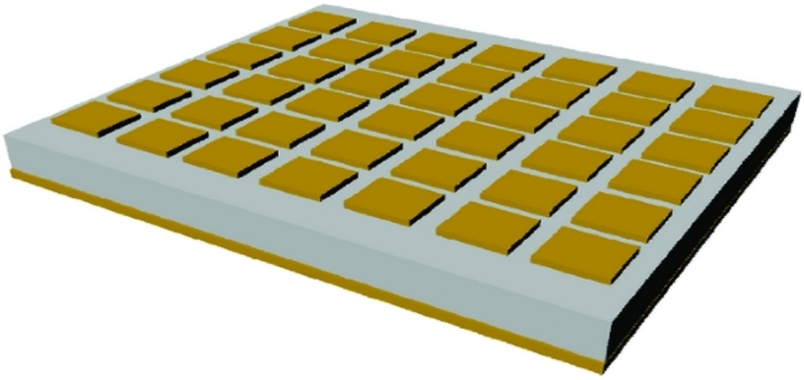


FIGURE 2: MICROSTRIP PATCH ARRAY ANTENNA

## 1.2PROBLEM STATEMENT

1. Power received at any antenna is given by

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$$

2. Free space path loss is inversely proportional to gain at transmitting and receiving antenna. Hence improving the gain reduces the net losses occurred at receiving antenna
3. Linearly polarized signals are more susceptible to reflectivity, absorption and multi-path fading
4. As evident from formulas power received and free space path loss it is evident that powerreceived by any antenna is directly proportional to the gain of transmitting and receiving antenna. Furthermore, free space path loss decreases with increase in gain of antenna. So, we conclude from these facts that gain of antenna is crucial parameter in enhancing the performance of any antenna which is a crucial part of any rectenna (antenna + rectifier) system.

## 1.3 APPROACH

1. Design a simplepatch antenna
2. Achieve circular polarization through central slot
3. Enhance the gain by introduction of circular notch
4. Increasing the gain by designing array antenna.
5. Design fabrication and testing the hardware.

## 1.4 OBJECTIVES

Our objective is to design a circularly polarized array antenna for wpt applications. The projected system will have following features:

1. Reduced Return Loss.
2. Improved Gain.
3. Circular Polarization.
4. Good radiation pattern.

## 1.5 ORGANIZATION

Document starts with the introduction which describes the main details of our project**High gain, Circularly Polarized 1 x 4 Antenna Array with Circular Slots for Wireless Power Transmission**, followed by problem statement, approach, scope, objectives and limitations. The literature review segment defines the several resources read online and in different books before the initiation of the project. They include knowledge about antenna basic parameters. Results of simulations in CST software and that of measured in Microwave Lab of Military College of Signals on Voltage Network Analyzer depicts that this antenna is suitable for use in WPT applications.

## 1.6 LIMITATIONS

This project has its limitations.

1. First, we had to go through the literature to find the suitable antenna design.
2. Then we had to truncate the sides to see its effect on overall gain of antenna.
3. FR4 substrate is the only option available to us as it is comparatively cheap and easily avaible. But due to the fact that it's a lossy material, it has its own disadvantages as well.
4. Central slot to achieve circular polarization has no specific formulas, rather its dimension is adjusted by optimization.
5. After the implementation of a single patch antenna converting it into 1 x4 array antenna while keeping the operating frequency same as that of single patch which was an arduous task.

# CHAPTER 2:

# 2. ANTENNAS FUNDAMENTAL PROPERTIES

The patch antenna was first presented inyear 1953by G.A. Deschamps. Its size is inverselyproportional to its frequency, hence at higher frequency size of antennas starts decreasing. Patch antenna is becoming very common in cellular technology and is being used for Bluetooth, WIFI and other such systems in cell phones.They are generally easy to fabricate since they have less cost as compared to other antennas. Few essential parameters of patch antenna will be discussed in the succeeding paragraphs.

## 2.1 NEAR-FIELD AND FAR-FIELD

In relation to source, various fields are generated around an antenna and are divided into 3 main areas. The first one is reactive near field the innermost area directly surrounding the antenna. Whereas, the outmost area is the far-field and in between these two is the radiating near-field. If an antenna is having a maximum dimension of D, then the far field condition would be as per Equation given below, here $\lambda$ represents wavelength of frequency on which antenna is operating.

$$\text{Far Field} \geq \frac{2D^2}{\lambda}$$

The inner most region with respect to far field is called near field region and it has further two sub-regions namely reactive and radiating near-field regions. The outmost limit of the boundary of reactive near field is as per following equation.

$$\text{Reactive Near Field} \leq 0.62 \times \sqrt{\frac{D^3}{\lambda}}$$

here $\lambda$ represents wavelength of frequency on which antenna is operating. Whereas D is the diameter of transmitting antenna.

## 2.2 ANTENNA RADIATION PATTERN

Antennas have three main categories, namely; isotropic, directional and Omni-directional antennas.

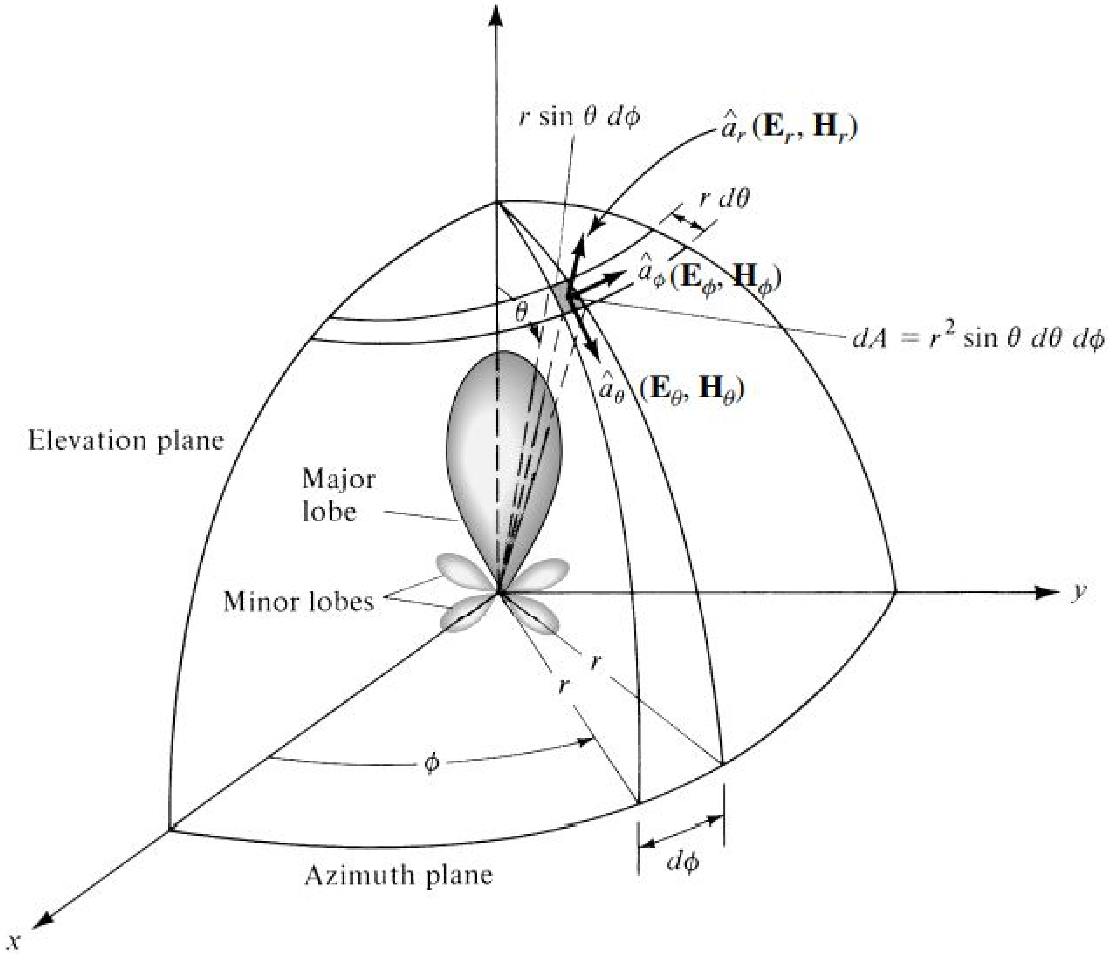



FIGURE 3: ANTENNA RADIATION PATTERN

## 2.3 DIRECTIVITY OF MICROSTRIP PATCH ANTENNA

There is a relationship between the directivity and direction, and is considered to be one of the main parameters which explain the degree by which thepower of a radiated antenna is being occupied towards some given direction with reference to some other directions. While discussing directivity without mentioning direction, then consider the only direction in which we have maximum radiation. Representation of directivity is given by following equation.

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} = \frac{4\pi}{\Omega_A}$$

Where U depicts the radiation intensity and Prad is said to be net total powerradiated in Watts.

## 2.4 REFLECTION COEFFICIENT

Another important parameter for antenna performance measurement is the reflection coefficient. Its main purpose is to measure how effectively transmission line and load are matched with each other. To determine reflection coefficient, we consider the following relation;

$$\Gamma_A = \frac{Z_L - Z_A}{Z_L + Z_A}$$

## 2.5 GAIN

Gain can be defined as one of the main parameters of an antenna that take into accounts both the directionality and efficiency of an antenna. Gain of an antenna is the measure that determines the efficiency with which the electrical power is converted into EM waves by antennas in a specific direction in comparison with an isotropic source. Gain will be considered maximum when the direction is not mentioned. It can be expressed as

$$G = \frac{4\pi U(\theta, \phi)}{P_{in}(\text{lossless isotropic source})}$$

Radiation intensity is represented by $U$ (Θ, ϕ), whereas, input power(Watts) received by the antenna is denoted by P*in*. Gain can also be calculated by multiplying Directivity with efficiency of antenna.

## 2.6 ANTENNA BANDWIDTH

For estimating the performance of an antenna the antenna bandwidth is an important factor. Bandwidth is the collection of frequencies where antenna effectively changes its input power to radiated power. Generally, the range of frequencies for antenna bandwidth are defined around the resonant frequency.

## 2.7 ANTENNA POLARIZATION

To determine the polarization of electromagnetic waves we consider the electric field plane in the propagation direction. The polarization of a radiated wave can also be described as the polarization of the E-field vector. Moreover, wave polarization is determined by the direction and the position of electric field relative to the ground.

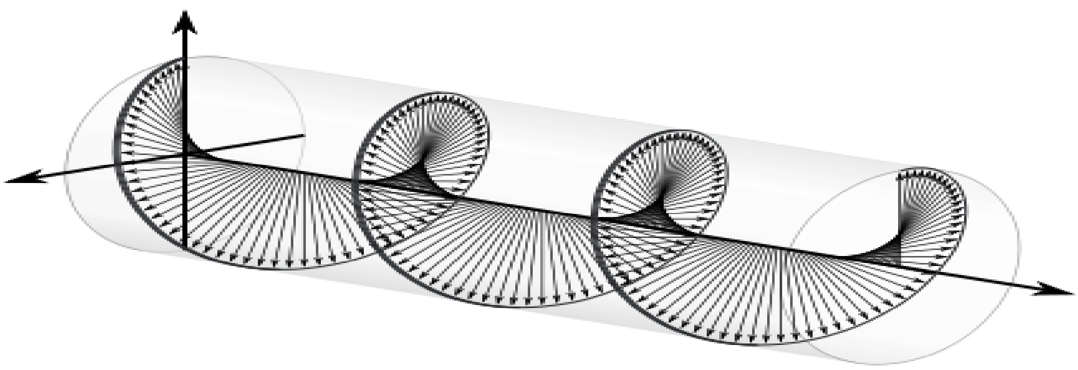


FIGURE 4: CIRCULARLY POLARIZED EM WAVES

# CHAPTER 3:

## 3.1 BACKGROUND STUDY

The area of research in microstrip patch antenna is a fast paced very rapidly growing. Since the last couple of years, a lot of exploration has been made in this field.The problem is that how we should design compact array antennas with improved gain. Circular polarized signals are less susceptible to multi path fading but design of patch antenna has to be truncated and the parameters of truncation has to be optimized as there are no fixed formulas to calculate them.

## 3.2 LITERATURE REVIEW

Our area of concern was to study and review literature about circular polarization, antenna arrays, different antenna design comparisons, different notch techniques and respective antenna performance. The electric field lines exhibit linear polarization from surface of patch antenna.

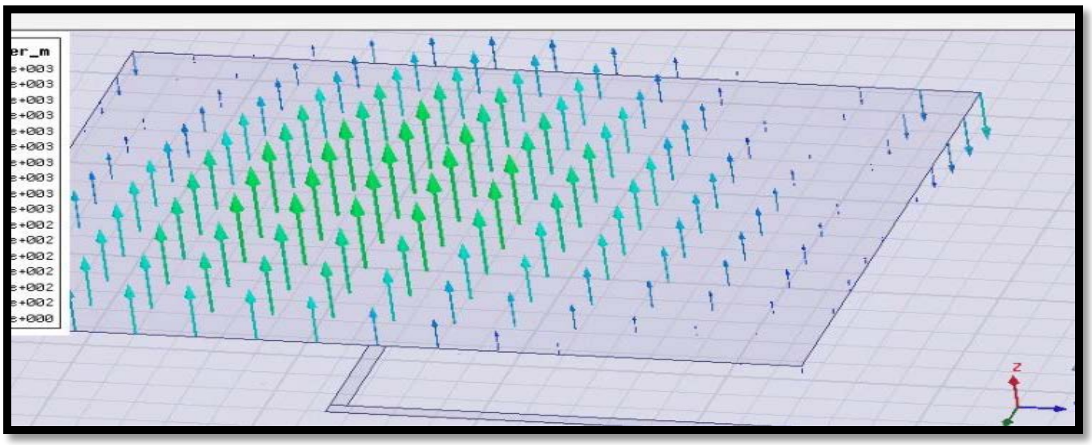


FIGURE 5: ELECTRIC FIELD LINES FROM OF LINEARLY POLARIZED PATCH

Our aim is to alter the design of patch antenna in such a way that axial ratio decreases. For a linearly polarized MSA AR is ( ∞ ) whereas ideal CP antenna would have AR of 1 which is generally not possible to achieve so if AR is less than 6 for any antenna would be considered as circularly polarized.

## 3.3 DELIVERABLES:

Our aim is to design antennas arrays which exhibits circular polarization and is having high gains due to truncated edges and array design. The final product is an antenna will be operating at central frequency of 2.45 GHz.

# CHAPTER 4

## 4.1 WHAT IS POLARIZATION?

The polarization of an antenna refers to the orientation of the electric field (E-plane) of the Electromagnetic wave with respect to the Earth's surface and is determined by the physical structure of the antenna and by its orientation. Thus, a simple straight wire antenna will have one polarization when mounted vertically, and a different polarization when mounted horizontally. As a transverse wave, the magnetic field of a radio wave is at right angles to that of the electric field, but by convention, talk of an antenna's "polarization" is understood to refer to the direction of the electric field

## 4.2 TYPES OF POLARIZATION

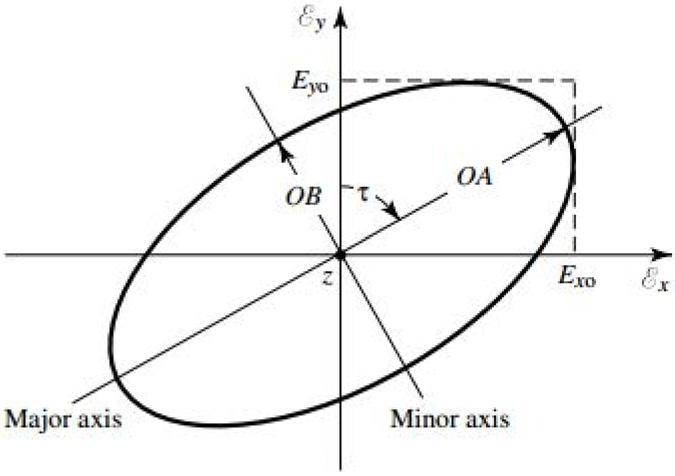
Three are three types of polarization as far as microstrip patch antennas are concerned

a. Linearly polarized
b. Circularly Polarized
c. Elliptically polarization

## 4.3 Circular polarization

In electrodynamics, circular polarization of an electromagnetic wave is a polarization state in which the electric field of the wave has a constant magnitude but its direction rotates with time at a steady rate in a plane perpendicular to the direction of propagation of wave. Parameter which describes the polarization of antenna is known as axial ratio. To design a circularly polarized patch antenna our main task will be to design of patch antenna in such a way that axial ratio decreases.

For a linearly polarized antennas AR is (∞) whereas ideal CP antenna would have AR of 1. So closer the value of AR to 0 better will be circular polarization achieved.




$$AR = \frac{\text{major axis}}{\text{minor axis}} = \frac{OA}{OB}, \quad 1 \le AR \le \infty$$

FIGURE 6: AXIAL RATIO FORMULA

## 4.4 METHODS OF DESIGNING CIRCULAR PACTH ANTENNAS

There are various methods of achieving circularly polarized patch antennas. Few of them are

a. By designing patch with two or more feeds

b. By using single feed with shifting location of patch

c. By introducing a central slot in the patch to achieve circular polarization

In the first method two feeds are feed to single patch with a phase difference of 90 degree between the two feeds as shown in following diagram

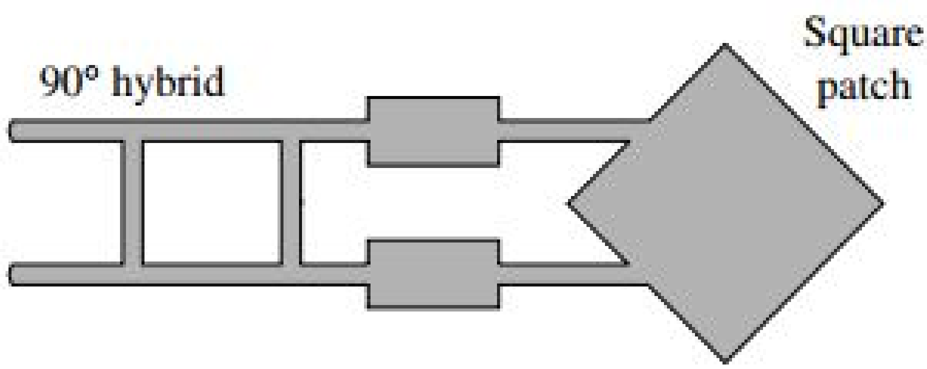



FIGURE 7: Two feeds simultaneously exciting patch having phase difference of 90 degree between them.

Second methoduses single feed but alters the position of patch in order to achieve circular polarization as depicted in following diagram

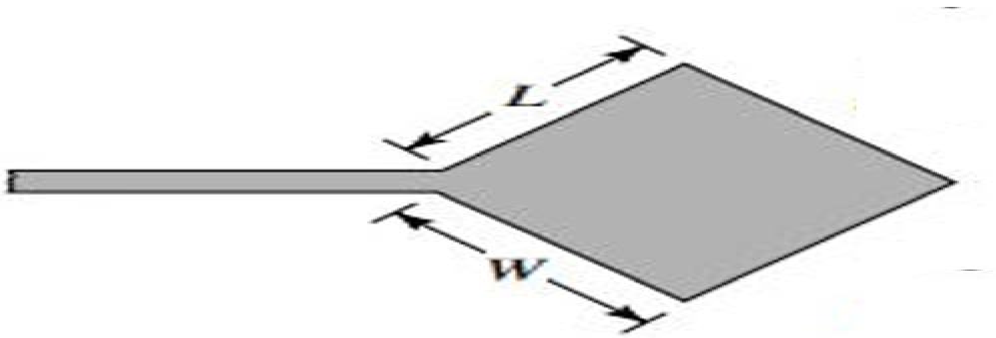



FIGURE 8: Single feed with patch rotated at 45 degrees with respect to the central feed line

Third method employees introducing a central slot in the patch to design circularly polarized patch antenna. Length and width of central slot has been optimized to reduce the axial ratio, which enhances the circular polarization of antenna.

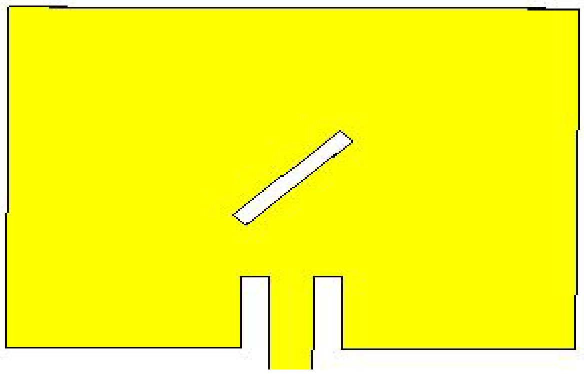


FIGURE 9: Circularly polarized patch antenna with central slots

## 4.5 APPLICATIONS OF CIRCULARLY POLARIZED ANTENNAS

a. Extensively used in space applications such as satellite communication and radar systems
b. Wireless power transmission applications
c. RFID readers applications

# CHAPTER 5:

## 5.1 DESIGN SELECTION

Performance of anyrectenna depends upon high performance antennas. Width of patch antennas is calculated by formula

$$Width = \frac{c}{2f\sqrt{\frac{\varepsilon r\ +1}{2}}}$$

Where f is operating frequency of patch antenna whereas$\varepsilon_r$is dielectric loss of substrate which in our case being FR-4 epoxy comes out to be 4.4. Length of patch antenna is given by formula

$$Length = \frac{c}{2f\sqrt{\varepsilon r}} - 0.824h(\frac{(\varepsilon r + 0.3)(\frac{W}{h} + \ \ 0.264)}{(\varepsilon r - 0.258)(\frac{W}{h} + 0.8)}$$

Height of substrate h is 1.6mm which is commonly available height in market.Following figure depicts inset feed at location

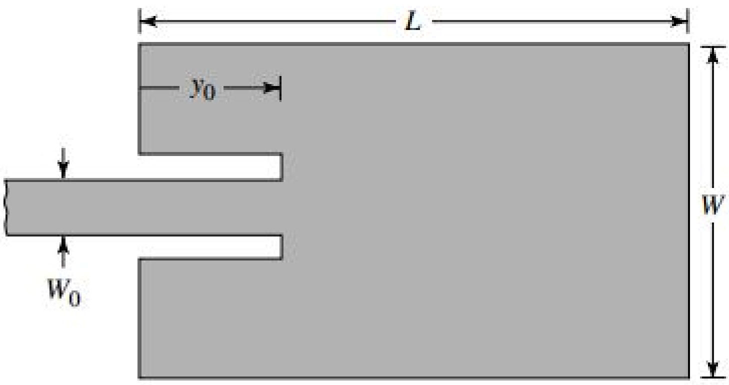



FIGURE 11: Recessed microstrip-line feed

Input resistance is a critical parameter to ensure proper matching between the patch and feed line.

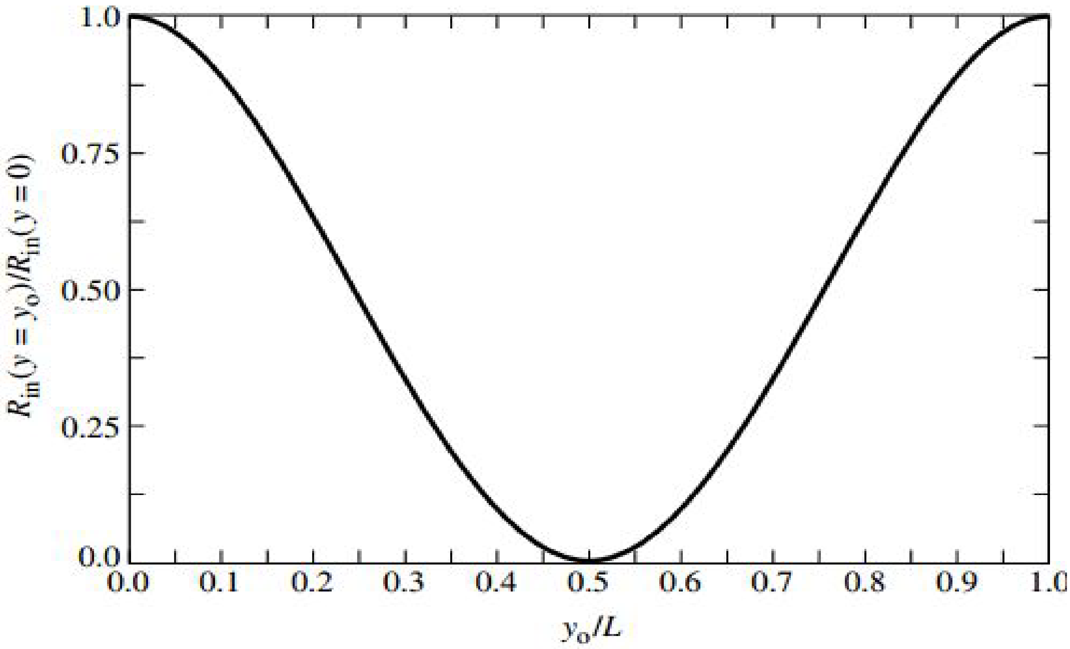



FIGURE 12: Normalized Input Resistance

Although the theory suggests that length of inset feed should be half of length of patch but in our scenario since we have a central slot in our design for circular polarization so we are restricted to optimize this length instead of using theoretical length of L/2. Central slot and circular slots do not have any fixed formulas in theory but few research papers have depicted their values but that too after optimization.

The length of various parameters has been depicted in the table on next page.

## 5.2 PARAMETRES VALUE

TABLE 1: VARIOUS PARAMETRES VALUES

| Ser | Parameters | Value (mm ) |
|---|---|---|
| 1. | W | 40 |
| 2. | L | 28.5 |
| 3. | Ws | 1.2 |
| 4. | Ls | 11 |
| 5. | Gf | 1.88 |
| 6. | Lf | 14.2 |
| 7. | Li | 6.12 |
| 8. | Wf | 1.512 |
| 9. | Y | 52 |
| 10. | Z | 104 |
| 11. | R | 2.2 |

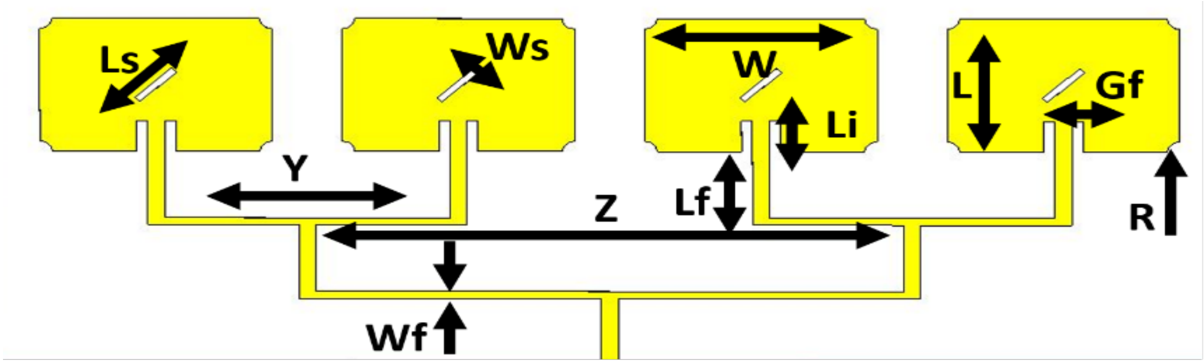



FIGURE 12: Antenna parameters

## 5.3 RESULTS OF DIFFERENT PATCH ANTENNAS

TABLE 2: VARIOUS PARAMETRES VALUES

| **Microstrip Patch Antenna** | **Return Loss** | **Gain (dBi)** | **VSWR (dB)** |
|---|---|---|---|
| Single patch antenna without circular polarization | -23.177 | 4.69 | 1.17 |
| Circularly polarized Single patch | -25.354 | 6.41 | 1.05 |
| Circularly polarized 1 x 2 Array | -32.856 | 7.97 | 1.04 |
| Circularly polarized 1 x 4 Array | -38.09 | 11.3 | 1.02 |

## 5.4 DESIGNSOFTWARE

The software selected for the design is CST which helps in simulating the designing of antenna. Next step was fabrication of our final model of antenna and verify or testing our results of practical antenna with the results of CST.

## 5.5 SUBSTRATE SELECTION

For most of the PCB applications, FR4 epoxy glass substrates are the best choice of material. The substance is very inexpensive as compared to others and it has exceptional mechanical characteristics which make it an ideal choice for a wide variety of electrical component applications. As now a day, more and more microwave systems designed at consumer markets are developed, there is a substantial notice in abating the cost of these systems.

## 5.6 CST SIMULATION DESIGN AND RESULTS

Microstrip patch antenna was designed in CST software. Various results are shown in succeeding paragraphs.

### 5.6.1 SINGLE PATCH ANTENNA WITHOUT CIRCULAR POLARIZATION

Formulas for width and length of patch antenna were used as shown in section 4.1.1. Substrate used was FR4 epoxy. Design of single patch antenna is shown below

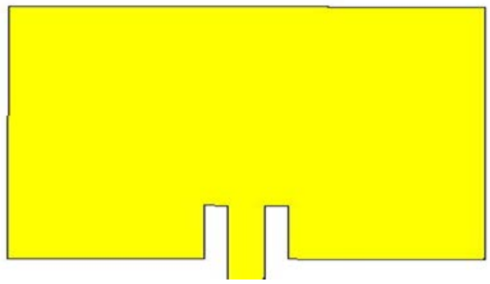


FIGURE 13: Single element design without circular polarization

### 5.6.2 SIMULATED RESULTS

Various results were simulated on CST which are shown in succeeding figures

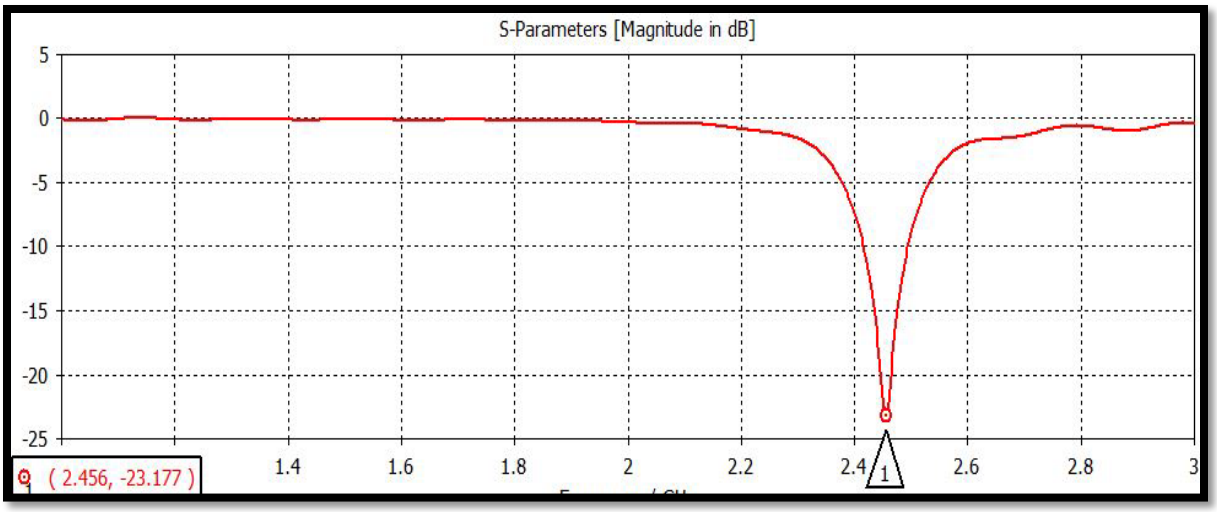



FIGURE 14: Return loss of patch without circular polarization

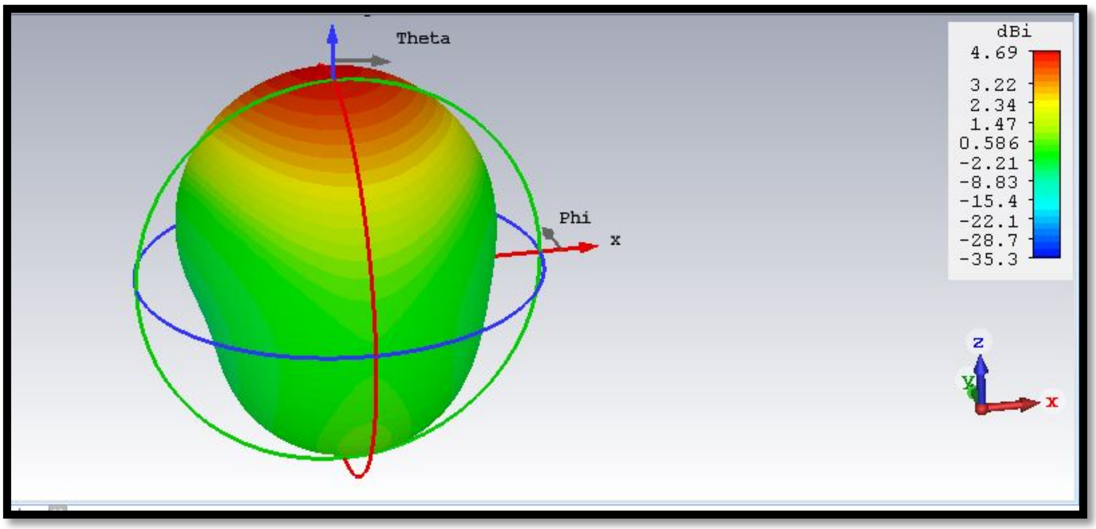



FIGURE 15: Gain of patch without circular polarization

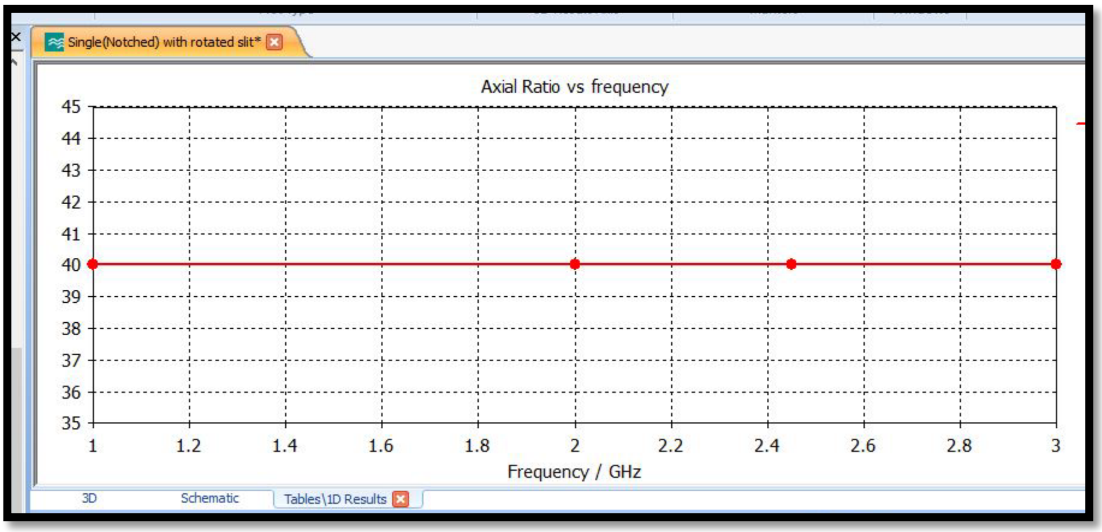



FIGURE 16: Axial Ratio without circular polarization

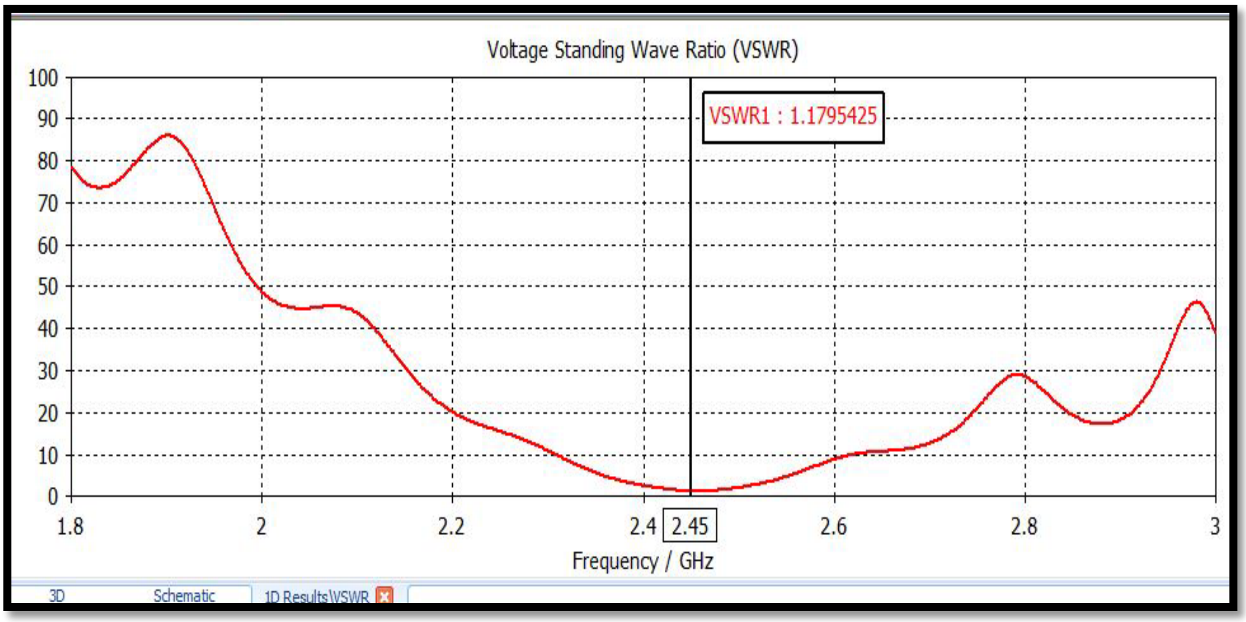



FIGURE 17: VSWR of patch without circular polarization

### 5.6.3 DISCUSSION OF RESULTS

Single patch antenna gives a return loss of -23 dB at the design frequency of 2.45 GHz and voltage to standing wave ratio of 1.17. Axial ratio which depicts the type of polarization is 40 dB which indicates that antenna is linearly polarized. Gain of antenna is 4.69 dBi.

### 5.6.4SINGLE PATCH WITH CIRCULAR POLARIZATION

After designing and verifying a single element edges where truncated with circular slots in order to improve the gain of single patch. After parametric analysis best results for gain and return loss were observed at slots with radius of 2 mm. The design of patch antenna is as :

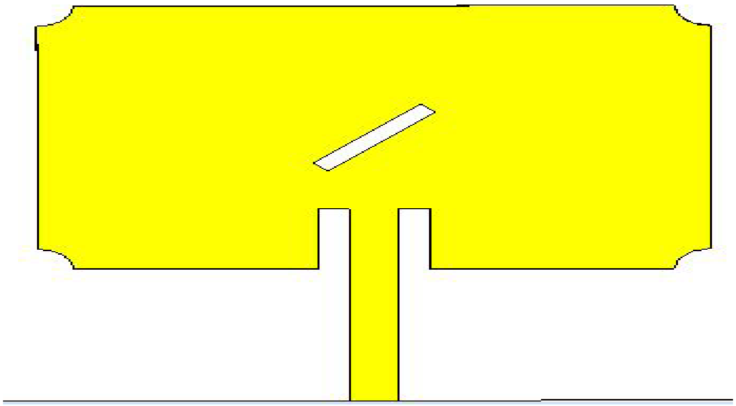


FIGURE 18: Single patch with circular polarization

### 5.6.5 SIMULATED RESULTS

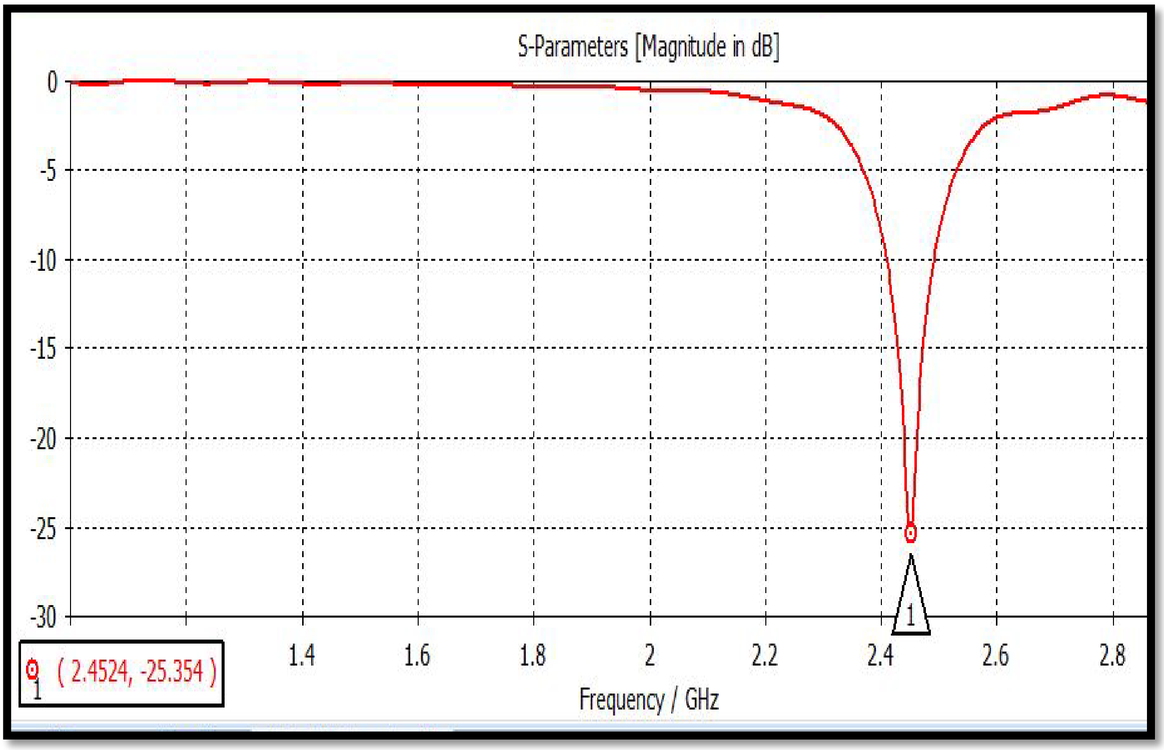



FIGURE 19: Return loss of single element with circular polarization

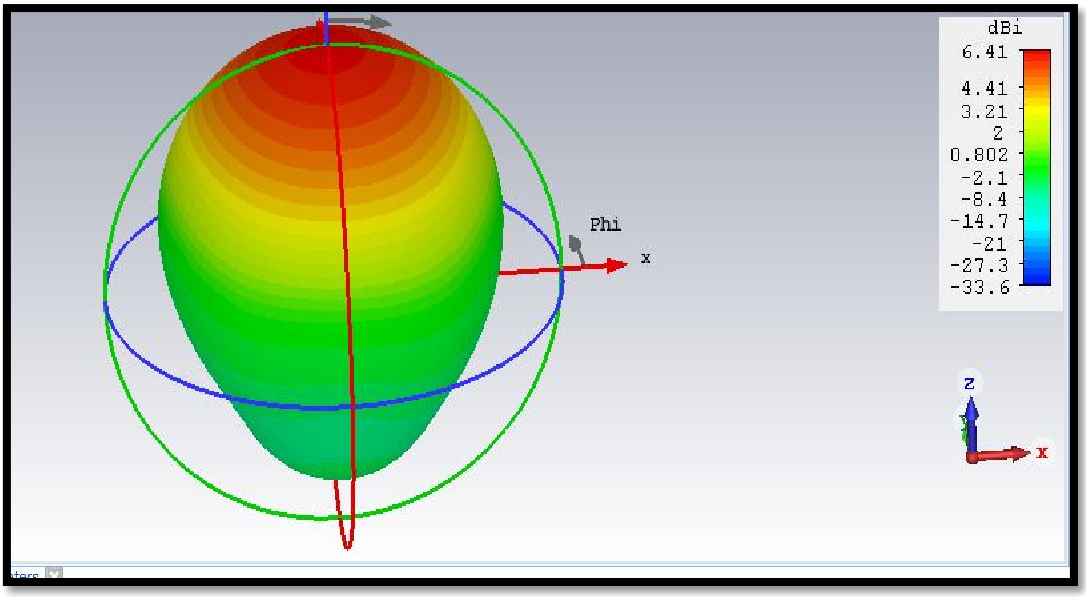



FIGURE 20:  Gain of single patch antenna with circular polarization


FIGURE 21:   VSWR of single patch with circular polarization

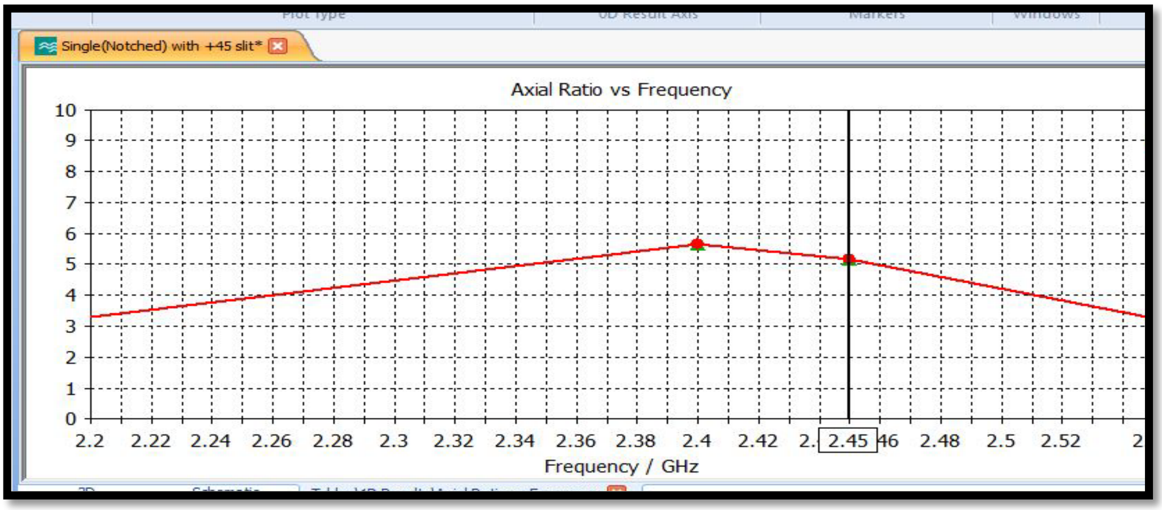



FIGURE 22: Axial ratio of single patch with circular polarization

### 5.6.6 DISCUSSION

After introduction of central slot,our patch is exhibiting circular polarization, which is being depicted by decrease in axial ratio from 40 dB to 5.14 dB as depicted in figure 23. Length and width of slot has been optimized to achieve improved value of axial ratio. Gain of patch has been increased from 4.6 dB TO 6.41 dB through introduction of circular slots at edges of patch antenna. Furthermore, return loss has been improved from -23 to -25 dB. Voltage to standing wave ratio has also shown improvement as it has decreased from 1.17 to 1.05.

## 5.6.7 CIRCULARLYPOLARIZED 1 x 2 ARRAY ANTENNA

After designing and verifying the results of single patch antenna with truncated edges main aim was to design an array antenna. The basic design of antenna array 1 x 2 is shown as

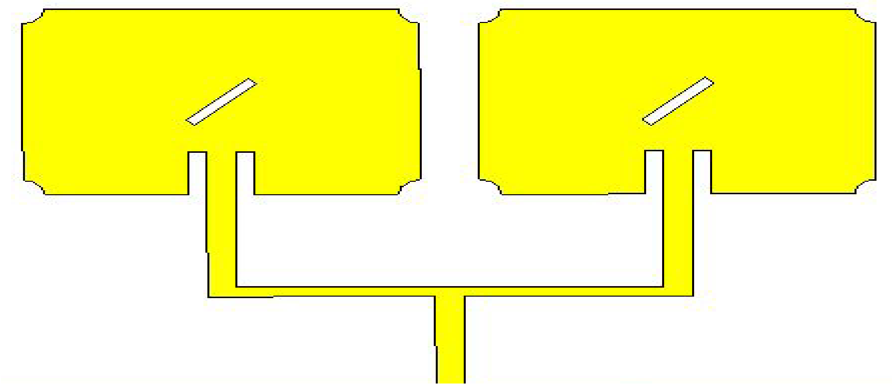


FIGURE 23: Circularlypolarized 1 x 2 array antenna

## 5.6.8 SIMULATED RESULTS

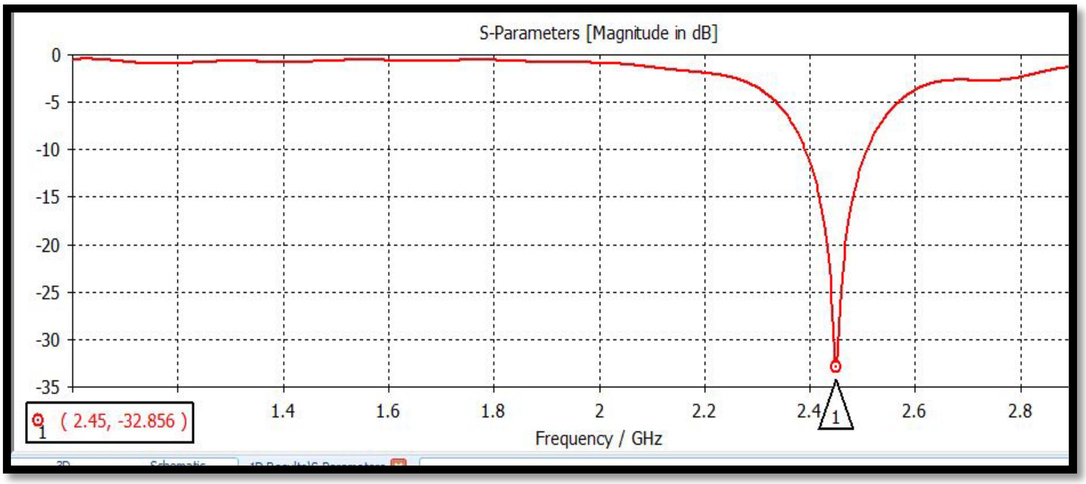



FIGURE 24: Return loss of circularly polarized 1 x 2 array antenna

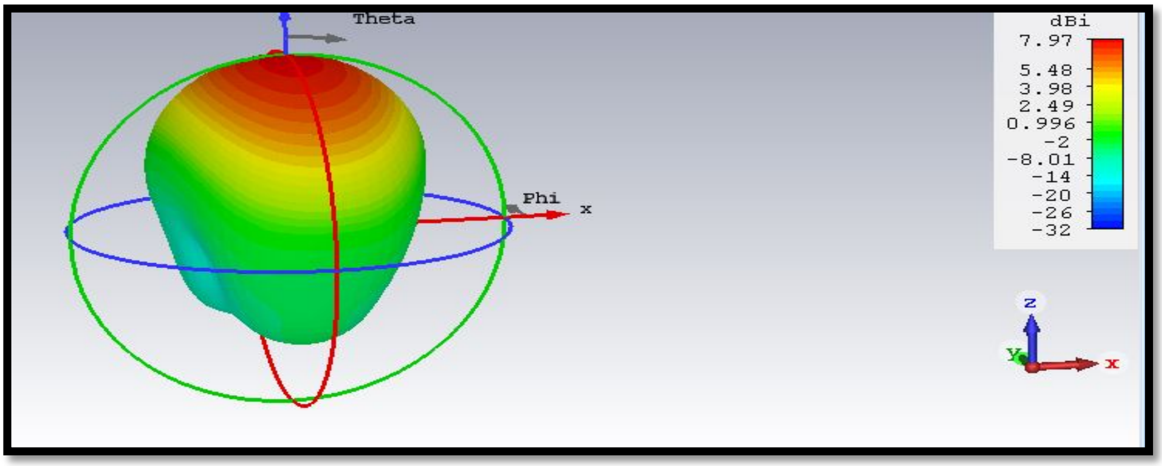



FIGURE 25:Gain of circularly polarized 1 x 2 array antenna

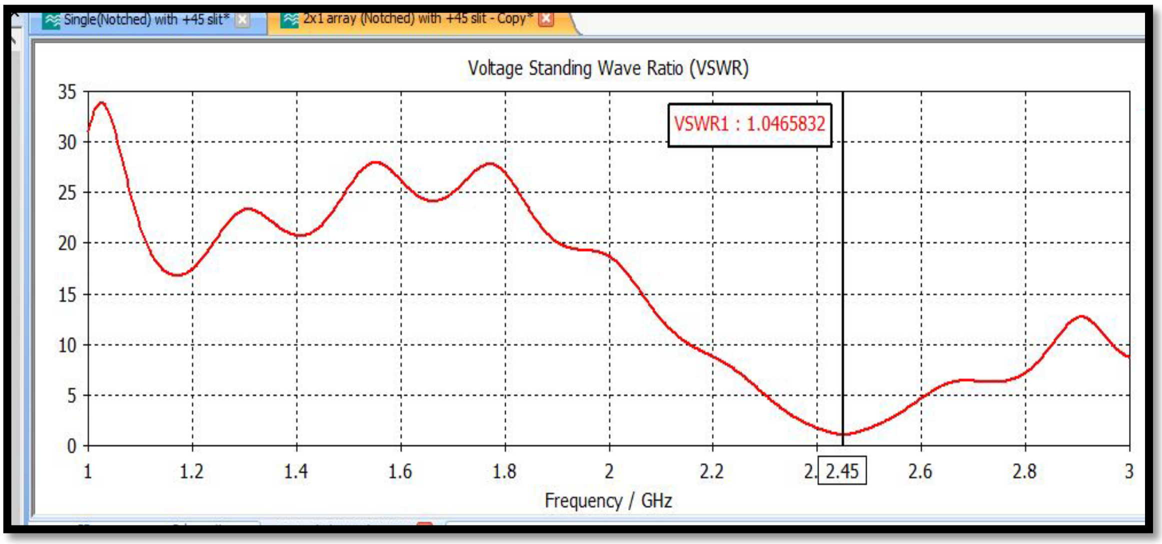



FIGURE 26:VSWR of circularly polarized 1 x 2 array antenna

### 5.6.9 Discussion

Basic aim to convert it into array antenna was to enhance the gain antenna which has been increased to 7.97 dB. An increase in return loss as observed from -25 dB to -32 dB. As a result of which voltage to standing wave ratio has also improved from 1.05 to 1.04.

### 5.6.10 CIRCULARLY POLARIZED 1 x 4 ARRAY ANTENNA

The basic design of antenna array 1 x4 is shown as

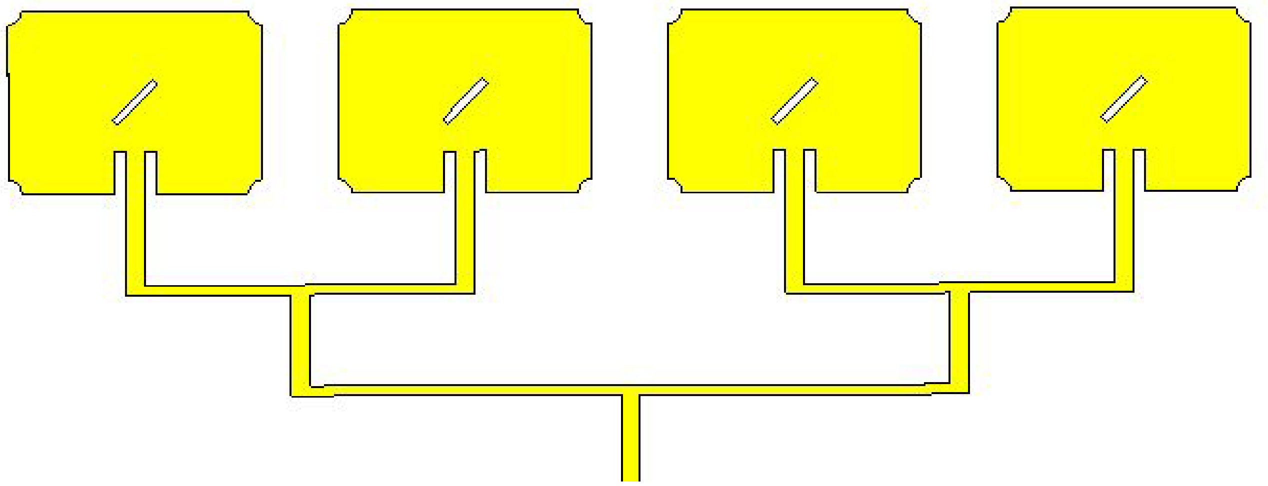


FIGURE 27:Circularly polarized 1 x4 array antenna

### 5.6.11 SIMULATED RESULTS

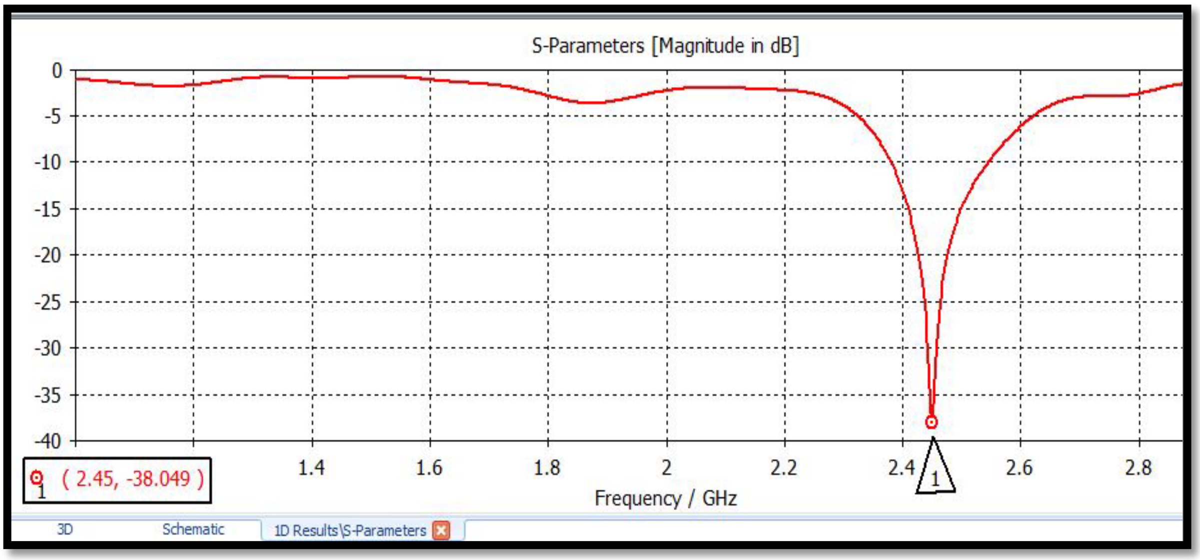



FIGURE 28: Return loss of circularly polarized 1 x4 microstrip patch array antenna

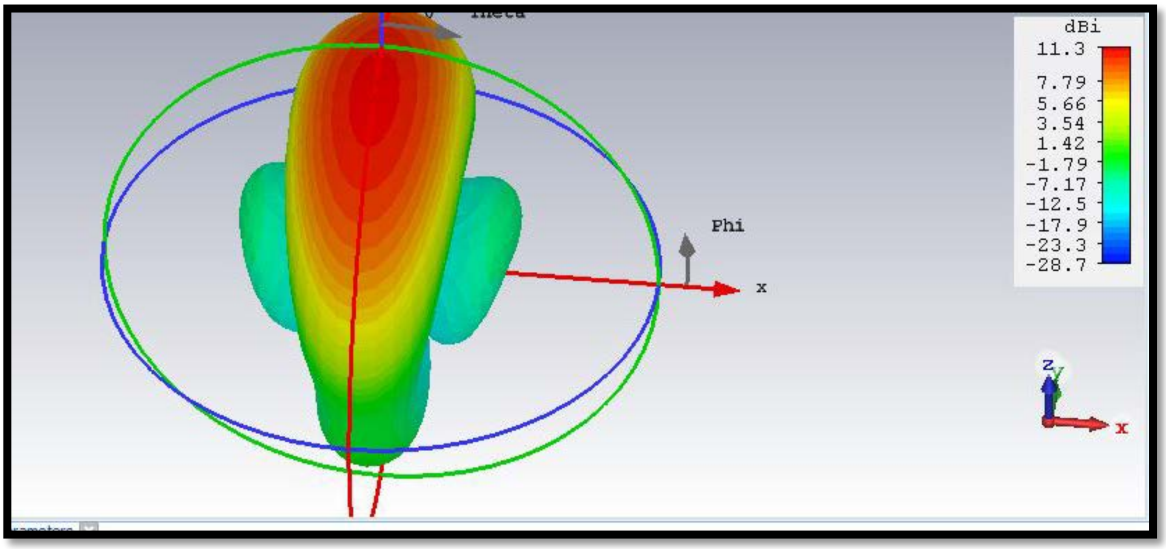



FIGURE 29 :Gain of circularly polarized 1 x 4 array antenna

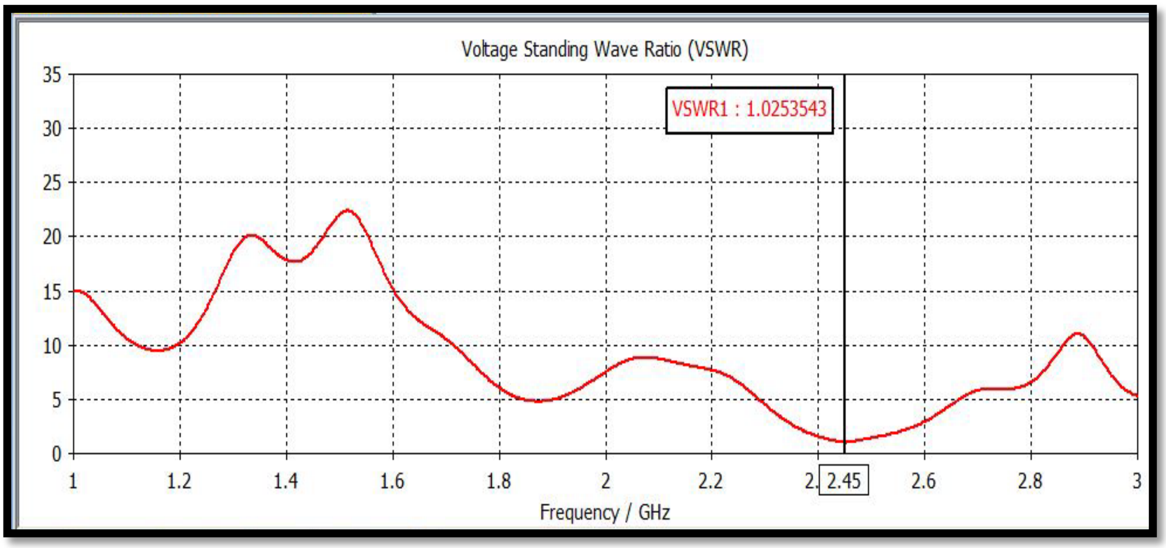



FIGURE 30:VSWR of circularly polarized 1 x 4 array antenna

## 5.6.12 DISCUSSION

Increasing the number of patches from 2 to 4 has increased the gain from 7.97 to 11.3 dB. Return loss has also shown remarked improvement from -23 to -38 dB. Voltage to standing wave ratio has also shown better result (1.02).

## 5.7 MEASURED RESULTS

Designed antenna was tested in Microwave lab of Military College of Signals on Vector Network AnalyzerR& S ZVL-3 . Measured results are in conformity with the simulatedresults. Achievement of circular polarization, high gain and results of return loss from the designated antenna depicts that the antenna is excellent choice for the use in WPT applications

FIGURE 31: Measurement of return loss of 1 x4 array antenna on VNA

Measured return loss of the said antenna at the designated frequency of 2.45 GHz is found to be -21 dB  shown in figure 31.

# CHAPTER 6:

## 6.1 FURTHER RESEARCH

The gain of antenna can be further enhanced by increasing the number of patch elements and by using innovative techniques of notching. From fabrication point of view the process can be further synthesized and the small details could be paid attention to to ensure that the losses are minimum due to the physical aspects such as copper insertion in slot, purity of copper, choosing less lossy substrate.

## 6.2 CONCLUSION

This project has provided a guideline for increasing the gain of antenna by notch and array technique. Together with circular polarization and high gain makes it ideal to be implemented in wireless power transmission applications.

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