# Design, Simulation and Characterization of a Compact Wireless Power Transfer Infrastructure for Electronic Peripherals

## B.E SENIOR DESIGN PROJECT REPORT

## Specialization in Electronics


**Prepared by**

| | |
|---|---|
| Muhammad Arif | (10045) |
| Shehriyar Masroor | (10014) |
| Syed Hamza Ali Sabir | (10025) |

**Project Advisor**

Dr. Sameer Hashmat Qazi

## College of Engineering

## Karachi Institute of Economics and Technology

## Karachi.

# Karachi Institute of Economics & Technology

Korangi Creek, Karachi-75190, Pakistan

## SDP COMPLETION DECLARATION

### ELECTRICAL ENGINEERING DEPARTMENT

We the students of Electrical Engineering department (College of Engineering), with batch **Spring-2019** hereby declare that we have completed our final year project titled **Design, Simulation and Characterization of a Compact Wireless Power Transfer Infrastructure for Electronic Peripherals** and have achieved all targets set forth in the project proposal.

It is requested that we may be examined.

| | NAME | REGISTRATION ID | SIGNATURE |
|---|---|---|---|
| 1. | **Muhammad Arif** | **10045** | Muhammad Arif |
| 2. | **Shehriyar Masroor** | **10014** | Shehriyar M. |
| 3. | **Syed Hamza Ali Sabir** | **10025** | Hamza |

**Confirmation by Project Supervisor:**

I **Dr. Sameer Hashmat Qazi**, as project supervisor for the above-mentioned group confirm that they have fulfilled all the necessary requirements of the final year project including the number of minimum visits for supervision, submission of all deliverables etc.

They may now be allowed to present and defend their work.

Signature with date

**FOR OFFICE USE ONLY**

| | | | | Remarks (If any) |
|---|---|---|---|---|
| 1. | Report submitted | ☑ Yes | ☐ No | |
| 2. | Project hardware & software fully functional | ☑ Yes | ☐ No | |
| 3. | All other deliverables received | ☑ Yes | ☐ No | |
| 4. | Presentation Date & Time | | | |

**Approved by Project Committee** ☑ Yes ☐ No

| | | SIGNATURE |
|---|---|---|
| 1. Chairperson | **Dr. Syed Safi Uddin Qadri** | For Safi |
| 2. Member | **Dr. Sameer Hashmat Qazi** | |
| 3. Member | **Miss Noor ul Ain** | For Safi |

**Approved by the Dean/Director:**

I certify, to the best of my knowledge, that the required procedures have been followed and the preparation criteria have been met for this project work.

Dated: ____________

**(Dean/Director CoE)**

**Karachi Institute of Economics & Technology**
Korangi Creek, Karachi-75190, Pakistan

## SDP CERTIFICATE OF COMPLETION

This is to certify that the following students of College of Engineering have completed their Senior Design Project under the title ***"DESIGN, SIMULATION AND CHARACTERIZATION OF A COMPACT WIRELESS POWER TRANSFER INFRASTRUCTURE FOR ELECTRONIC PERIPHERALS"*** in partial fulfillment of the requirement of the **Bachelor of Engineering in Electrical Engineering.**

| GROUP MEMBERS: | REGISTRATION ID |
|---|---|
| **Muhammad Arif** | **10045** |
| **Shehriyar Masroor** | **10014** |
| **Syed Hamza Ali Sabir** | **10025** |

**Project Advisor:**

(Name & *Signature)*

**Senior Design Project Committee:**

For

**Dr. Syed Safi Uddin Qadri**
**(Chairperson)**

**Dr. Sameer Hashmat Qazi**
**(Member)**

**Miss Noor ul Ain**
**(Member)**

**Assoc. Prof. Dr. Sameer Hashmat Qazi**
Head of Department (HoD)
Electrical Engineering Department

**Gp Capt (R) S. Najeeb Haider Jafri**
Director, College of Engineering
KIET

**Karachi Institute of Economics & Technology**
Korangi Creek, Karachi-75190, Pakistan

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They may now be allowed to present and defend their work.

________________________________
Signature with date

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| 4. | Presentation Date & Time | ________________ | | |

**Approved by Project Committee** ☐ Yes ☐ No

| | | SIGNATURE |
|---|---|---|
| 1. Chairperson | **Dr. Syed Safi Uddin Qadri** | ________________ |
| 2. Member | **Dr. Sameer Hashmat Qazi** | ________________ |
| 3. Member | **Miss Noor ul Ain** | ________________ |

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I certify, to the best of my knowledge, that the required procedures have been followed and the preparation criteria have been met for this project work.

Dated: ________________

________________________________
**(Dean/Director CoE)**

**Karachi Institute of Economics & Technology**
Korangi Creek, Karachi-75190, Pakistan

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|---|---|
| **Muhammad Arif** | **10045** |
| **Shehriyar Masroor** | **10014** |
| **Syed Hamza Ali Sabir** | **10025** |

**Project Advisor:**

(Name & *Signature)*

**Senior Design Project Committee:**

| | | |
|---|---|---|
| **Dr. Syed Safi Uddin Qadri** | **Dr. Sameer Hashmat Qazi** | **Miss Noor ul Ain** |
| **(Chairperson)** | **(Member)** | **(Member)** |

**Assoc. Prof. Dr. Sameer Hashmat Qazi**
Head of Department (HoD)
Electrical Engineering Department

**Gp Capt (R) S. Najeeb Haider Jafri**
Director, College of Engineering
KIET

# FINANCIAL SPONSORSHIP

The project is financially sponsored by Pakistan Engineering Council (PEC). We are thankful to the PEC team for shortlisting our project after a competitive analysis of projects.

Ref No: PEC/PPDC/22/ 262

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It is to certify you that Final Year Design Project

Design, Simulation and Characterization of a Compact Wireless Power Transfer Infrastructure for Portable Electronic Peripherals.

(Electrical Department, PAF-KIET, Karachi)

of your university has been approved for financial assistance by PEC

**CONGRATULATIONS**

It is required to complete this Design Project in accordance with the PEC standards so it can be included in the Capstone Expo-2023 and have it uploaded to the PEC E-library.

ENGR. MIR MASOOD RASHID
Convener, PPDC, PEC

ENGR. DR. NASIR M. KHAN
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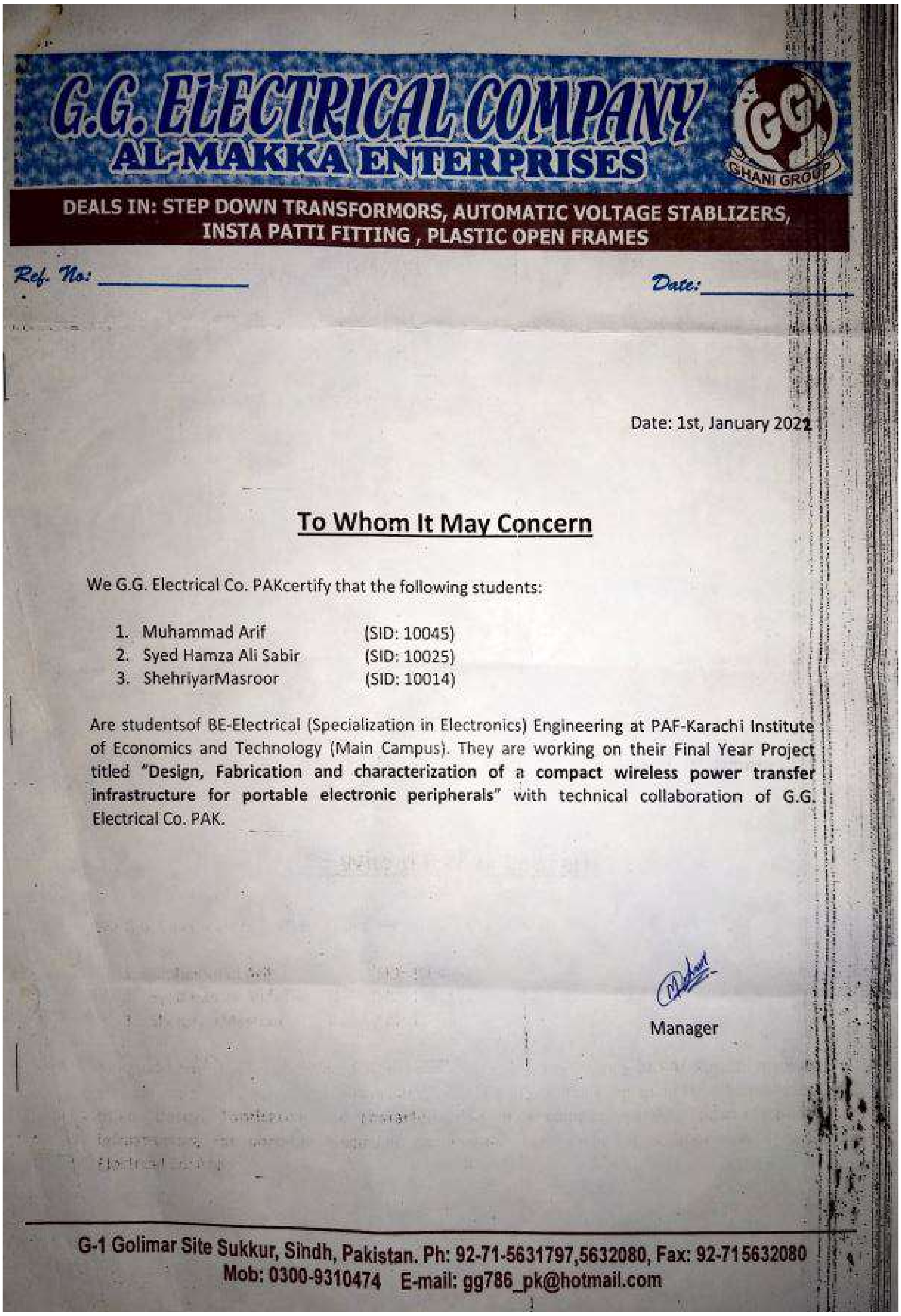

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Date: 1st, January 2022

**To Whom It May Concern**

We G.G. Electrical Co. PAKcertify that the following students:

1. Muhammad Arif (SID: 10045)
2. Syed Hamza Ali Sabir (SID: 10025)
3. ShehriyarMasroor (SID: 10014)

Are studentsof BE-Electrical (Specialization in Electronics) Engineering at PAF-Karachi Institute of Economics and Technology (Main Campus). They are working on their Final Year Project titled **"Design, Fabrication and characterization of a compact wireless power transfer infrastructure for portable electronic peripherals"** with technical collaboration of G.G. Electrical Co. PAK.

Manager

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# PLO RUBRICS

| PLOs | Mapping | Page No. |
|---|---|---|
| PLO1 | Knowledge of the math, science, and engineering specialization have been applied to foresee the main challenges in project and their possible solutions. | 2-4 |
| PLO2 | Principles of engineering are thoroughly applied to identify the problems, followed by analysis and literature review to address the actual scope of project. | 1, 2 |
| PLO3 | Transformation of idea (scope) into design that complies with existing standards of respective field and fulfills all requirements including safety, conservation and economics within realistic constraints. | 5-7 |
| PLO4 | Designed problem and its solutions were properly investigated in a methodical way resulting in synthesis of information. Further valid conclusions have been derived after testing multiple case studies, through experiments and simulations. | 22-55 |
| PLO5 | Employed techniques, resources, and modern engineering and IT tools, including prediction and modeling, in the feasibility or the development phases for designing, testing, debugging, and optimization of the project. | 27-39 |
| PLO6 | Highlight any social, economic and cultural effects (if any) of the project, and an attempt is made to address them in their designed solution. | 92 |
| PLO7 | Highlight the societal and environmental impact of the engineering project solutions and justify the sustainability of designs. | 5 |
| PLO8 | Provide a proof that you have followed ethical principles, commit to professional ethics and responsibilities, and norms of engineering practice and haven't forged or exaggerating the actual contribution, result in violation of research ethics. (plagiarism report) | At the beginning of Report |
| PLO9 | Exhibit soft skills needed to actuate teamwork. Demonstrate roles of each project member from the team lead to a supporting role depending upon the nature of tasks and milestones achieved. (Resource allocation in Gantt Chart) | Xvii |

| | | |
|---|---|---|
| PLO10 | Effectively explain their work in the form of oral presentations and (written) technical report using charts, graphs, figures etc. | Full Report, 81-90 |
| PLO11 | Demonstrated management skills through effective project planning, resource and budget utilization, task scheduling and meeting deadlines. (Gantt Chart) | xvii |
| PLO12 | Emphasize on the possibility that Industry project has future commercialization potential and/or Academia funded project has Innovative research aspect. | ii, 91 |

# ACKNOWLEDGMENT

We would thank almighty Allah for His countless blessings which has enabled us to withstand and overcome the challenges during this project.

It is an immense pleasure to acknowledge the gratitude of project advisor **Dr. Sameer Qazi** and project co-advisor **Bilal Sanauddin Pirzada**, without their continuous support and guidance it was impossible to complete this project.

It is our pleasure to thank **Dr. Syed Arsalan Jawed** for guiding and allowing us to use the resources of EDCAS Design Center. We would also like to thank the EDCAS Design Center staff (Sir Mustafa, Sir Irfan Muqim) for guiding us regarding the usage of new technology and tools.

# ABSTRACT

This project focuses on the designing, fabrication and testing of efficient wireless power transmitter and receiver modules using microwave technique. The transmitter module is consist of a VCO which generates a signal of 2.4GHz with power level of 7.6dBm, which is then fed to a 1x2 RF Power Divider which divides the signal into two parts, the output of Power Divider is 3.8dBm and contains Power Amplifiers which amplifies the signal to a level of 31.5dBm. The power is fed to transmitting antenna of two 2x2 matrices microstrip patch antenna with a measured gain of 7.67dBi. At first, single element antenna was designed but was having low gain, to enhance the gain, the number of patch elements were increased gradually from 1 to 2, then 4 and finally 8. The antennas are designed on an FR-4 substrate with permittivity of 4.4F/m and the height of substrate is 1.6mm. The antennas are designed in the rectangular form and inset feeding technique is incorporated to ensure optimum impedance matching. Similarly, the same antennas are fabricated for the receiving module and an extra antenna-4 Elements Array Form is designed for the receiving end. The antenna is connected to an in-house designed Charge Pump & Rectifier circuit with 1nF capacitor and SMS7630 schottky diodes, which rectifies and amplifies the voltages to 5V and 0.6mA DC current, which is stored in the Super Capacitor. The output of Super Capacitor is connected to a mobile phone for charging.

# KEYWORDS

Voltage Controlled Oscillator, Antenna Gain, Beam width, Directivity, Efficiency, FR-4 Substrate, ISM Band, Microstrip Patch Antenna, Power Amplifier, Schottky Diodes, Smith Chart, S11 parameter, Super Capacitor

**ACRONYMS:**

WPT: Wireless Power transfer

TX: Transmitter

RX: Receiver

RF: Radio frequency

VSWR: Voltage standing wave ratio

VCO: Voltage controlled oscillator

VNA: Vector Network Analyzer

S-parameters: Scattering parameters

ISM: Industrial Scientific and Medical

COTS: Commercial of the shelf

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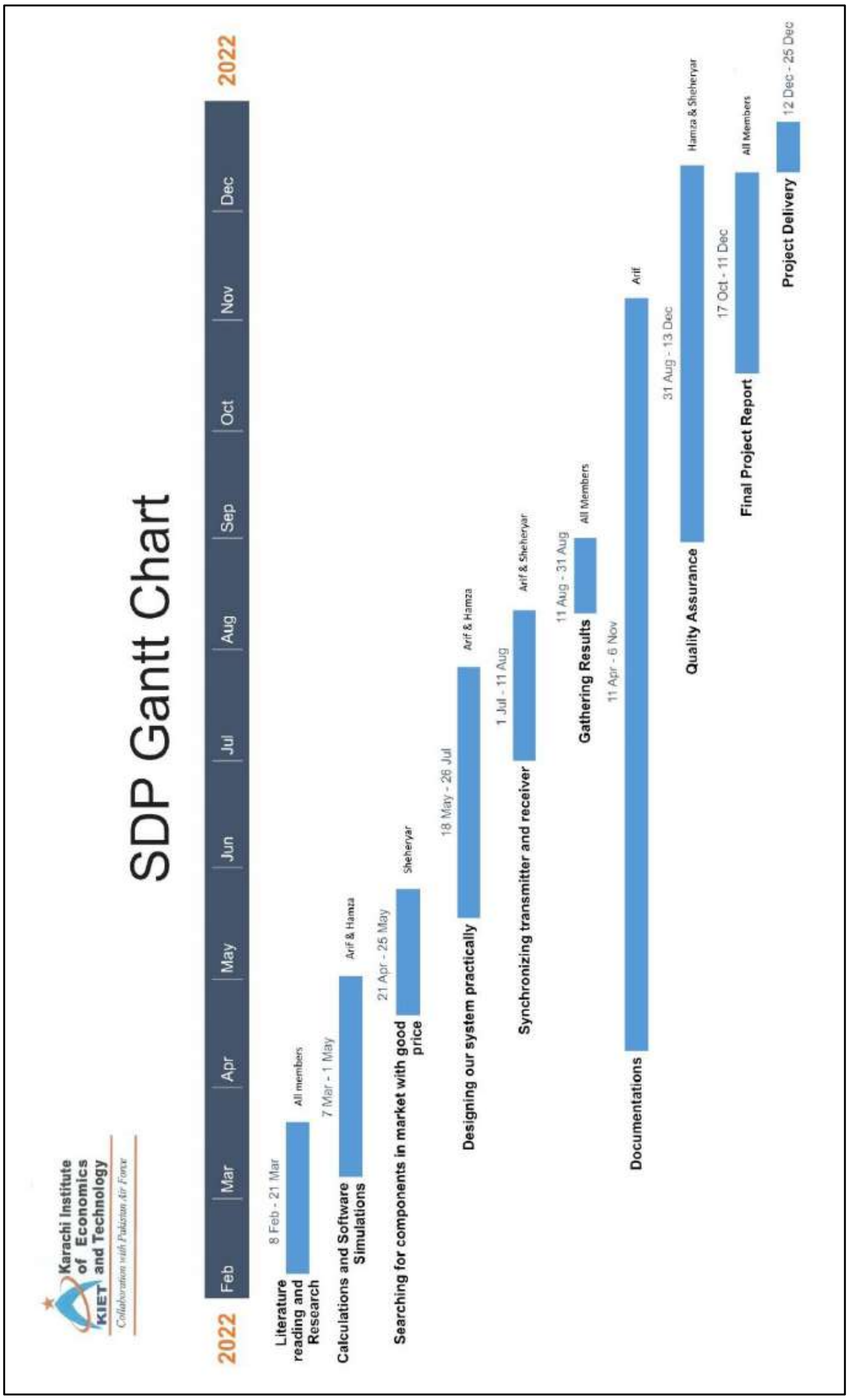
# PROJECT PLAN



# CHAPTER 1: INTRODUCTION TO THE WPT SYSTEMS AND THEIR ANALYSIS

## 1.1 Concept of Wireless Power Transmission

Wireless power transmission systems are emerging in the fields of electrical and electronics engineering, having vast applications in portable devices such as smartphones, laptops and tablets. Such portable devices are in constant need of recharging due to their small battery sizes and large energy consumption. Wired charging systems have hindered their property of mobility, as the user would be required to stick around the power socket. Wireless energy is already in use in different types of communication systems, which utilizes power to communicate between different devices.

In this project, a technique of transferring energy without using wires is proposed which will be capable of transferring 1 Watt of power through a distance of 1-5 meters, which will make it possible to charge our portable devices wirelessly and will remove the constraint of wired charging to be sticking around a socket and eventually will increase the portability and usability of the devices. This system consists of a transmitter module and a receiver module. The transmitter module consists of directional patch antennas to transmit power in a more sophisticated way to the receiver module to enhance efficiency and to remove losses. The receiver module consists of receiving patch antennas and a charge pump and rectifier circuit which will generate DC voltages which will be used to charge our devices.

This type of system will enhance the portability of the devices and will be used in the field of biomedical engineering and electric vehicles charging systems.

## 1.2 Literature Review

During the early 19th century, Nikola Tesla experimented with a system which was able to transfer the energy in air without any type of wire. This experiment of Tesla was a milestone in the field of wireless power transmission systems. Tesla wanted to make this world wireless. However, due to the lack of technology and resources, he was unable to implement it on a large scale. But now, electrical and electronics systems have made rapid growth and it is now possible to implement such systems and transfer the electricity wirelessly.

There is a rapid growth in portable devices such as smartphones, laptops, smartwatches etc., which requires an energy storing unit such as battery to make these devices operational [1]. However, the battery's storage capacity is not according to the requirement of these devices and makes the battery discharge in no time. Therefore, continuous wired charging of these devices has become a constraint in the portability [2]. And at the same time, there is also a limitation of dangling wires which reduces the safety of users. Therefore, there is a need for commercially designed wireless power transmission systems which will transfer power through distances [2].

To design a WPT system it is very important to make the system efficient by greater than 50% with a good range of 1 to 5 meters and should have manageable size of transmitter and receiver modules [3]. According to WHO, a higher amount of power cannot be transferred to observe safe transmission for human beings [4]. There are some frequency bands which are made available for research, medical and industrial purposes which can be used without any further permission or license.

## 1.3 Different types of WPT Techniques

In many techniques of wireless power transmission, the following three techniques stand out among them and a vast amount of research has been done on them in laboratories and in theory. The three techniques of WPT [18] are:

1. The first one is Laser aided technique, in which a laser beam is used to transmit energy at far distances.
2. The second is magnetic resonance technique, in which a mutual coupling method is used.
3. The third one is microwave technique, in this technique an oscillator is used to generate a wave of higher frequency and transmitted to the receiver using an antenna.

These techniques are further elaborated below:

### 1.3.1 Laser Aided Technique

In this technique, a laser beam containing photons is transmitted to the receiver unit. The receiver consists of photovoltaic cells that are used to convert the light energy of a specific wavelength into electrical energy.

In this method, the electricity is first converted into light or laser and then directed towards the receiver by using a converging phenomenon to converge the beam. The photovoltaic receiver receives the light and converts it back to electrical energy. This method is expensive and has very low efficiency. It can transmit energy to low ranges and can harm human tissues. This method is very difficult to implement [5].

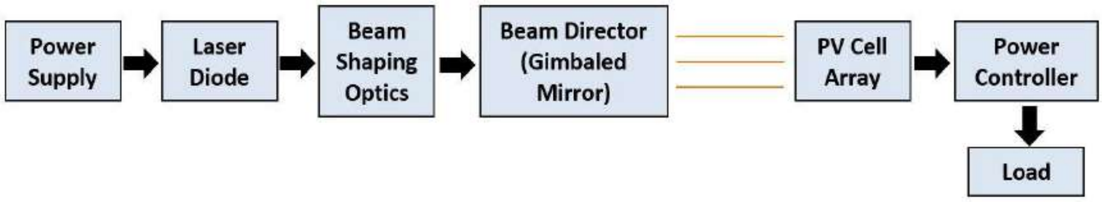



**Figure 1-1: Block Diagram of Laser Aided Technique**

### 1.3.2 Magnetic Resonance Technique

According to the Maxwell’s law, when coil carrying alternating current is placed near another coil, the alternating current produces electromagnetic fields in the vicinity of the first coil, and this field interacts with the second coil and induces alternating current in it [6].

The same phenomenon is used in this technique. The primary coil is given the power source and is placed near the secondary coil, the magnetic field of the primary interacts with the secondary coil due to mutual induction and induces an alternating current in it. The secondary circuit consists of a coil containing a rectifier and regulator circuit which rectifies the alternating current to direct current and then the regulator regulates the required output [7]. This technique has low efficiency and very low range. However, it doesn't damage human tissues.

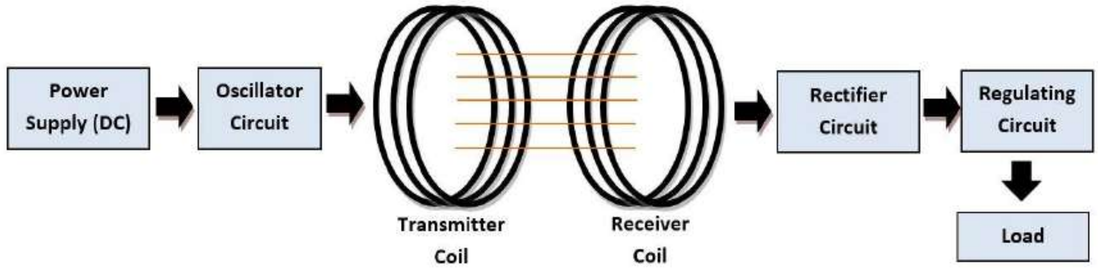



**Figure 1-2: Block Diagram of Magnetic Resonance Technique**

### 1.3.3 Microwave Technique

In this technique, an oscillator produces microwaves in frequency range of 1GHz-1000GHz, these waves are beamed towards the receiver using a directional transmitter antenna. The waves from the receiving antenna are converted back into electrical power and a rectifier circuit is used to convert these microwaves into direct current [5].

This technique is having maximum efficiency as compared to other techniques and having maximum range. However, it can also damage human tissue if safe transmission is not observed.

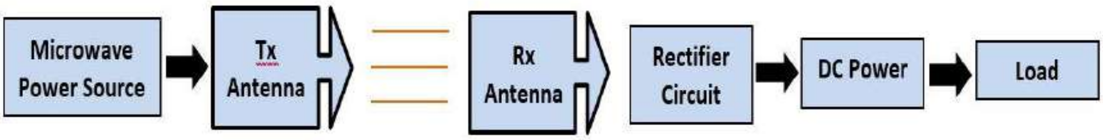



**Figure 1-3: Block Diagram of Microwave Technique**

### 1.3.4 Technique Selected

| Technique | Power Output | Distance | Cost | Efficiency | Effects on Humans |
|---|---|---|---|---|---|
| **Laser Aided** | < Kilowatts | Few Kilometers | Expensive | About 30% | May damage tissues if safety is compromised |
| **Magnetic Resonance** | Few Watts | < 1 meter | Expensive | About 40% | Doesn't damage tissues |
| **Microwave** | < Kilowatts | Few Kilometers | Mid-Range | About 55% | May damage tissues if safety is compromised |

**Table 1-1: Comparison between different WPT systems**

For this project, we have selected Microwave Transmission technique due to its properties on the other techniques. It has good efficiency and good range as compared to other techniques and can be implemented easily.

## 1.4 Microwave and a Myth

There is a myth that microwaves of every energy level are dangerous for human health. However, that's not true. Microwave radiations are electromagnetic (EM) rather than ionizing (as in nuclear). Mobile Phone signals, Television, Radio, GPS and other EM radiation passing through the human body daily and doing no harm. In this project, the transmitting power is under the limitation of FCC (Federal Communication Commission). Besides this, our antenna will radiate in a particular direction which is safe if there is no human in the path.

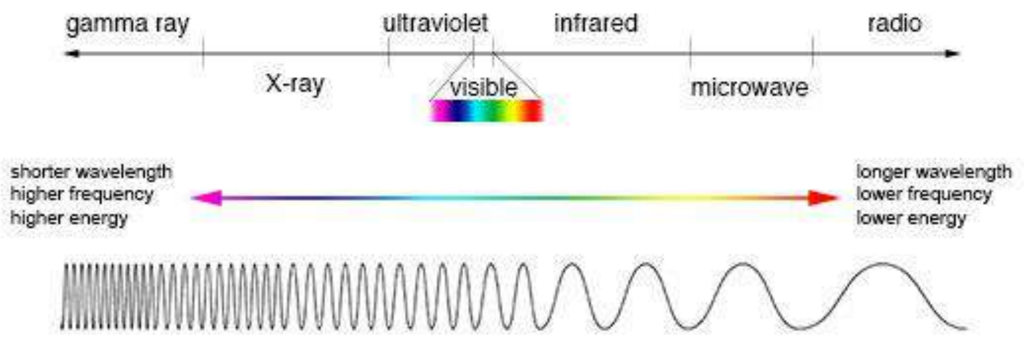



**Figure 1-4: Frequency and Wavelength Analysis**

## 1.5 Selection of Operating Frequency

To select operating frequency for the system, it is necessary to analyze its effect on the system efficiency and other aspects. The range analysis, avoidance of obstacles and antenna size is analyzed with respect to the operating frequency, below.

### 1.5.1 Range Analysis

Range is a very crucial aspect in this project, as to effectively transmit power to the distant receiver, the frequency should be opted very carefully.

Range is dependent on the wavelength of the waves. The larger the wavelength (smaller the frequency) of waves the farther distance it can cover.

### 1.5.2 Penetration in Obstacles

Penetration in obstacles is also a key aspect of this project. To ensure effective transmission while the obstacles are present in the path of transmitter and receiver the frequency should be opted carefully. Penetration of waves is dependent on the wavelength of the waves. The larger the wavelength (smaller the frequency) of waves the more it can pass any obstacle coming in its way.

### 1.5.3 Antenna Size

Antenna size is dependent on the operating frequency. By increasing the frequency the antenna size becomes smaller. The antenna length calculation formula is given as:

$$\lambda = \frac{c}{f}$$

$$length = \frac{\lambda}{4}$$

Where,

*c = speed of RF Signal (3x10^8 m/s)*

*f = frequency (2.4GHz)*

$\lambda$ *= wavelength*

*length = antenna length*

### 1.5.4 Frequency Selected

| Frequency | Range | Penetration in Obstacles | Antenna Size |
|---|---|---|---|
| **Increasing** | Decreasing | Decreasing | Decreasing |
| **Decreasing** | Increasing | Increasing | Increasing |

**Table 1-2: Frequency-Range-Antenna Size analysis**

From the above analysis, we can conclude that a mid-range of frequency should be used to tackle every problem. Hence, the operating frequency of 2.4GHz is chosen for this project, which is also an ISM band. And [8] also shows that 2.4GHz is the frequency which is having good efficiency for converting microwave power.

# CHAPTER 2: DESIGNING AND TESTING OF TRANSMITTER MODULE COMPONENTS

## 2.1 Overview of transmitter module components

The transmitter module consisted of a Voltage Controlled Oscillator VCO which is generating a power signal of operating frequency 2.4GHz. The signal is fed to a 1x2 power divider board and an antenna of 2 channels is deployed to ensure constructive interference at the end of the transmitter antenna. The transmitter antenna is two 2x2 matrices of rectangular patch elements. The power signal is amplified at the output of the power divider board by using a power amplifier of optimum gain.

## 2.2 Voltage-Controlled Oscillator

A voltage controlled oscillator or VCO is an electronic circuit which gives an output of a certain frequency depending upon the applied input controlling voltage. In the transmitter module, a voltage controlled oscillator labeled as COTS KVCO-2400 is deployed, which is a commercially available VCO. The VCO is operated with a 5V biasing voltage and a controlling voltage 0-5V for controlling the frequency of output signal. The VCO generates an RF signal of 2.4GHz with Power level of 7.6dBm. The signal is generated using varying voltages of 0.76V. The VCO deployed in Tx module is shown below:


**Figure 2-1: Voltage-Controlled Oscillator**

The spectrum analyzer shows the strength or power level of the generated power signal at 2.4GHz by VCO is shown below:

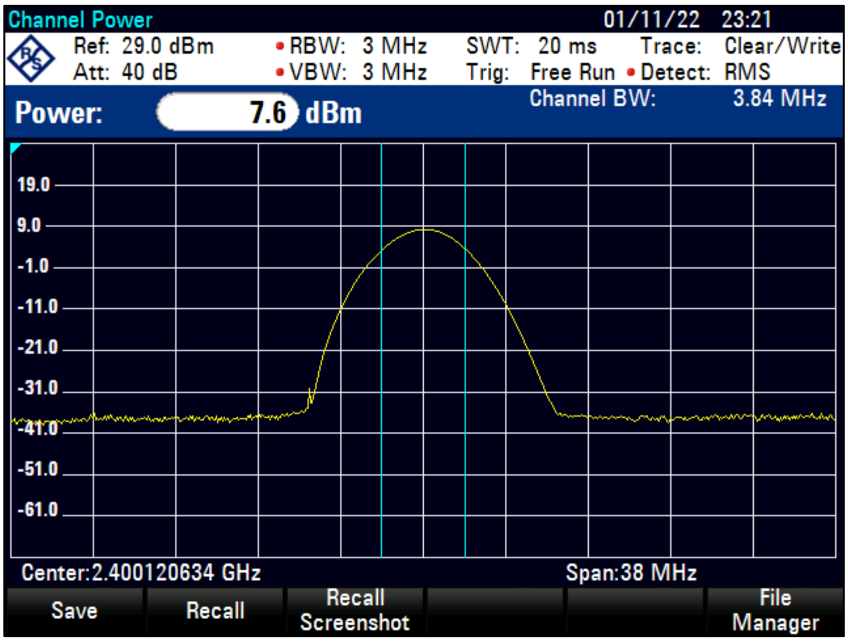


**Figure 2-2: Output Power of VCO at Spectrum Analyzer**

The input power given to the VCO and the varying voltages for controlling the frequency of output power signal is shown below:

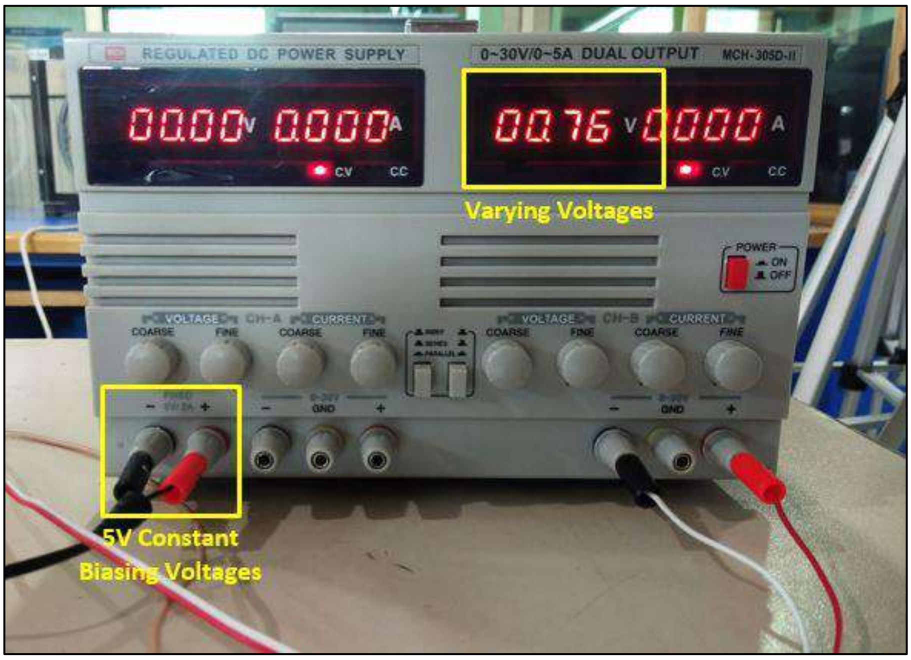


**Figure 2-3: Biasing and Varying Control Voltages of VCO**

## 2.3 1x2 RF Power Divider

The RF Power Divider circuit is used in the transmitter chain because if the power from VCO which is 7.6dBm is directly fed or amplified with only one amplifier of 40dB gain and fed to the transmitter antenna, then nothing or very less amount of power will be received at the receiver antenna. To overcome this problem a power divider circuit is used in such a way that the power from the VCO is fed to the divider input and then at both the outputs of the divider, there we connect amplifiers of 40dB gain. These signals are in parallel and in the same phase, so an optimum amount of power will be fed to the transmitter antenna.

The RF Power Divider board is designed at a center frequency of 2.4GHz using ADS software. This board is fabricated on an FR-4 substrate material with dielectric of 4.4F/m. Layout of the RF Divider Board is given below.

### 2.3.1 Simulated RF Divider

The RF Power divider is designed on ADS software. The input of the divider is 55.82Ω line and the output is also having impedance of 55.82Ω. Quarter wave technique is used to match the impedances of input and output. In quarter wave technique, a quarter wave line impedance is calculated according to the below formula.

$$Z_{line} = \sqrt{Z.Z_s}$$

Where,

$Z_{line}$ *= Impedance of a quarter wave line*

$Z_s$ *= Impedance of the input*

$Z$ *= Impedance of the output or patch*

In our case, a quarter wave line with 70.41Ω is used to match the impedance of 55.82Ω line and 100.09Ω line.

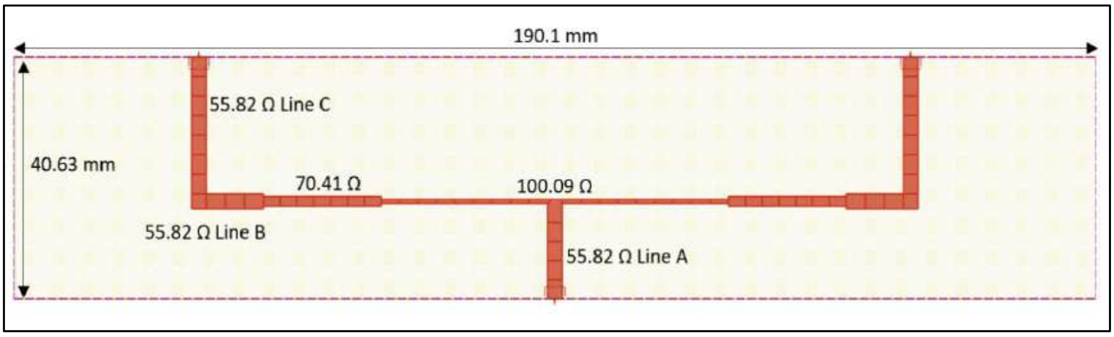



**Figure 2-4: Simulated 1x2 RF Power Divider Board**

The dimensions of each lines are given below:

| Dimensions | 55.82 Ω Line A | 55.82 Ω Line B | 55.82 Ω Line C | 70.41 Ω Line | 100.09 Ω Line |
|---|---|---|---|---|---|
| Length (L) in mm | 16 | 12.6 | 23 | 20.7 | 61 |
| Width (W) in mm | 2.55 | 2.55 | 2.55 | 1.62 | 0.709 |

**Table 2-1: Dimensions of 1x2 RF Power Divider**

#### 2.3.1.1 Simulated Sxx Parameter of Power Divider

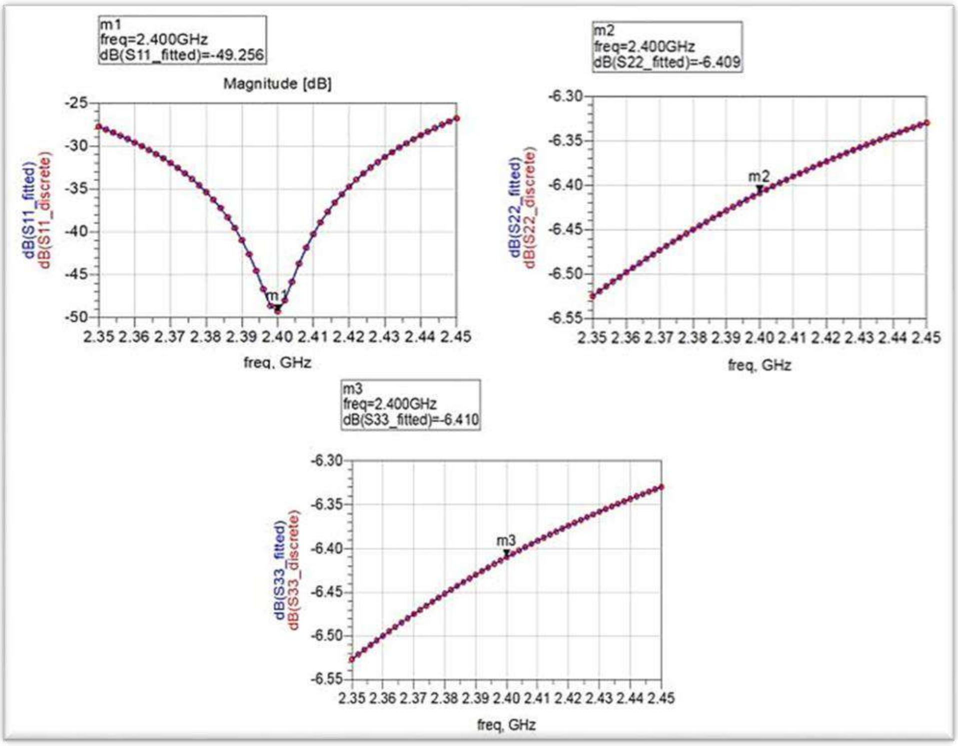



**Figure 2-5: Simulated S11, S22 and S33 parameters of 1x2 RF Power Divider**

Sxx parameter is the reflection coefficient of any antenna or divider. From the above results, we can conclude that the divider is having S11 of -49.25dB and the S22 of -6.40dB and S33 of -6.41dB. The S22 and S33 is same which indicates that the power reflected back from these ports are the same in magnitude, which is the ideal case.

### 2.3.1.2 Simulated Snm Parameter of Power Divider


**Figure 2-6: Simulated S12 and S13 parameters of 1x2 RF Power Divider**

Snm represents the power reflected from the port m to the port n. From the above results, both S12 and S13 are -3.51dB, so we can conclude that a very small amount of power is reflected back to the Port 1 or input port. Which indicates that the power divider is working efficiently.

### 2.3.1.3 Simulated Snm Phase Angles of Power Divider

The phase angle of S21 is -161.25 and S31 is -161.21. Both are almost same.

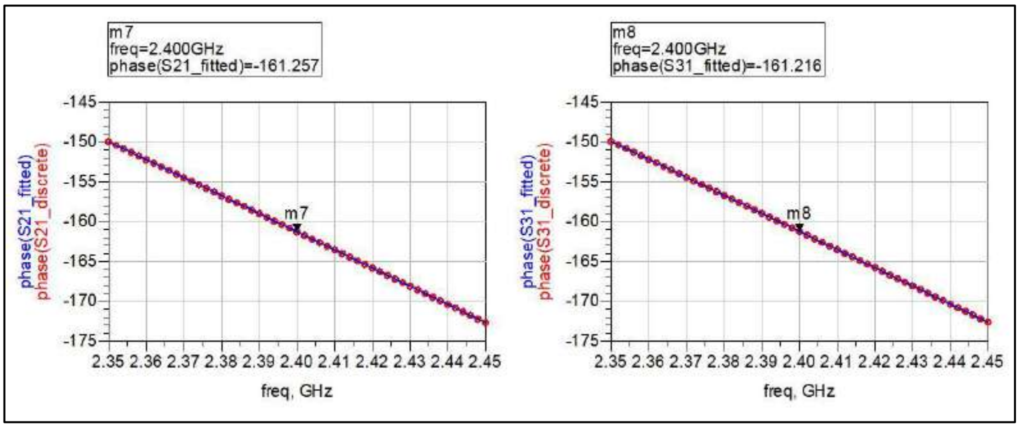



**Figure 2-7: Simulated S21 and S31 Phase Angles of 1x2 RF Power Divider**

### 2.3.2 Fabricated Power Divider

The RF power divider board is fabricated on FR-4 substrate. The results of the board are given below:

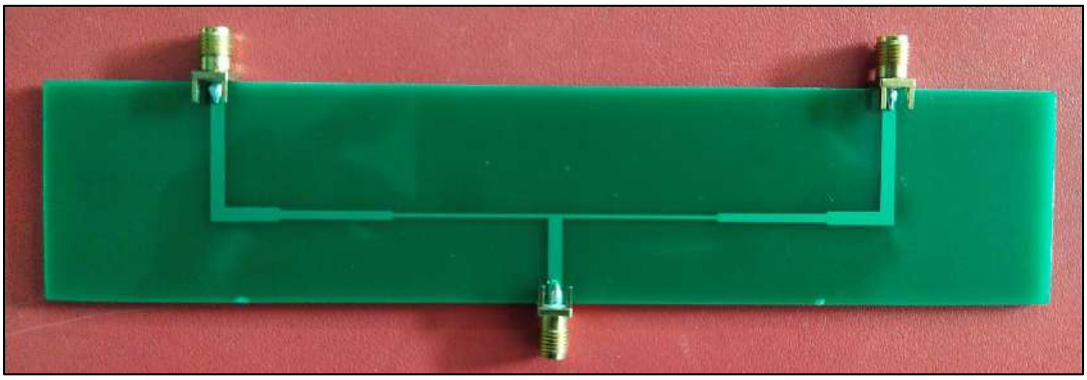


**Figure 2-8: Fabricated 1x2 RF Power Divider**

#### 2.3.2.1 Measured Sxx Parameter of Power Divider

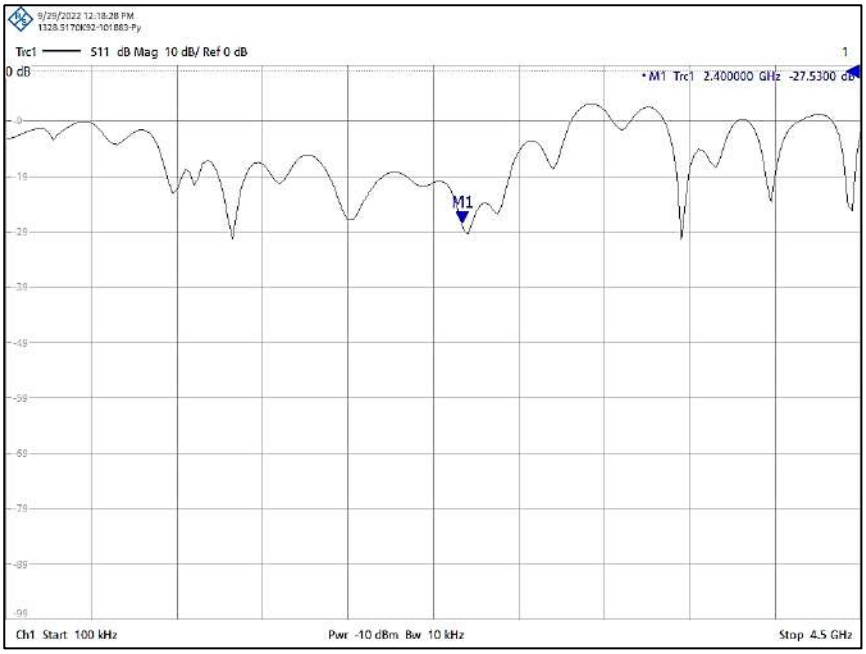



**Figure 2-9: Measured S11 Parameter of 1x2 RF Power Divider**

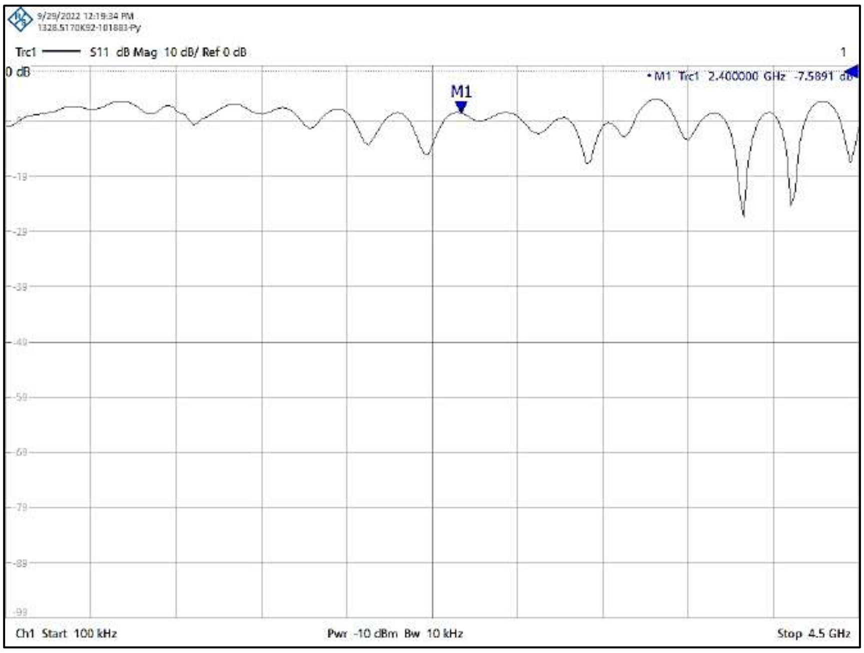



**Figure 2-10: Measured S22 Parameter of 1x2 RF Power Divider**

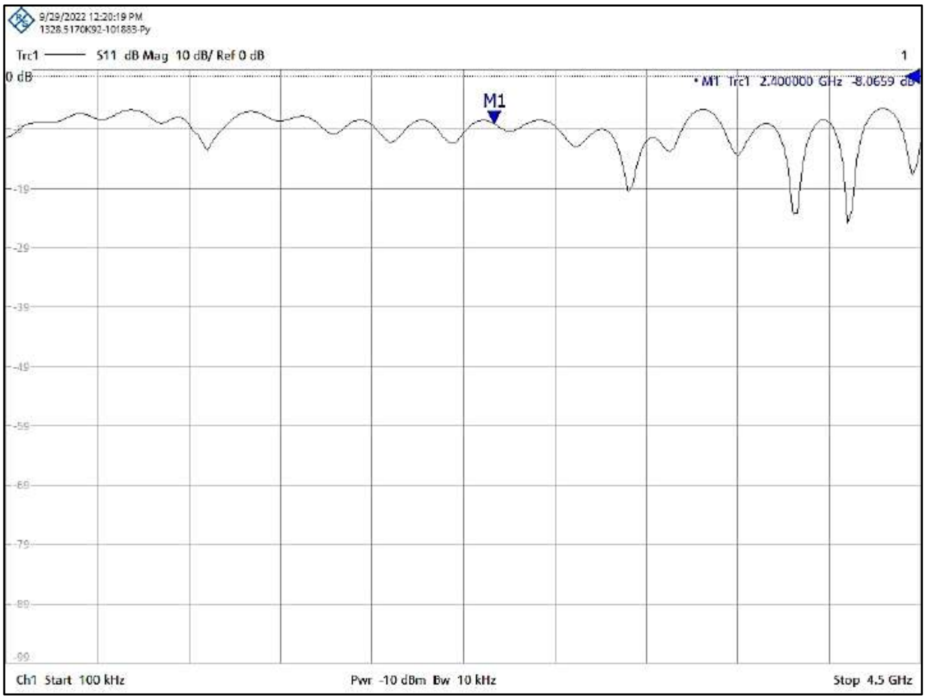



**Figure 2-11: Measured S33 Parameter of 1x2 RF Power Divider**

The Sxx-parameters of 1x2 RF Power Divider is measured on Vector Network Analyzer. From the above results, we can conclude that the measured S11 parameter of our divider board is -27.53dB. The S22 is -7.58dB and S33 is -8.06dB.

### 2.3.2.2 Measured Snm Parameter of Power Divider

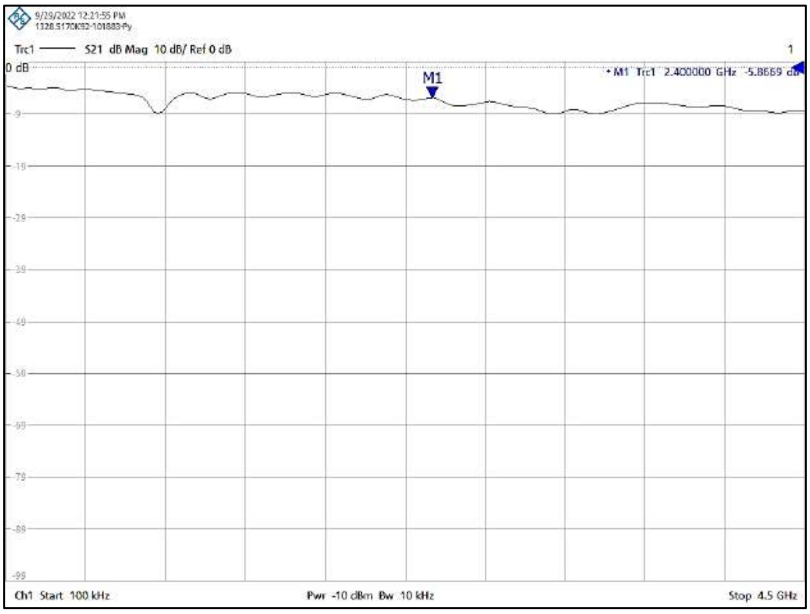



**Figure 2-12: Measured S12 Parameter of 1x2 RF Power Divider**

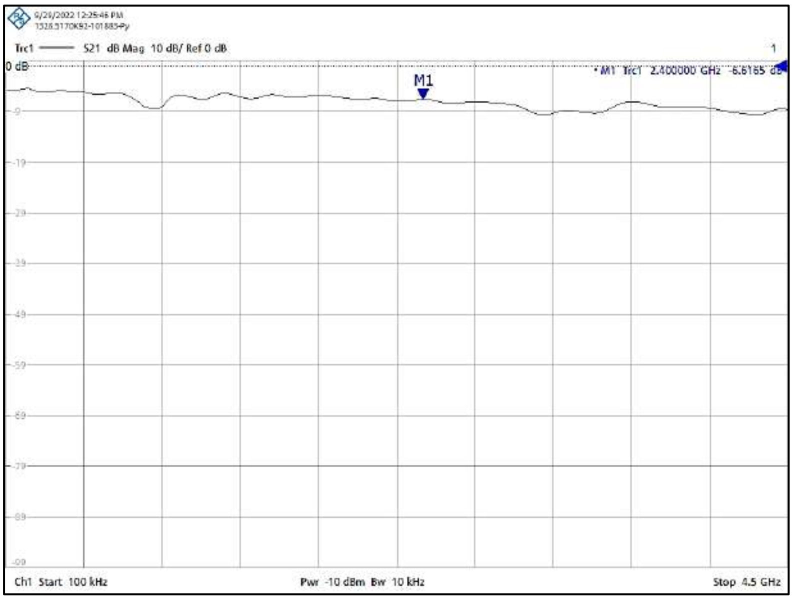



**Figure 2-13: Measured S13 Parameter of 1x2 RF Power Divider**

The Snm-parameters of 1x2 RF Power Divider is measured on Vector Network Analyzer. The above results show the S12 parameter to be -5.86dB and S13 parameters to be -6.61dB, which are in good numbers.

### 2.3.2.3 Measured Snm Phase Angles of Power Divider

The Snm phase angles of 1x2 RF Power Divider is measured on Vector Network Analyzer. The results show the S21 phase angle to be -148.53 degrees and S31 phase angle to be -144.44 degrees, which are almost same and in good numbers.

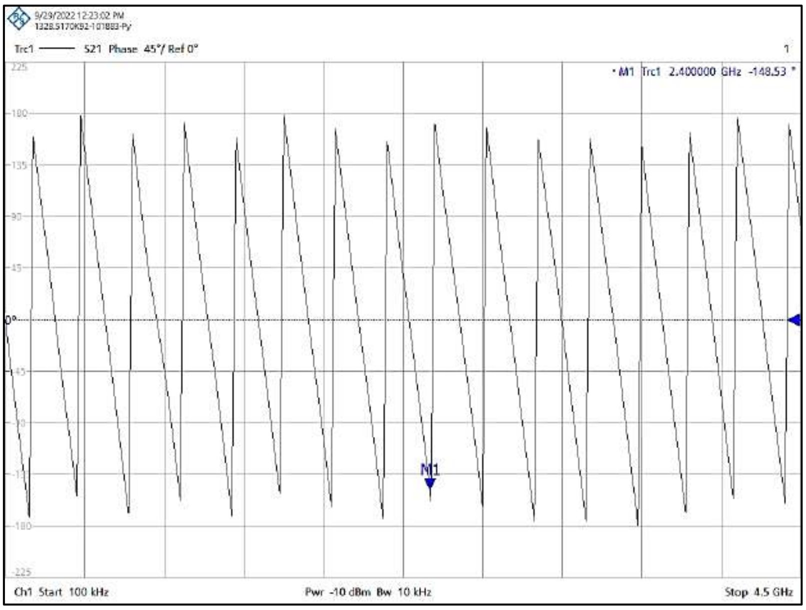



**Figure 2-14: Measured S21 Phase Angle of 1x2 RF Power Divider**

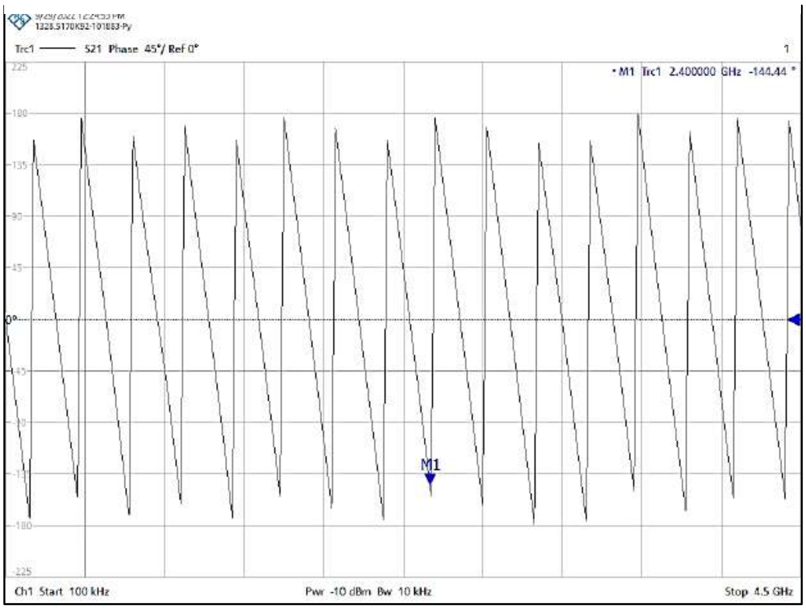



**Figure 2-15: Measured S31 Phase Angle of 1x2 RF Power Divider**

### 2.3.3 Comparing Simulated and Measured S Parameters of Power Divider

| Power Divider | S11 | S22 | S33 | S12 | S13 |
|---|---|---|---|---|---|
| **Simulated** | -49.25 | -6.40 | -6.41 | -3.51 | -3.52 |
| **Measured** | -27.53 | -7.58 | -8.06 | -5.86 | -6.61 |

**Table 2-2: Comparison between simulated and measured S-parameters of Power Divider**

From the above simulated and measured results, we can conclude that after fabricating the divider on FR-4 substrate, its S11 parameter is degraded a little bit due to the fact that the FR-4 substrate is a lossy substrate. However, the results are still in range and we can use the above fabricated board in the project.

## 2.4 Power Amplifier

The signal at the output of the Power divider board is not that powerful enough to be fed to the transmitter antenna without any type of further amplification, therefore Power amplifiers are used in the Transmitter module. The Power level of the signal from the VCO is 7.6dBm which is then divided in the power divider board by factor of 2 and made signals of 3.8dBm at both the output of the divider board. This power is very small to be fed directly to the transmitting antenna therefore, Power Amplifiers of 40dB gain are deployed at the outputs of the divider.


**Figure 2-16: Power Amplifier**

Power amplifier amplifies the Signal without amplifying the noise level and without changing the mode, structure and format of the signal. This amplifier works on a biasing voltage of 5V with 2A current. The gain graphs are given below:

### 2.4.1 Amplifier Rated Gain

According to the datasheet of Power Amplifier, it should give a gain of 40dB at 2.4GHz frequency.

### 2.4.2 Amplifier Measured Gain

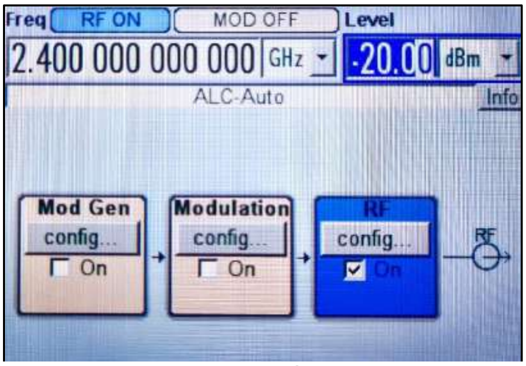


Figure 2-17: Input Power of Function Generator

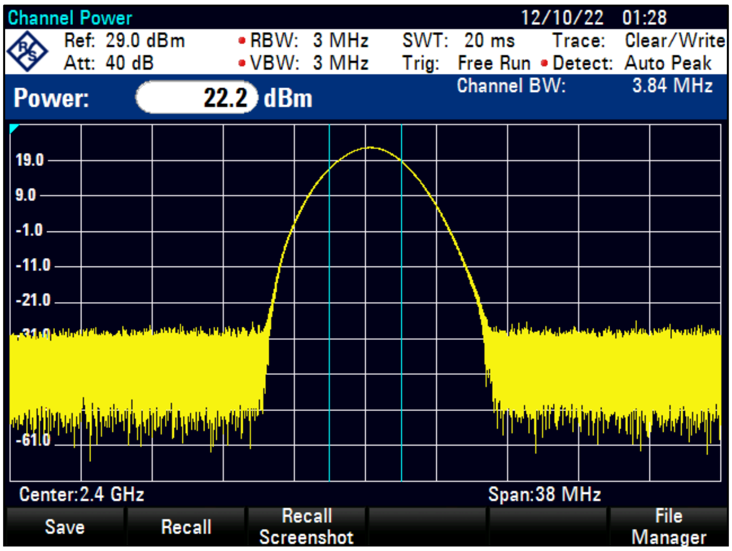


Figure 2-18: Output Power of Power Amplifier Analyzed at Spectrum Analyzer

The gain of the power amplifier is measured in real time by using a spectrum analyzer and a function generator. A signal of 2.4GHz with power level of -20dBm is given to the input of the power amplifier, which yields an output signal of 22.2dBm. Which proved that the gain of the amplifier is 42.2dB.

### 2.4.3 Amplifier Saturation Power Output

The amplifier maximum output power is 31.5dBm which is the saturation state or saturation power of the amplifier. It cannot amplify the signal more than that. So by giving the input of 3.8dBm of signal which is the case in the project, the amplifier goes into saturation and gives an output of 31.5dBm.

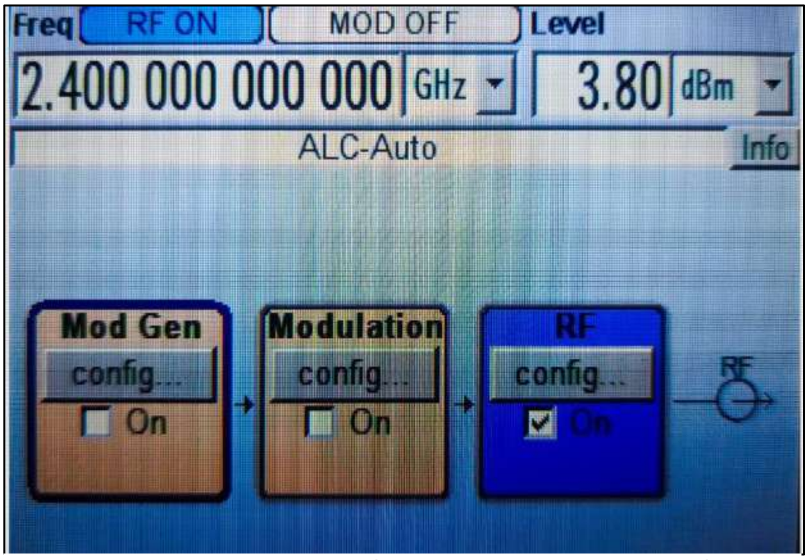



Figure 2-19: Input Power of 3.8dBm to the Power Amplifier

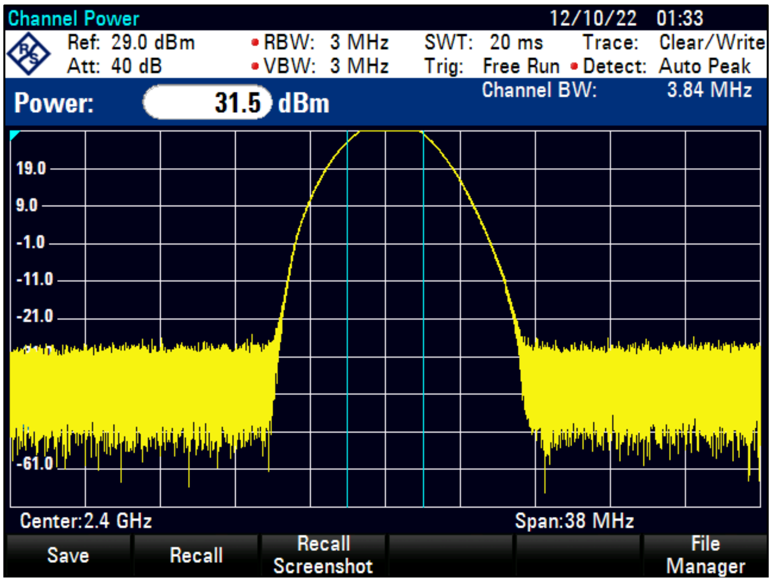



Figure 2-20: Output Power Analyzed at Spectrum Analyzer

## 2.5 Selection of Transmitter Antenna

There are various types of antennas available, however for our application, it is necessary to choose a suitable one which could perform well in this project. Major antenna types are:

### 2.5.1 Omni-directional Antenna

An Omni-directional antenna is a type of antenna which radiates or receives signals with the same power in every direction [17]. The radiation pattern of these types of antennas consists of 360 degrees.

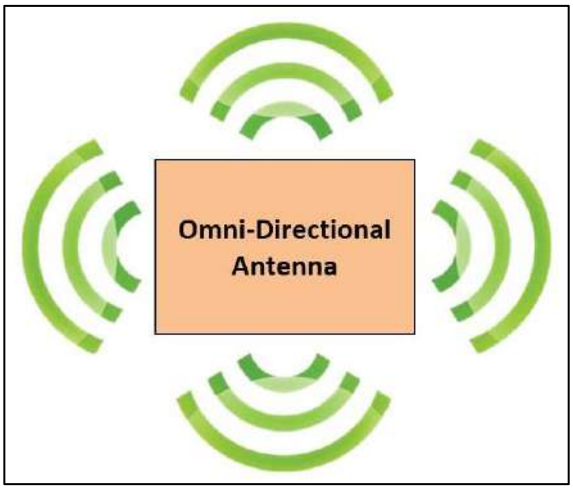



**Figure 2-21: Omni-directional Antenna Radiation Pattern**

### 2.5.2 Uni-directional Antenna

A unidirectional antenna is a type of antenna which can converge its radiation beam in one direction, which eventually makes the signal strong enough to travel long distances [17]. It can also reduce the interference from other directions.

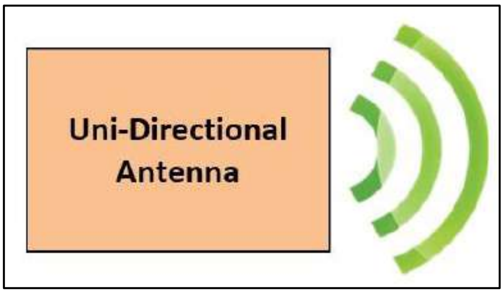



**Figure 2-22: Uni-Directional Antenna Radiation Pattern**

### 2.5.3 Antenna Selected

Since we need more power at long distance and only in the direction of the receiver module, therefore a unidirectional antenna is chosen for this project. Unidirectional antennas are also in large numbers. However, we have chosen Microstrip Patch Antennas due to their low cost, high efficiency, low return loss and they are easy to fabricate [16].

## 2.6 Microstrip Patch Antenna

Microstrip patch antennas are low cost, high efficiency, lightweight and easy to fabricate antennas. These antennas are small in size and are used in communications systems, Radar systems and mobile phones etc. A high gain and high directivity can be achieved using this antenna. These antennas can be designed using different shapes such as circular, rectangular or any custom shape.

Microstrip antenna contains 3 layers, the upper and lower layers are conducting metals like copper. While the middle layer is a substrate which doesn't conduct. The upper layer is in the shape of our proposed antenna.


**Figure 2-23: Microstrip Patch Antenna Substrate**

In the Microstrip patch antennas, the fringing fields are responsible for the radiation. The fringing fields around the antenna can help explain why the microstrip antenna radiates. Consider the side view of a patch antenna shown below. This can be seen as a capacitor in which two parallel metal plates are separated by an electrolyte and an electrostatic field is created between them. According to Maxwell, this E-Field leads to generation of magnetic fields and finally an Electromagnetic wave is generated and we call it Radiation in case of Antennas.

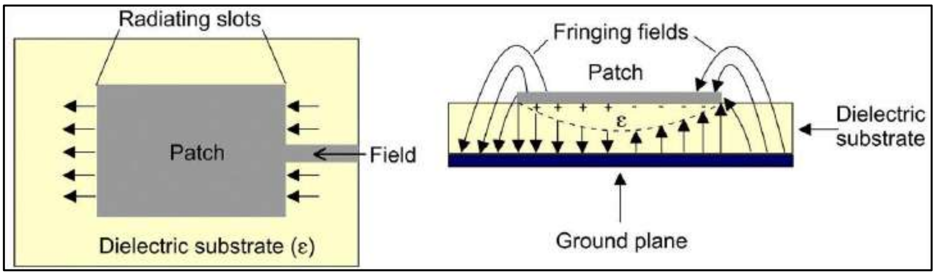


**Figure 2-24: Fringing Fields and Radiating Edges of Patch Antenna**

### 2.6.1 Design Theory

Microstrip Patch Antennas are designed on a substrate with smaller relative permittivity. The smaller the relative permittivity, the better the substrate. In this project, the antenna is designed on a FR-4 substrate with dielectric of 4.4 F/m. This substrate is chosen because it is easily available as well as it is cost effective [14]. The height of the substrate also plays an important role in the working of the antenna. The substrate height decides the bandwidth as well as the dimensions of the patch element. The more the height the better the bandwidth as well as the smaller the size of the patch element. The height of the substrate which we used in this project is:

**h = 1.6mm**

This height is chosen because it is easily available. So the design parameters of the antenna are:

| Parameters | Values |
|---|---|
| Operating Frequency | 2.4 GHz |
| Substrate | FR-4 |
| Di-electric Constant | 4.4 F/m |
| Height of Substrate | 1.6 mm |
| Loss Tangent TanD | 0.008 |
| Copper Thickness | 0.035 mm |

**Table 2-3: Proposed Antenna Substrate Parameters**

### 2.6.2 Dimensions of Proposed Antenna

For this project, rectangular microstrip patch antennas are designed and tested. The dimensions of the antenna element is calculated by using the formulae given in the Balanis Book [3], which are as follows:

$$W = \frac{c\ (\frac{\varepsilon_r+1}{2})^{\frac{-1}{2}}}{2f_o}$$

$$L = \left[\frac{c}{2.f_o.\varepsilon^{\frac{-1}{2}}}\right] - 2\Delta L$$

$$\varepsilon_e = \left(\frac{\varepsilon_r+1}{2}\right) + \left(\frac{\varepsilon_r-1}{2}\right)\left[1 + 12\frac{h}{W}\right]^{\frac{-1}{2}}$$

$$\frac{\Delta h}{L} = 0.412\ \frac{(\varepsilon_r+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_r-0.258)\left(\frac{W}{h}+0.8\right)}$$

Where,

$c$ = speed of RF Signal (3x10^8 m/s)

$f_o$ = Operating frequency (2.4GHz)

$\mathcal{E}_r$ = Relative permittivity of the substrate (4.4F/m)

$\varepsilon_e$ = Effective permittivity of the substrate material

$W$ = Patch width

$h$ = Substrate thickness (1.6mm)

$L$ = Patch Length

$\Delta L$= the extra length provided by the patch's bordering fields on both sides

By doing the calculations, we will get the width of the patch element $W$ = 38.03mm and the Length of the patch element $L$ = 29.44mm. However, physical parameters don't necessarily have to be the same, because we always tweak the antenna parameters for best results.

The antenna dimensions are also confirmed using an online tool (emtalk) to find out the Length and Width of our proposed antenna. The impedance at the edge of the patch element for the specific dimensions is found out to be:

$$Z = 243\Omega$$

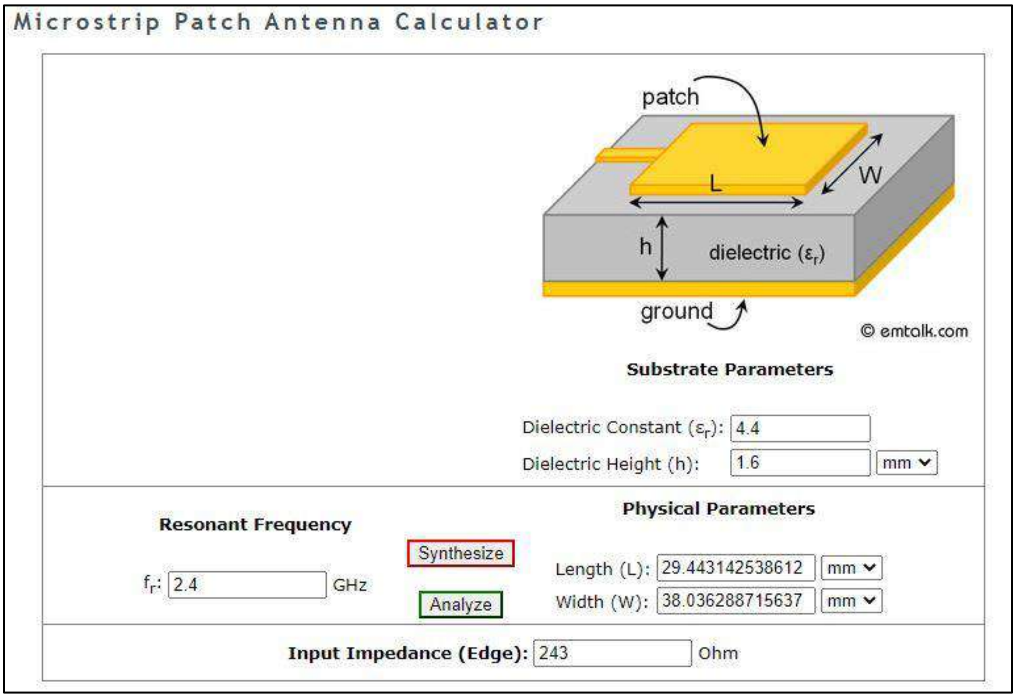



**Figure 2-25: Patch Dimensions at Online calculator emtalk**

Since, the source which we are using in this project is having both input and output impedances of 50Ω therefore, it is necessary to match the impedance of both the element and the source through some means. For doing so, two techniques are assessed in this project, and the one with good results will be opted.

### 2.6.3 Different Feeding Techniques and their Analysis

Choosing the feeding technique for an antenna is a very important part. The feeding technique should be chosen very carefully as the whole impedance matching is dependent over this part. If the impedance of the antenna is matched with the impedance of the source then maximum power will be transferred from the source to the antenna [12] and eventually the antenna will transmit more power efficiently. The feeding techniques [15] which we will be comparing in this project are:

1) Quarter Wave Feeding Technique
2) Inset Feed Feeding Technique

#### 2.6.3.1 Analysis of Quarter Wave Feeding Technique Antenna

From the calculations done above for the patch dimensions we got the results of *W*=38.03mm and *L*=29.44mm and the impedance at the edge of the patch is $Z$ = 243Ω. Since the edge is having impedance of 243Ω while the source is having impedance of $Z_S$=50Ω, we need to match this difference by some means. In this case, a quarter wave feeding technique or a quarter wave line is used. The calculations for this line is given below:

$$Z_{line} = \sqrt{Z.Z_S}$$

Where,

$Z_{line}$ = *Impedance of a quarter wave line*

$Z_S$ = *Impedance of the source*

$Z$ = *Impedance of the load or patch*

From the above formula, we have calculated the impedance of the quarter wave line to be 110.22Ω. And for this impedance, the dimensions for the line is calculated using an online microstrip line calculator (emtalk), which yielded the dimensions to be W=0.53mm and L=18.10mm.

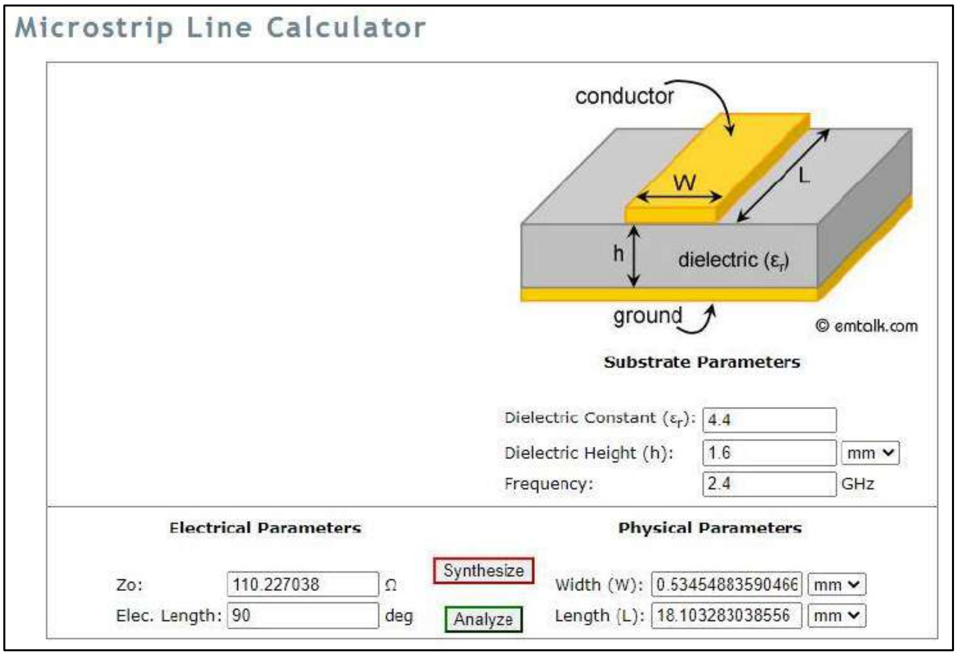



**Figure 2-26: 110.22Ω Line Dimensions at Online Calculator emtalk**

Since the source is having a 50Ω of impedance, therefore a 50Ω line is also attached at the end of the quarter wave line to match the impedance. The dimensions of the 50Ω input is found out from an online calculator (emtalk), which yielded the dimensions to be W=3.05mm and L=17.12mm.

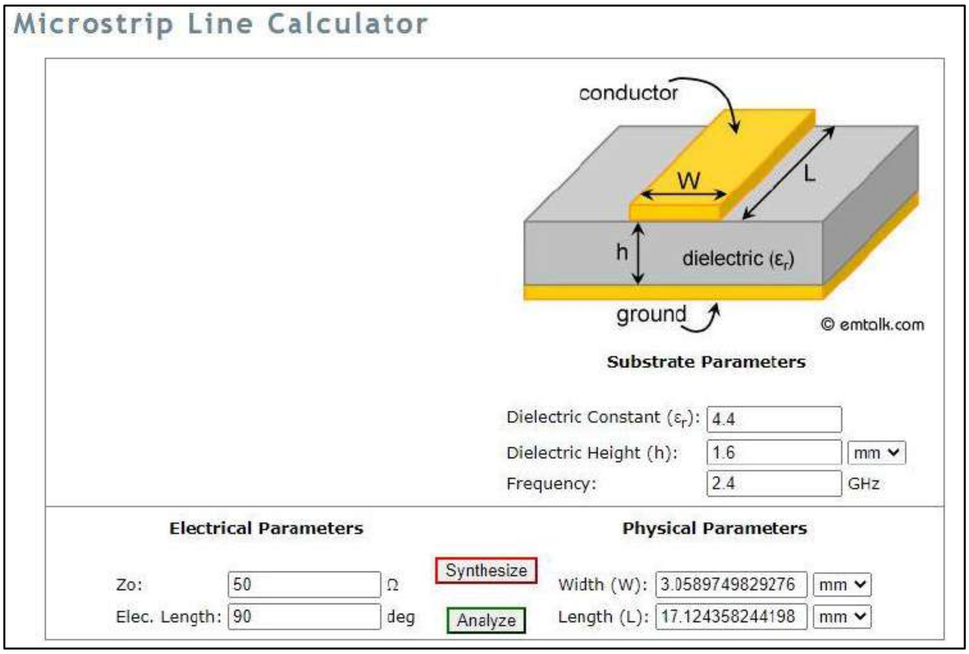



**Figure 2-27: 50Ω Line Dimensions at Online Calculator emtalk**

- **Since, it is stated above that the physical dimensions don't necessarily need to be the same however, these results are taken as a reference for designing, as we always tweak the antenna dimensions for perfect results. Therefore, the physical antenna dimensions and results are given below.**

#### 2.6.3.1.1 Simulated Single Element Quarter Wave Antenna

The simulated antenna on ADS software is given below:

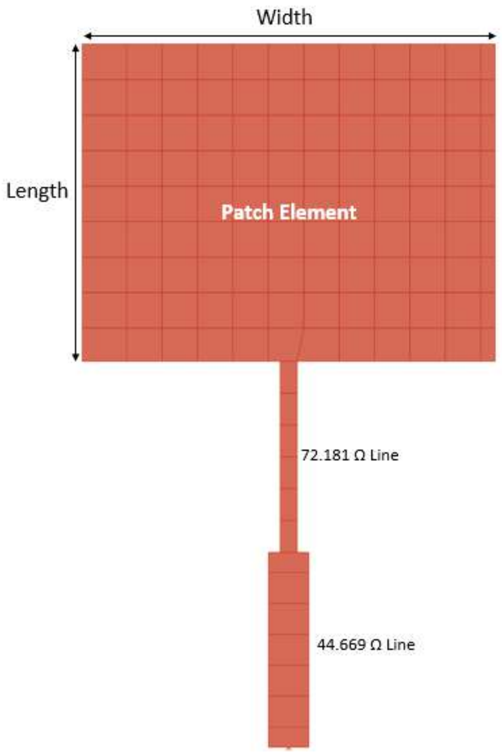



**Figure 2-28: Simulated Single Element Quarter Wave Antenna**

| Dimensions | Patch Element | 44.669 Ω Line | 72.181 Ω Line |
|---|---|---|---|
| **Length (L) in mm** | 29.15 | 17.8845 | 17.53 |
| **Width (W) in mm** | 38.04 | 3.7 | 1.55 |

**Table 2-4: Dimensions of Single Element Quarter Wave Antenna**

#### 2.6.3.1.2 Simulated S11 Parameter of Single Element Quarter Wave Antenna

The simulated S11 parameter of a single element quarter wave feeding antenna is found to be -28.845dB. Given below:

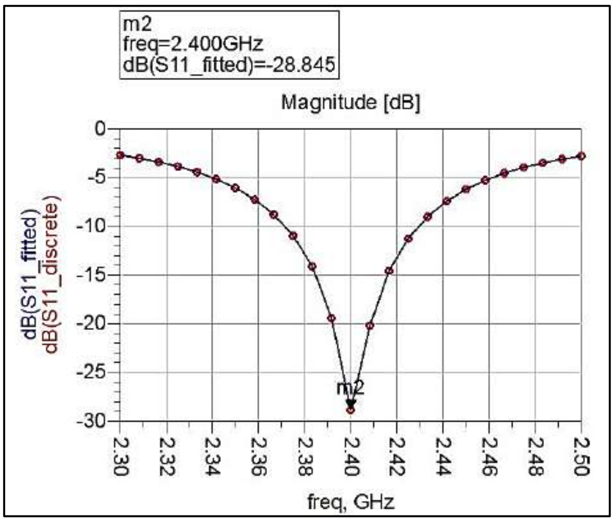



**Figure 2-29: Simulated S11 Parameter of Single Element Quarter Wave Antenna**

#### 2.6.3.1.3 Simulated Smith Chart of Single Element Quarter Wave Antenna

The simulated Smith Chart impedance normalized at 50Ω of a single element quarter wave feeding antenna is found to be 1.075-j0.008Ω. Given below:

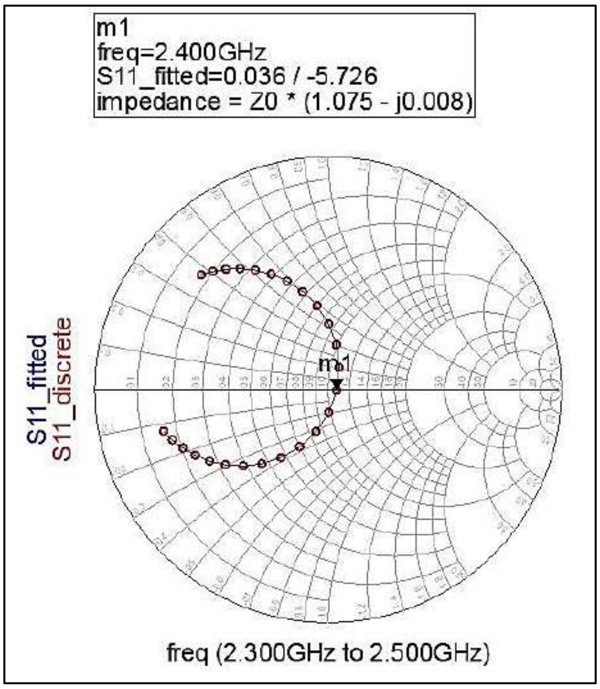



**Figure 2-30: Simulated Smith Chart of Single Element Quarter Wave Antenna**

### 2.6.3.1.4 Simulated Gain, Directivity and Efficiency of Single Element Quarter Wave Antenna

The simulated directivity, gain and efficiency is found to be 6.179dBi, 1.78dBi and 36.3175% respectively. Given below:

| Antenna Parameters | |
|---|---|
| Frequency (GHz) | 2.4 |
| Input power (Watts) | 0.00249674 |
| Radiated power (Watts) | 0.000906753 |
| Directivity(dBi) | 6.17905 |
| Gain (dBi) | 1.78021 |
| Radiation efficiency (%) | 36.3175 |

**Figure 2-31: Simulated Directivity, Gain and Efficiency of Single Element Quarter Wave Antenna**

### 2.6.3.1.5 Simulated Radiation Pattern of Single Element Quarter Wave Antenna

The Simulated 2D and 3D radiation patterns are given below:

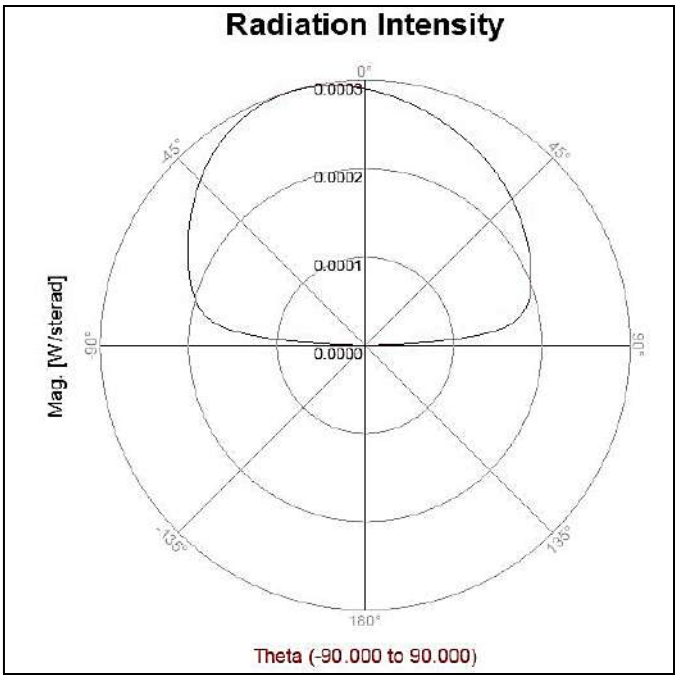



**Figure 2-32: Simulated 2D Radiation Pattern of Single Element Quarter Wave Antenna**

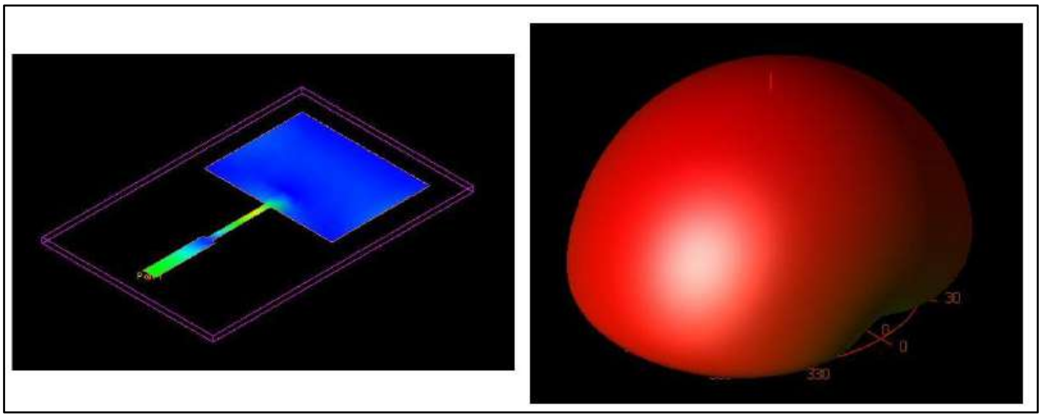


**Figure 2-33: Simulated 3D Radiation Pattern of Single Element Quarter Wave Antenna**

From the radiation pattern, we can have an idea that the antenna is designed very efficiently so that there are no side lobes which can lose our signal in other or none wanted directions [11]. The whole signal is converged into one direction and so that the signal will travel a longer distance.

### 2.6.3.2 Analysis of Inset Feed Feeding Technique Antenna

From the calculations done above for the patch dimensions we got the results of W=38.03mm and L=29.44mm and the impedance at the edge of the patch is 243Ω. However, the more we go at the center of the patch the more the impedance of the patch reduces.

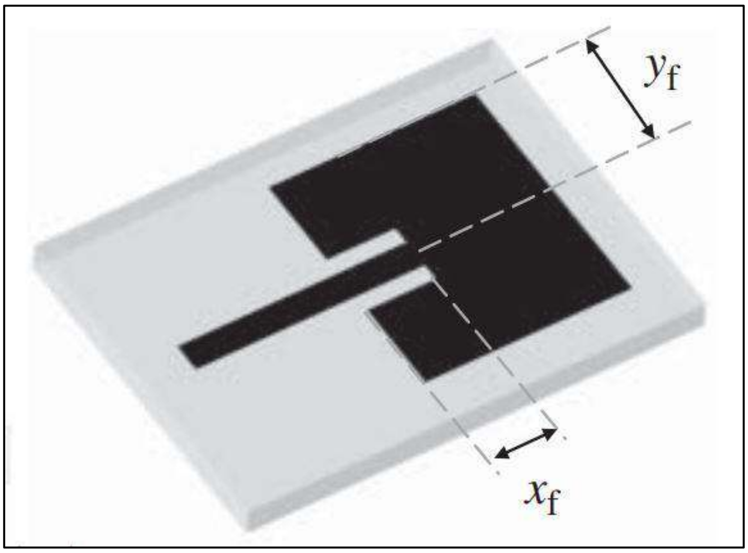



**Figure 2-34: Inset Feed Antenna**

To match the impedance of the source 50Ω with the patch, we calculate the point in the patch where the impedance is 50Ω so that the matching is done efficiently. The calculations for the matching point is done by using the below formulas [13]:

$$y_f = \frac{W}{2}$$

$$x_f = \frac{L}{2} \text{ x } \frac{c_7 \varepsilon_r{}^7 + c_6 \varepsilon_r{}^6 + c_5 \varepsilon_r{}^5 + c_4 \varepsilon_r{}^4 + c_3 \varepsilon_r{}^3 + c_2 \varepsilon_r{}^2 + c_1 \varepsilon_r + c_0}{10^4}$$

Where,

$x_f$ = *distance from bottom edge*

$y_f$ = *distance from side edge*

$c_7$ = *0.001699,* $c_6$ = *0.13761,* $c_5$ = *-6.1783,* $c_4$ = *93.187,* $c_3$ = *-682.69,* $c_2$ = *2561.9,* $c_1$ = *-4043,* $c_0$ = *6697*

From the above formulas, the results are $y_f$ = 19.02mm and $x_f$ = 9.042mm. At this point we will be having the patch impedance of 50Ω which can be matched with the source impedance of 50Ω through a 50Ω microstrip line. The 50Ω line is calculated above.

- **Since, it is stated above that the physical dimensions don't necessarily need to be the same however, these results are taken as a reference for designing, as we always tweak the antenna dimensions for perfect results. Therefore, the physical antenna dimensions and results are given below.**

#### 2.6.3.2.1 Simulated Single Element Inset Feed Antenna

The simulated inset feed antenna is shown below:

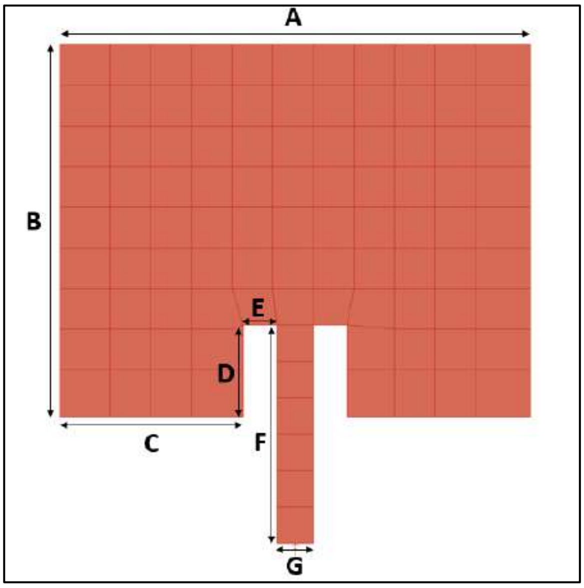



**Figure 2-35: Simulated Inset Feed Single Element Antenna**

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| **Length in mm** | 38.04 | 30.06 | 14.8297 | 7.4126 | 2.6803 | 17.624 | 3.02 |

**Table 2-5: Dimensions of Inset Feed Single Element Antenna**

#### 2.6.3.2.2 Simulated S11 Parameter of Single Element Inset Feed Antenna

The simulated S11 parameter of a single element inset feed antenna is found to be -57.78dB. Given below:

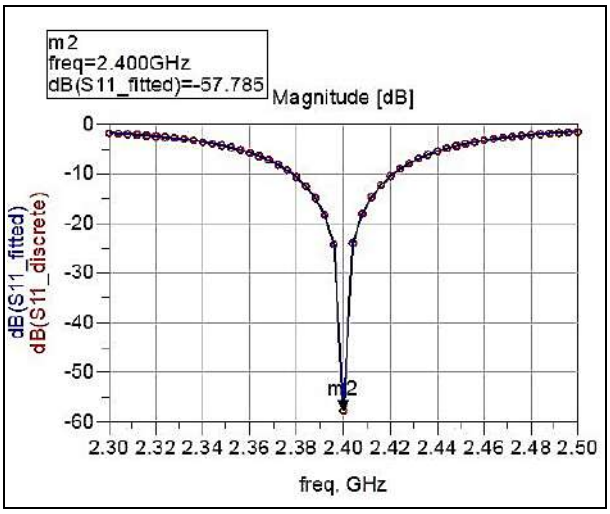



**Figure 2-36: Simulated S11-parameter of Inset Feed Single Element Antenna**

### 2.6.3.2.3 Simulated Smith Chart of Single Element Inset Feed Antenna

The simulated Smith Chart impedance normalized at 50Ω of a single element inset feed antenna is found to be 0.999+j0.002Ω. Given below:

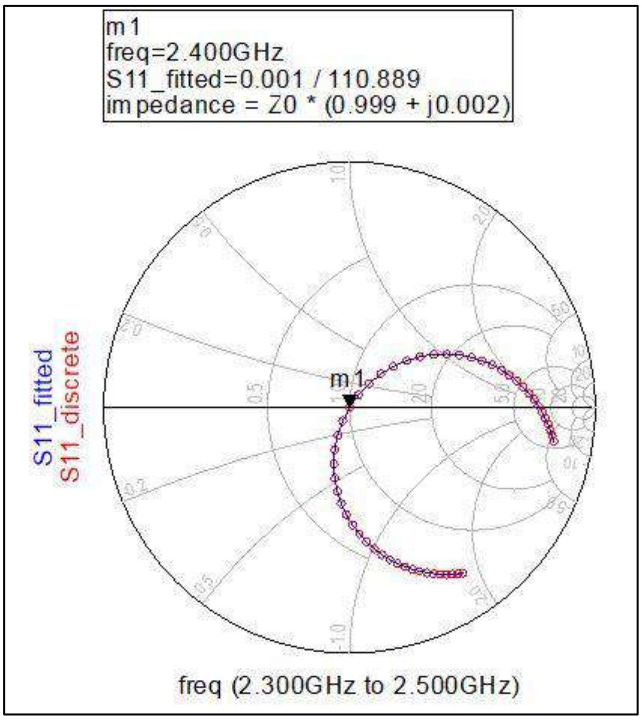



**Figure 2-37: Simulated Smith Chart of Inset Feed Single Element Antenna**

### 2.6.3.2.4 Simulated Gain, Directivity and Efficiency of Single Element Inset Feed Antenna

The simulated directivity, gain and efficiency is found to be 6.433dBi, 3.348dBi and 49.15% respectively. Given below:

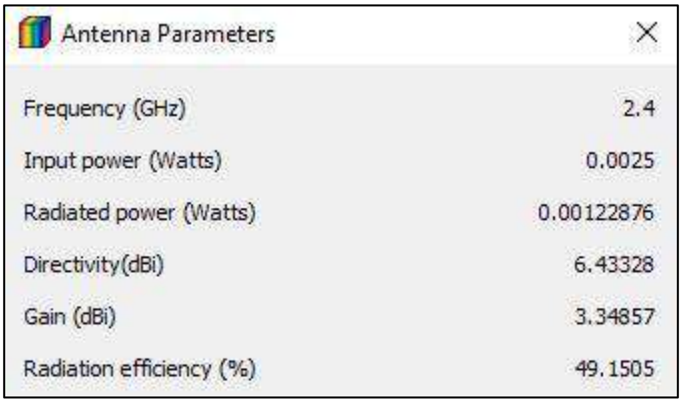



**Figure 2-38: Simulated Directivity, Gain and Efficiency of Inset Feed Single Element Antenna**

#### 2.6.3.2.5 Simulated 2D and 3D Radiations of Single Element Inset Feed Antenna

The 2D and 3D simulated radiation pattern is given below:

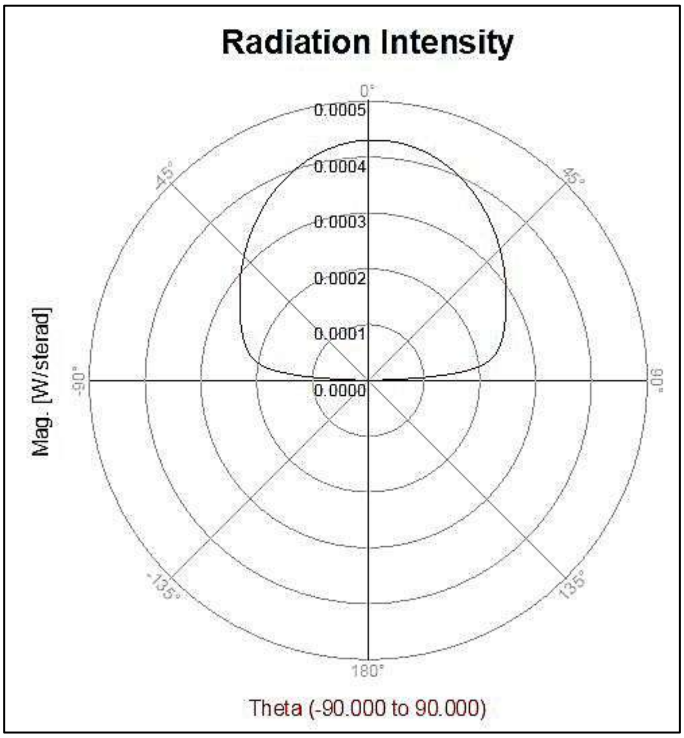



**Figure 2-39: Simulated 2D Radiation Pattern of Inset Feed Single Element Antenna**

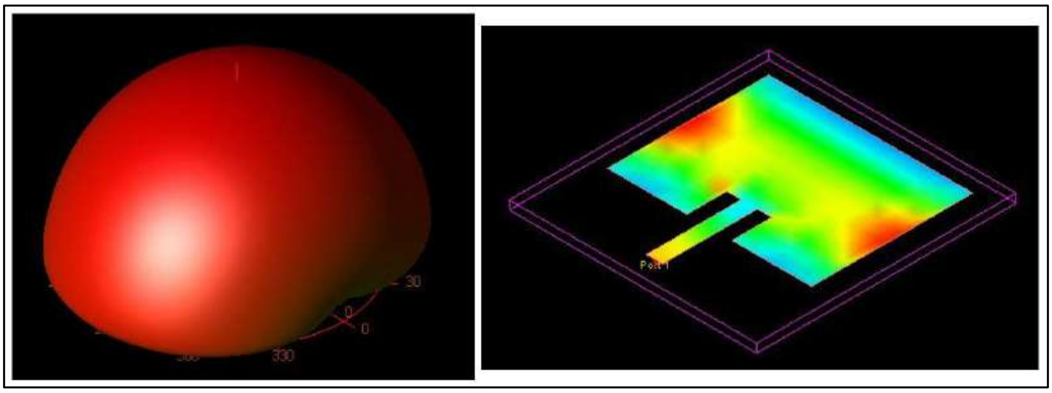


**Figure 2-40: Simulated 3D Radiation Pattern of Inset Feed Single Element Antenna**

From the radiation pattern, we can have an idea that the antenna is designed very efficiently so that there are no side lobes which can lose our signal in other or none wanted directions [11]. The whole signal is converged into one direction and so that the signal will travel a longer distance.

#### 2.6.3.3 Comparing Results and Choosing Best Feeding Technique

| Antenna | Frequency | S11 (dB) | Gain (dBi) | Directivity (dBi) | Efficiency (%) | Normalized Smith Chart Impedance (Ω) |
|---|---|---|---|---|---|---|
| **Quarter Wave** | **2.4 GHz** | -28.845 | 1.78 | 6.179 | 36.3175 | 1.075-j0.008 |
| **Inset Feed** | **2.4 GHz** | -57.78 | 3.348 | 6.433 | 49.15 | 0.999-j0.002 |

**Table 2-6: Comparison between Quarter Wave and Inset Feed Antenna**

From the results above, we can conclude that the inset feed feeding technique is having good directivity, gain and efficiency with a good value of return loss (S11) as compared to the quarter wave feeding technique [10]. Therefore, we have chosen the Inset Feeding Technique for our proposed antenna for matching the impedance. Therefore, the inset feeding antenna is fabricated and the physical results are tested using Vector Network Analyzer.

### 2.6.4 Fabricated Single element Inset Feed Antenna

The single element inset feed antenna is fabricated on an FR-4 substrate material, and analyzed its working.

**Figure 2-41: Fabricated Inset Feed Single Element Antenna**

#### 2.6.4.1 Measured S11 Parameter

The return loss (S11) of the fabricated single element inset feeding technique antenna is measured on a Vector Network Analyzer and the results are attached:

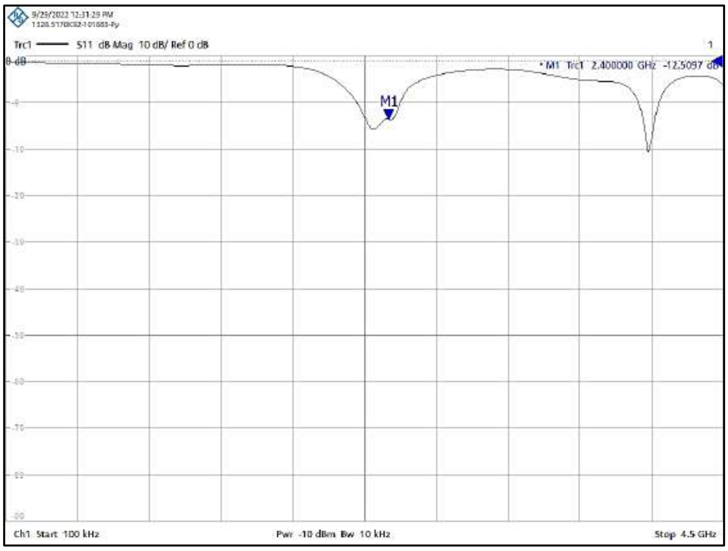



**Figure 2-42: Measured S11-parameter of Inset Feed Single Element Antenna**

From the above graph, the S11 parameter is found to be -12.50dB which is less than -10dB. So the S11 parameter is in the range of acceptable value.

#### 2.6.4.2 Measured Smith Chart

The measured smith chart normalized impedance at 50Ω of the single element inset feed antenna is analyzed using Vector Network Analyzer and found to be 0.662-j0.221Ω. Given below:

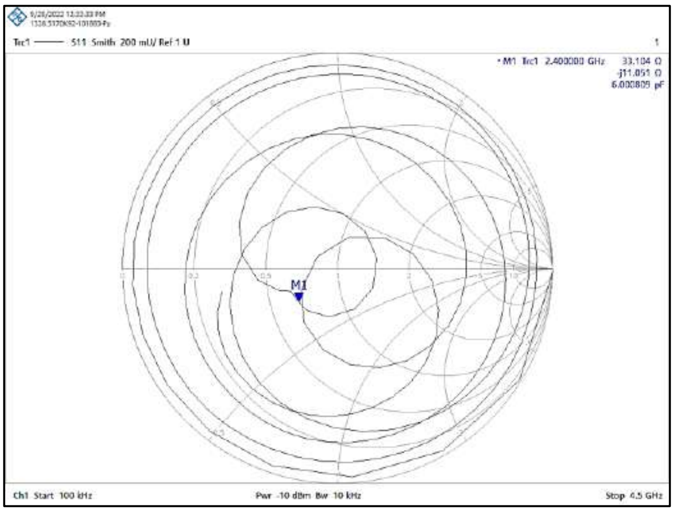



**Figure 2-43: Measured Smith Chart of Inset Feed Single Element Antenna**

#### 2.6.4.3 Measured VSWR

The measured VSWR of the inset feed single element is 1.623U.

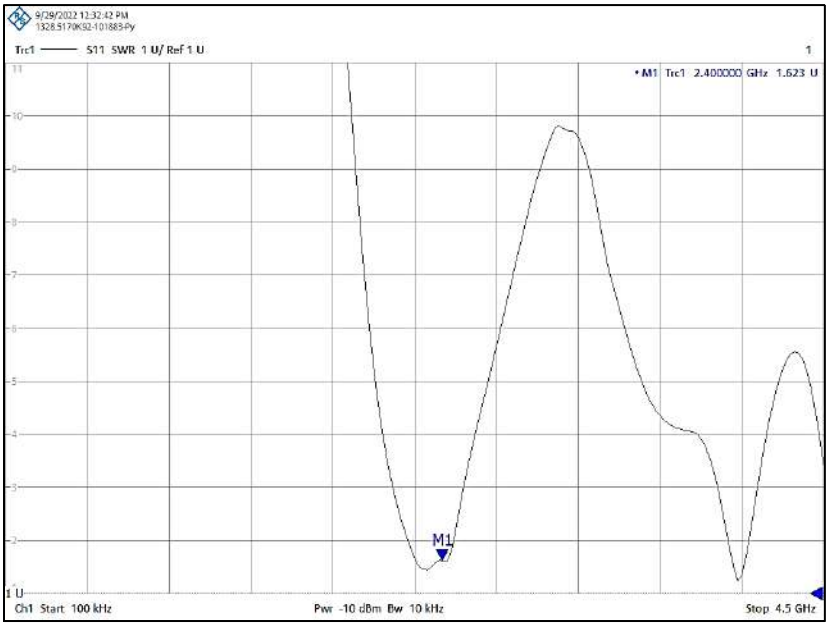



**Figure 2-44: Measured VSWR of Inset Feed Single Element Antenna**

#### 2.6.4.4 Measured Radiation Pattern

The radiation pattern of the single element inset feed antenna is plotted on a polar graph. The radiation pattern is measured for both the Far and Near Fields. Both of these distances are dependent upon the largest dimensions of the antenna calculated as:

$$Near\ Field \leq \frac{2D^2}{\lambda}$$

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

Where,

*D = Maximum Dimension of the Antenna*

*λ = Wavelength of 2.4GHz*

From the above calculations, for the largest dimension of 5cm, the far field distance is calculated to be > 40cm and the near field distance to be < 40cm. Therefore, the Far field pattern is measured at a distance of 60cm while the Near Field pattern is measured at a distance of 35cm.

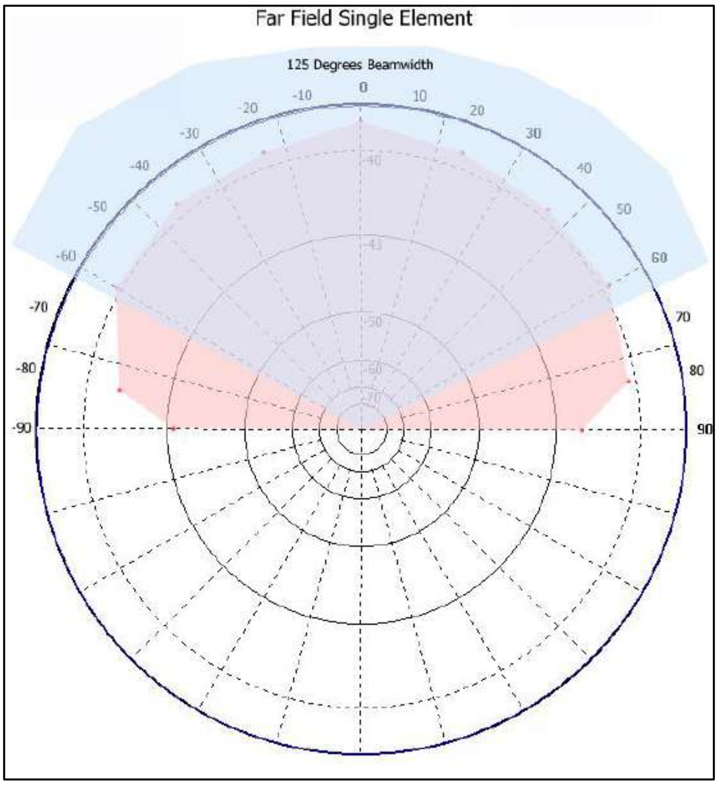



**Figure 2-45: Measured Far Field Radiation Pattern of Inset Feed Single Element Antenna**

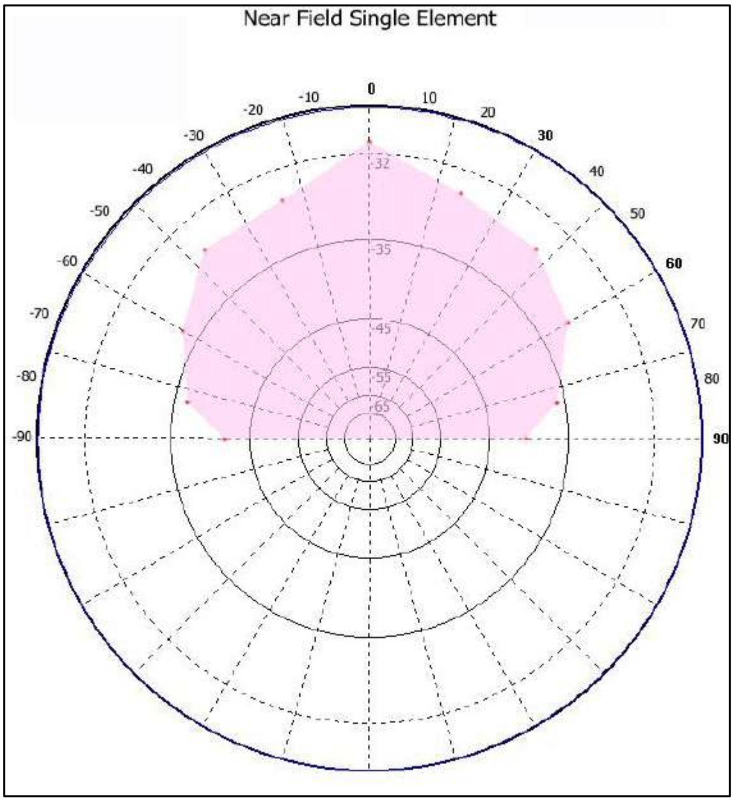



**Figure 2-46: Measured Near Field Radiation Pattern of Inset Feed Single Element Antenna**

From the radiation pattern, we can conclude that the single element antenna has very small directivity, as all the power is transmitted into each direction equally. Due to which the power will not be able to travel far distances. From the radiation pattern, it is also clear that the gain of the antenna is very small.

### 2.6.5 How to Improve Gain, Efficiency and Directivity of Antenna?

The gain, directivity and efficiency values of the above single element antenna is very low as compared to the application of this project. We will need a high directive and high gain antenna to transmit the power efficiently to the long distances. To improve these parameters, we will need to increase the number of elements of the antenna. Therefore, the 2, 4 and 8 elements inset feed antenna is designed and the results are discussed below.

### 2.6.6 Designing of Two Elements Inset Feed Antenna

The two element inset feed antenna is designed using the calculated values of the patch element calculated above. However the physical dimensions of the patch vary according to the application. In 2 elements, the input is taken as a 50Ω line and which is divided into two 100Ω parallel lines so that the equivalent resistance will become 50Ω. The 100Ω line is connected with the 50Ω inset feed line of the patch. The feeding point is also calculated using above formulas and values. The distance from the center of two elements must be $\lambda/2$ distance to minimize the effects of side lobes and loss of signal [9] [11].

#### 2.6.6.1 Simulated Two Elements Inset Feed Antenna

The simulated two elements antenna is given below with its dimensions:

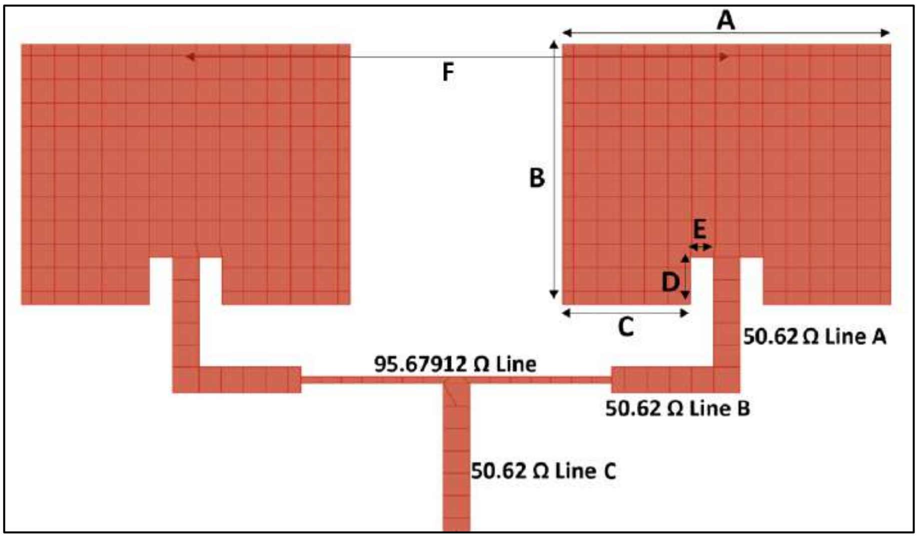



**Figure 2-47: Simulated two Elements Inset Feed Antenna**

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| **Length (L) in mm** | 38.04 | 30.2 | 14.83 | 5.4426 | 2.68 | 62.518 |

**Table 2-7: Dimensions of two Elements Inset Feed Antenna**

| | 50.62Ω Line A | 50.62Ω Line B | 50.62Ω Line C | 95.67912Ω Line |
|---|---|---|---|---|
| **Length (L) in mm** | 15.654 | 11.7905 | 17.124 | 35.98 |
| **Width (W) in mm** | 3.02 | 3.02 | 3.02 | 0.8 |

**Table 2-8: Dimensions of Feed Lines of two Elements Inset Feed Antenna**

### 2.6.6.2 Simulated S11 Parameter of Two Element Inset Feed Antenna

The simulated S11 parameter of a two element inset feed antenna is found to be -57.161dB. Given below:

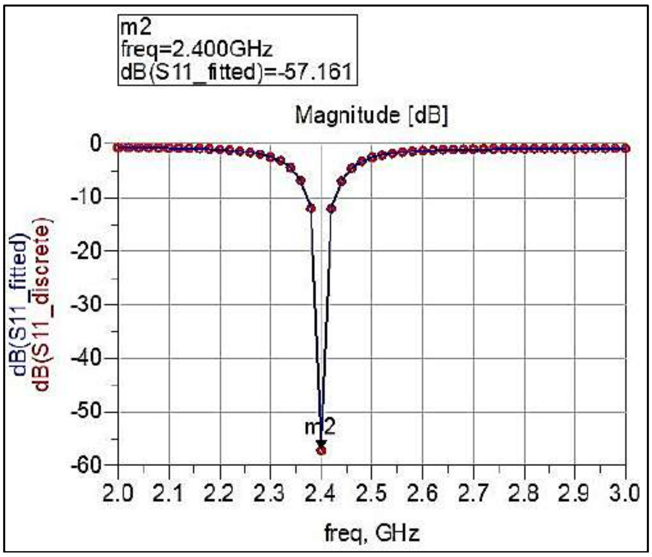



**Figure 2-48: Simulated S11-parameter of two Elements Inset Feed Antenna**

### 2.6.6.3 Simulated Smith Chart of Two Element Inset Feed Antenna

The simulated smith chart impedance normalized at 50Ω of a two element inset feed antenna is found to be 1.002+j0.002Ω. Given below:

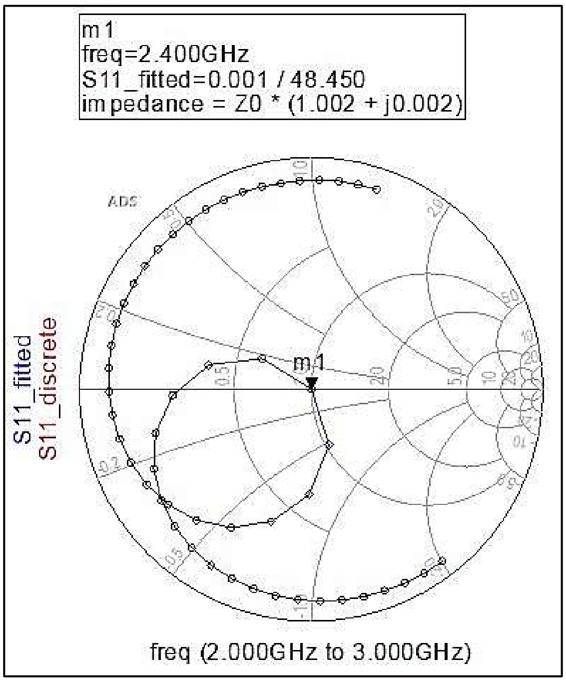
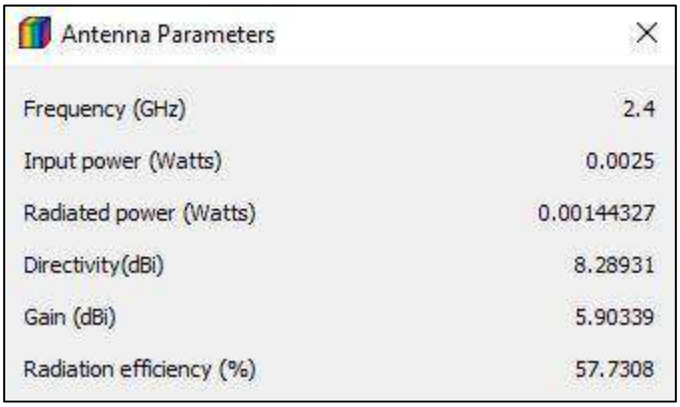



**Figure 2-49: Simulated Smith Chart of two Elements Inset Feed Antenna**

### 2.6.6.4 Simulated Gain, Directivity and Efficiency of Two Element Inset Feed Antenna

The gain, directivity and efficiency is found to be 5.9dBi, 8.289dBi and 57.73% respectively. Given below:



| Antenna Parameters | |
|---|---|
| Frequency (GHz) | 2.4 |
| Input power (Watts) | 0.0025 |
| Radiated power (Watts) | 0.00144327 |
| Directivity(dBi) | 8.28931 |
| Gain (dBi) | 5.90339 |
| Radiation efficiency (%) | 57.7308 |

**Figure 2-50: Simulated Gain, Directivity and Efficiency of two Elements Inset Feed Antenna**

### 2.6.6.5 Simulated 2D and 3D Radiation Patterns of Two Element Inset Feed Antenna

The 2D and 3D simulated radiation patterns of two elements antenna are given below:

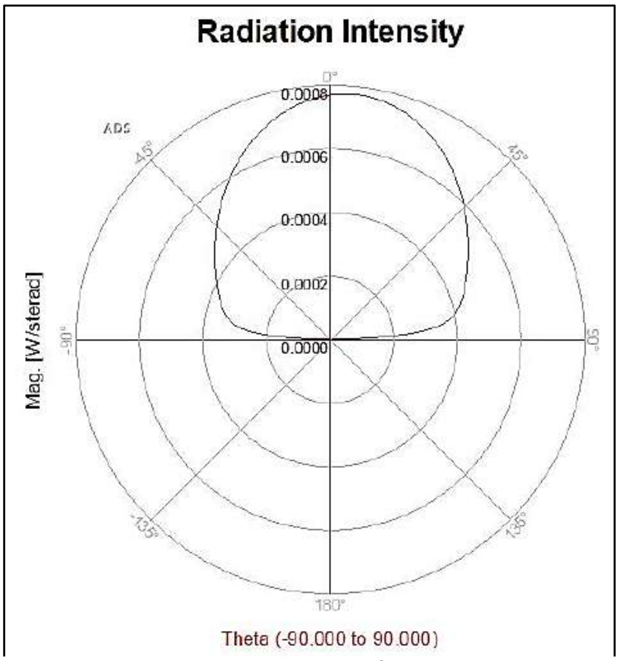



**Figure 2-51: Simulated 2D Radiation Pattern of two Elements Inset Feed Antenna**

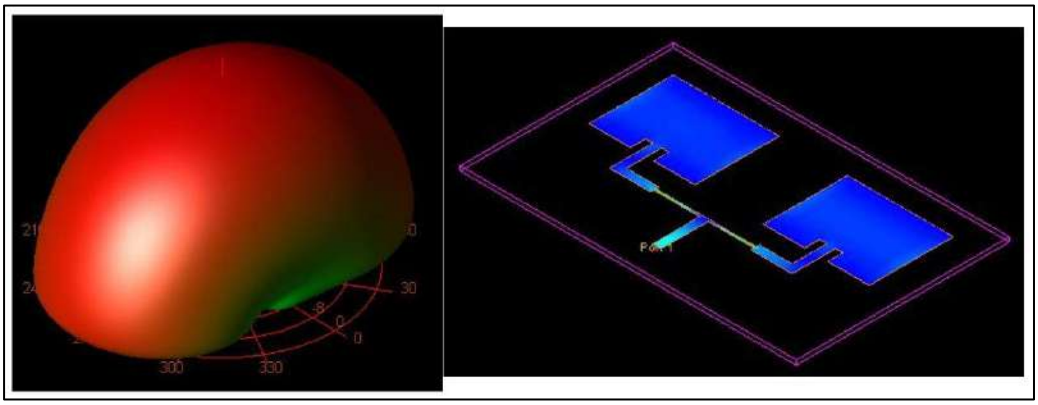


**Figure 2-52: Simulated 3D Radiation Pattern of two Elements Inset Feed Antenna**

From the radiation pattern, we can have an idea that the antenna is designed very efficiently so that there are no side lobes which can lose our signal in other or none wanted directions [11]. The whole signal is converged into one direction and so that the signal will travel a longer distance.

From the above results, we can conclude that by increasing the patch elements and making its impedance matched, the gain, directivity and efficiency is improved. Therefore, an antenna of 4 elements with the configuration of 2x2 matrix is finally designed to have maximum efficiency, gain and directivity.

### 2.6.7 Designing of 2x2 Matrix Form Antenna

The 2x2 matrix of inset feed antenna is designed using the calculated values of patch elements and the transmission line values. The matrix design is selected so that the antenna length will not get too large. Antenna is designed in a way to have maximum gain and directivity with no side lobes. To minimize the side lobes, the distance from the center of two elements should be >= $\lambda/2$ [9] [11]. The side lobes are minimized so that no power will be transmitted in unwanted directions. The impedance is matched using the inset feeding technique. The input to the 2x2 antenna is also a 50Ω transformer so that the electronic modules with 50Ω can match the impedance and no power will be reflected back.

The 2x2 designed patch antenna is given below:

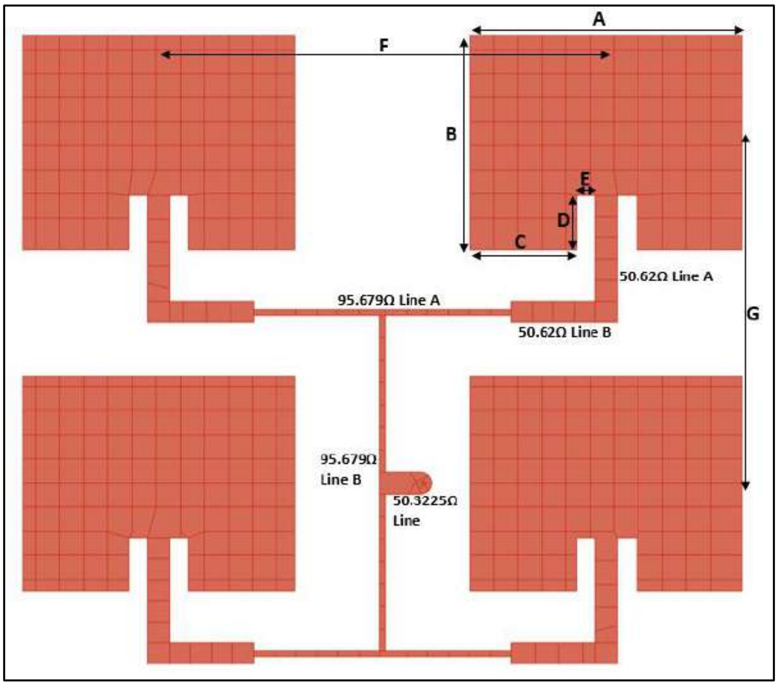



**Figure 2-53: Simulated 2x2 Matrix form Antenna**

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| **Length (L) in mm** | 38.04 | 30.07 | 14.8295 | 7.5926 | 2.6805 | 62.581 | 47.8 |

**Table 2-9: Dimensions of 2x2 Matrix form Antenna**

| | **50.62Ω Line A** | **50.62Ω Line B** | **50.3225Ω Line** | **95.679Ω Line A** | **95.679Ω Line B** |
|---|---|---|---|---|---|
| **Length (L) in mm** | 17.804 | 11.7905 | 5 | 35.98 | 47 |
| **Width (W) in mm** | 3.02 | 3.02 | 3.05 | 0.8 | 0.8 |

**Table 2-10: Dimensions of Feed Lines of 2x2 Matrix form Antenna**

### 2.6.7.1 Simulated S11 Parameter of 2x2 Matrix Form Antenna

The simulated S11 parameter of a 2x2 matrix form antenna is found to be -39.71dB. Given below:

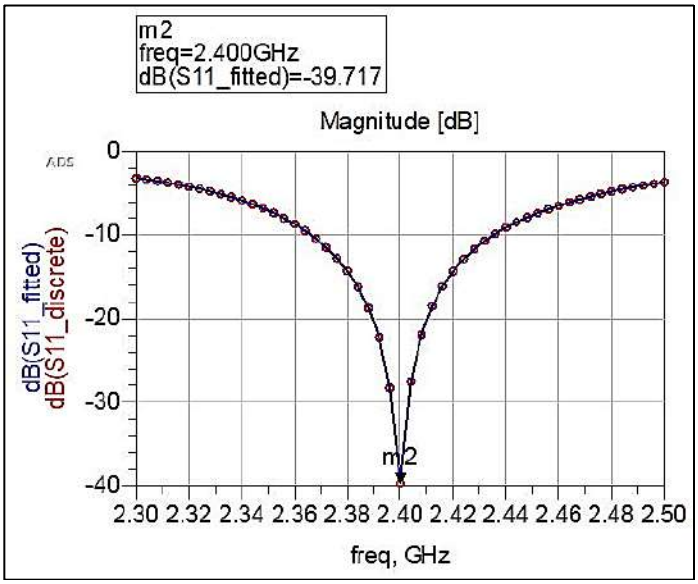



**Figure 2-54: Simulated S11-parameter of 2x2 Matrix form Antenna**

### 2.6.7.2 Simulated Smith Chart of 2x2 Matrix Form Antenna

The Smith Chart impedance normalized at 50Ω of a 2x2 matrix form antenna is found to be 0.988+j0.017Ω. Given below:

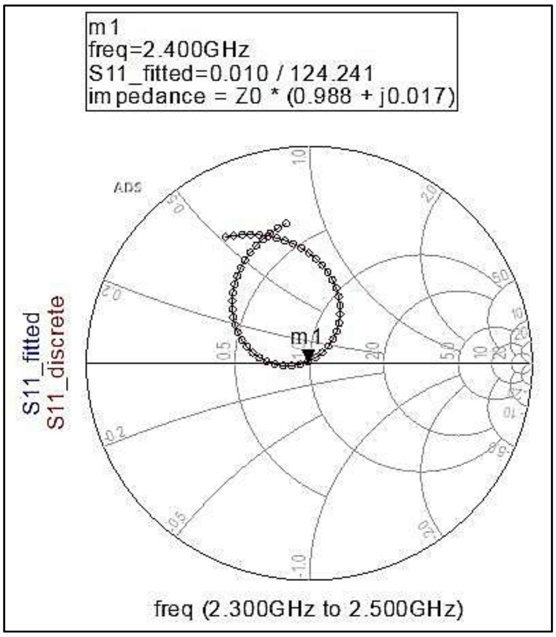
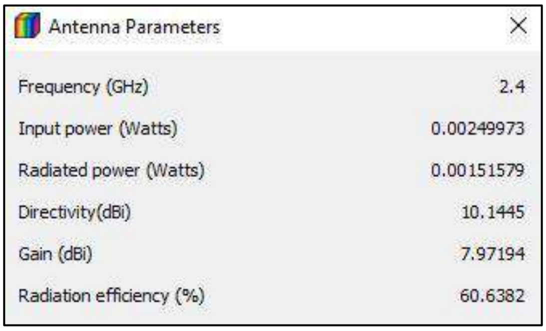



**Figure 2-55: Simulated Smith Chart of 2x2 Matrix form Antenna**

### 2.6.7.2 Simulated Gain, Directivity and Efficiency of 2x2 Matrix Form Antenna

The simulated gain, directivity and efficiency of the 2x2 matrix form antenna is found to be 7.97dBi, 10.1445dBi, and 60.638% respectively. Given below:



Antenna Parameters

| | |
|---|---|
| Frequency (GHz) | 2.4 |
| Input power (Watts) | 0.00249973 |
| Radiated power (Watts) | 0.00151579 |
| Directivity(dBi) | 10.1445 |
| Gain (dBi) | 7.97194 |
| Radiation efficiency (%) | 60.6382 |

**Figure 2-56: Simulated Gain, Directivity and Efficiency of 2x2 Matrix form Antenna**

### 2.6.7.3 Simulated 2D and 3D Radiation Patterns of 2x2 Matrix Form Antenna

The simulated 2D and 3D radiation patterns are illustrated below:

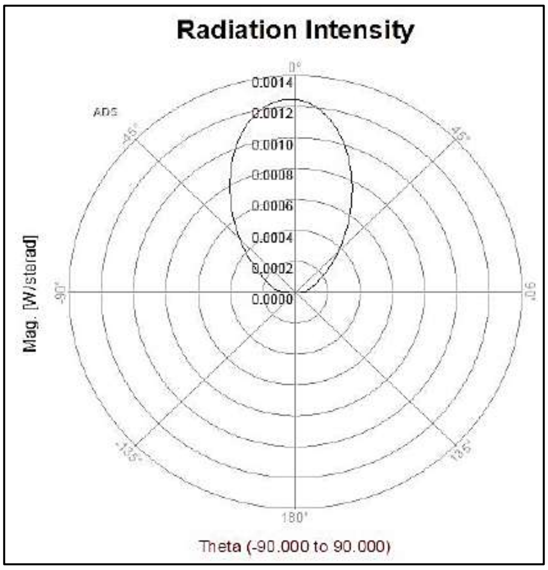



**Figure 2-57: Simulated 2D Radiation Pattern of 2x2 Matrix form Antenna**

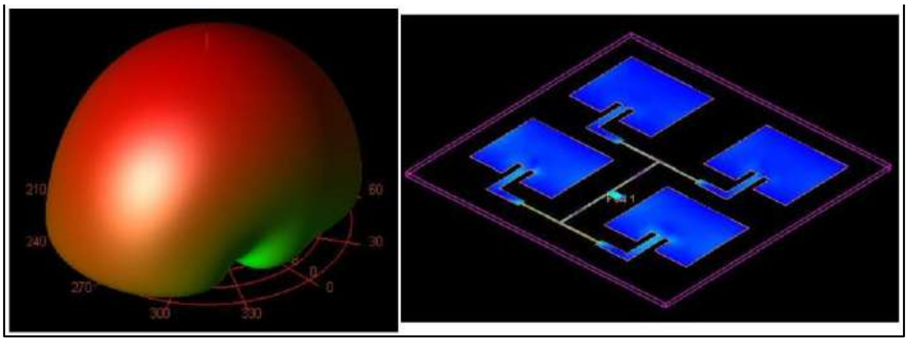



**Figure 2-58: Simulated 3D Radiation Pattern of 2x2 Matrix form Antenna**

### 2.6.8 Fabricated 2x2 Matrix Form Antenna

The 2x2 element feed antenna is fabricated on an FR-4 substrate material, and analyzed its working.

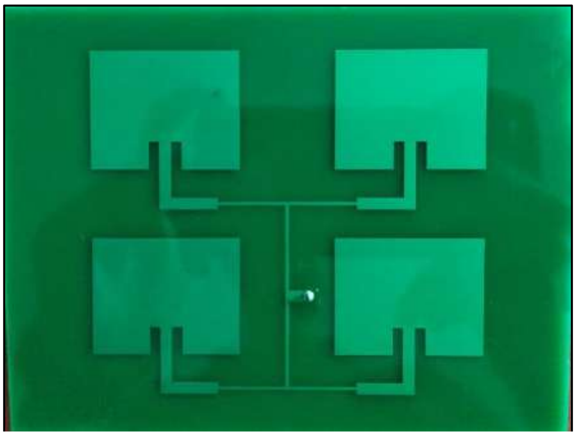


**Figure 2-59: Fabricated 2x2 Matrix form Antenna**

#### 2.6.8.1 Measured S11 Parameter of 2x2 Matrix Form Antenna

The return loss (S11) of the fabricated 2x2 element antenna is measured on a Vector Network Analyzer and the results are attached:

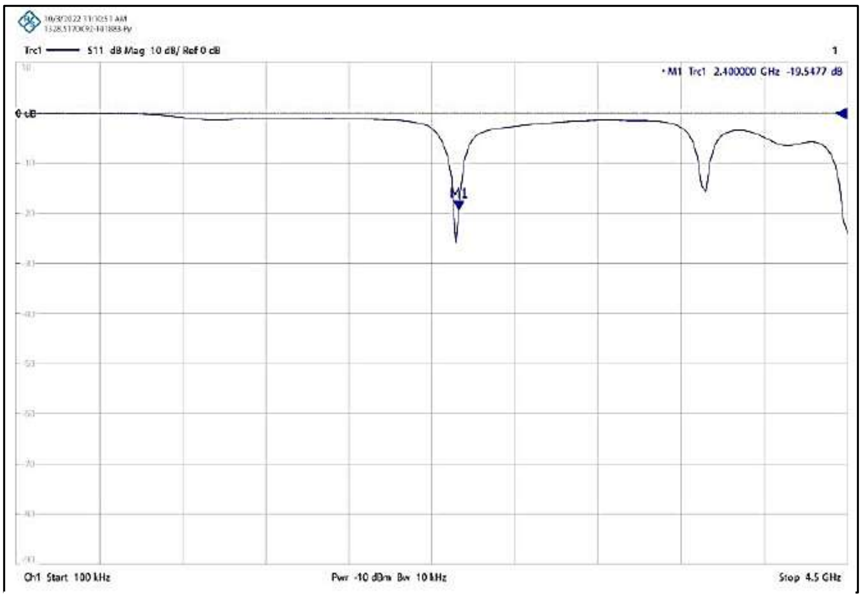



**Figure 2-60: Measured S11-parameter of 2x2 Matrix form Antenna**

From the above graph, the S11 parameter is found to be -19.54dB which is less than -10dB. So the S11 parameter is in the range of acceptable value.

### 2.6.8.2 Measured Smith Chart of 2x2 Matrix Form Antenna

The measured smith chart normalized impedance at 50Ω of the 2x2 matrix form antenna is analyzed using Vector Network Analyzer and found to be 0.783+j0.099Ω. Given below:

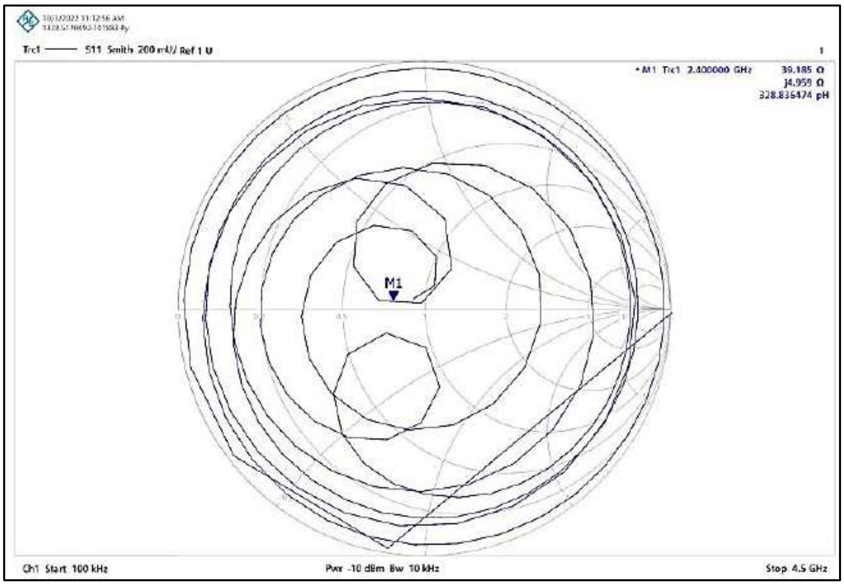



**Figure 2-61: Measured Smith Chart of 2x2 Matrix form Antenna**

### 2.6.8.3 Measured VSWR of 2x2 Matrix Form Antenna

The VSWR of the 2x2 element antenna is found to be 1.317U. Given below:

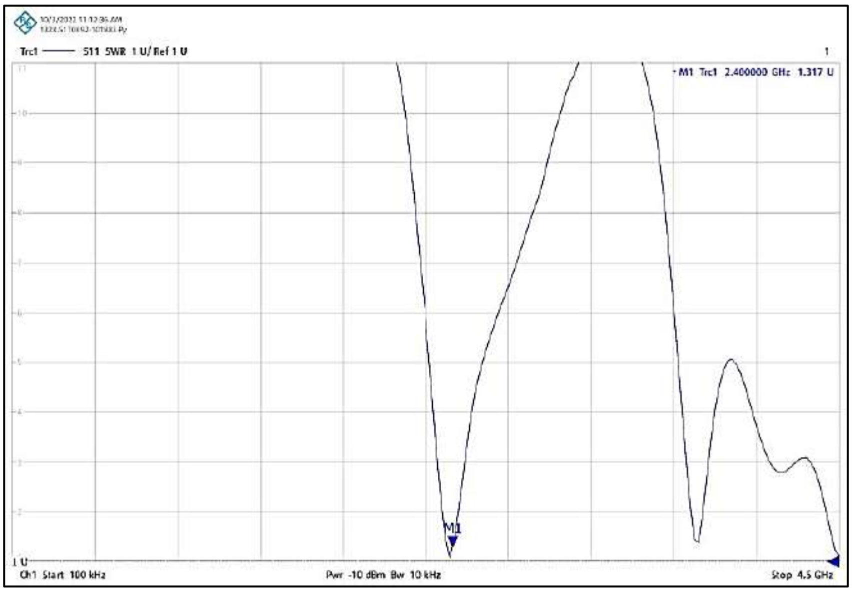



**Figure 2-62: Measured VSWR of 2x2 Matrix form Antenna**

#### 2.6.8.4 Measured Radiation Pattern and Gain of 2x2 Matrix Form Antenna

The radiation pattern of the 2x2 antenna is drawn by using a monopole antenna of 2-3 dBi gain and giving 0dBm power to the monopole antenna. Since the monopole antenna transmits the power in all directions with same power values therefore for radiation patterns, this antenna is used. On the other hand, the transmitter antenna is connected to the spectrum analyzer to receive the power transmitted from the monopole antenna and the power levels by rotating the antenna at different angles are observed. The radiation pattern is drawn for Near (Fresnel) and Far Field (Fraunhofer) distances. The distances is found by using the below formulas:

$$\textit{Near Field} \leq \frac{2D^2}{\lambda}$$

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

Where,

*D = Maximum Dimension of the Antenna*

*$\lambda$ = Wavelength of 2.4GHz*

The maximum dimension of the fabricated antenna is 14.5cm. So by calculations, we found out the Near Field distance < 33cm and the Far Field distance > 33cm.

The gain of the fabricated antenna is found by observing the power level received by the transmitter antenna at 0 degrees of angle from the monopole antenna at a Far Field Distance selected to be 50 cm. The power level which should be received by the antenna with a simulated gain of 7.97dBi is found out by calculating using the Friis Transmission Equation.

$$P_r = P_t + G_t + G_r + 20log_{10}\left(\frac{\lambda}{4\pi d}\right)$$

Where,

*$P_r$ = Power received by the receiver antenna (2x2 Transmitter Antenna)*

*$P_t$ = Power transmitted by the transmitter antenna (Monopole Antenna)*

*$G_t$ = Gain of the transmitting antenna*

*$G_r$ = Gain of the receiving antenna*

$\lambda$ = *Wavelength of 2.4GHz*

*d = distance between Tx and Rx antennas*

Power level that should be observed at the receiving end is calculated using this equation is -24.06dBm.

So, a power level of -24.06dBm should be observed by the antenna if we claim (simulated) gain to be 7.97dBi. However, there is always a 2-3 dBm power loss due to SMA connectors. So, by subtracting 2dBm, the required observed power should be -26.06dBm. The power levels received at different degrees or the radiation pattern is given below:

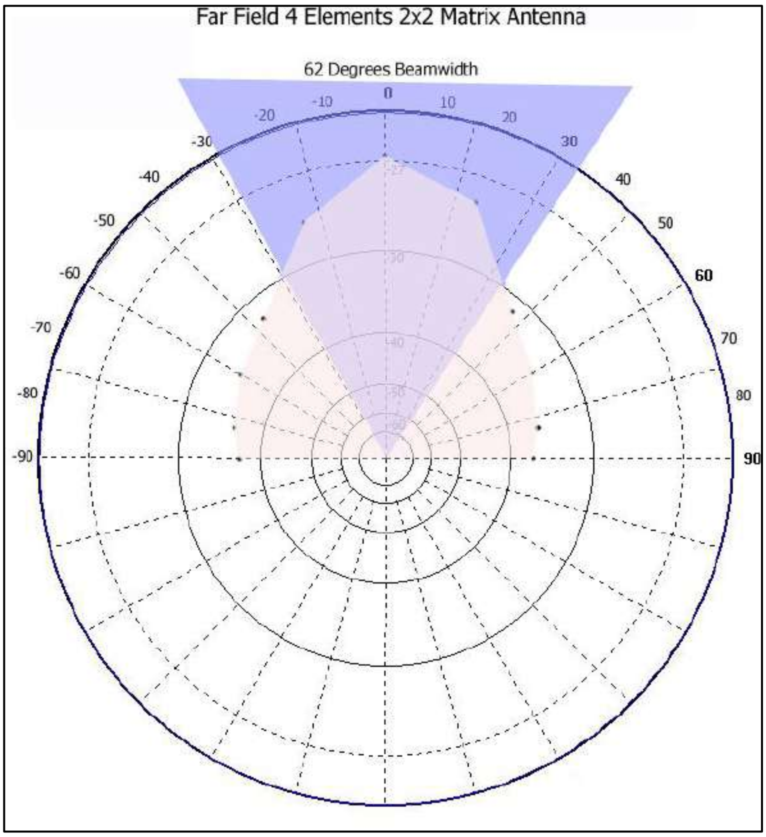



**Figure 2-63: Measured Far Field Radiation Pattern of 2x2 Matrix form Antenna**

From the above graph, the Power level received at 0 degrees is -26.9dBm. So by taking the difference of the observed and calculated power, we can get the gain loss or the dBi loss.

Loss = Power should be observed - Power Observed

Loss = -26.06 - (-26.9)

Loss = 0.84dBm

So, by subtracting the Loss from the simulated gain, we can have the measured gain of the transmitter antenna.

Measured Gain = Simulated Gain - Loss

Measured Gain = 7.97 - 0.84

**Measured Gain = 7.13dBi**

From the above results, we can conclude that the 2x2 antenna has a measured gain of 7.13dBi. And the beamwidth of the antenna is found by plotting the half power points at -3dB and finding out the angle. So from the measured graph, the beam width is found out to be 62 degrees.

The Near Field Radiation Pattern is measured at a distance of 25cm and is given below:

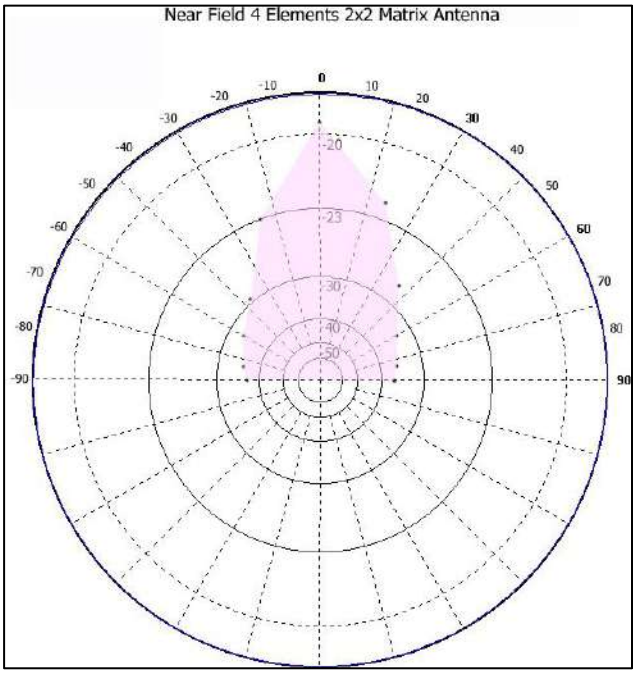



**Figure 2-64: Measured Near Field Radiation Pattern of 2x2 Matrix form Antenna**

#### 2.6.8.5 Comparing Simulated and Measured Results of 2x2 Matrix Form Antenna

| | S11 (dB) | Gain (dBi) | Normalized Smith Chart Impedance (Ω) |
|---|---|---|---|
| **Simulated Results** | -39.71 | 7.97 | 0.988+j0.017 |
| **Measured Results** | -19.54 | 7.13 | 0.783+j0.099 |

**Table 2-11: Comparison between Simulated and Measured results of 2x2 Matrix form Antenna**

From the above results, we can conclude that by increasing the patch elements and matching the impedance, we have improved the gain, directivity and efficiency of the antenna [12]. And the side lobes are also minimized by placing the patches in a calculated distance from each other [9] [11].

The power divider board has two outputs, so that the antenna should also consist of two matrices. Therefore, the final antenna of two 2x2 matrices is designed. The antenna parameters are given below:

### 2.6.8 Designing Two 2x2 Elements Antenna for Transmitter Module

The final version of the transmitter module antenna is designed using Advanced Design System Software. The antenna consists of two 2x2 elements inset feed antennas designed above with separation distance of $\lambda/2$ from each other. The separation distance is selected such that the side lobes don't appear and the power doesn't lose to unwanted directions [9] [11]. The antenna is illustrated below:

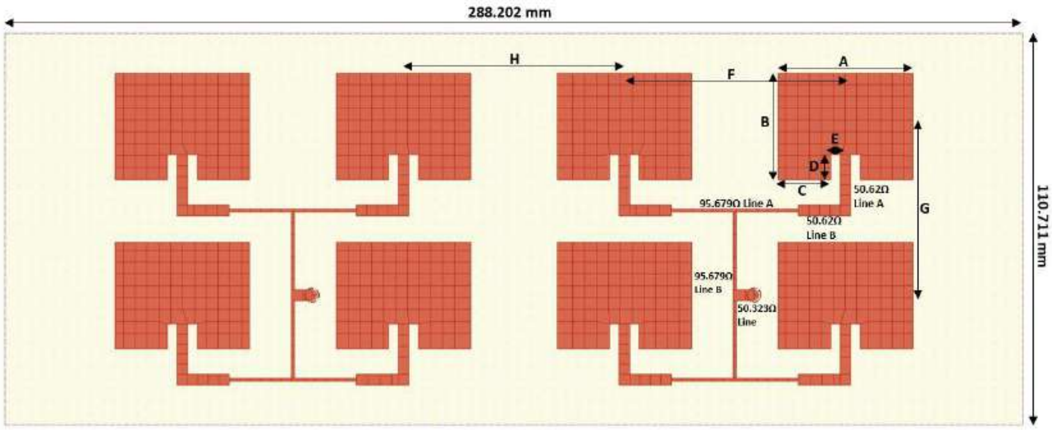



**Figure 2-65: Simulated Transmitter Antenna**

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| **Length(L) in mm** | 38.04 | 30.2 | 14.8295 | 7.1426 | 2.6805 | 62.581 | 47.8 | 62.5 |

**Table 2-12: Dimensions of Transmitter Antenna**

| | 50.62Ω Line A | 50.62Ω Line B | 95.679Ω Line A | 95.679Ω Line B | 50.323Ω Line |
|---|---|---|---|---|---|
| **Length(L) in mm** | 17.354 | 11.7905 | 35.98 | 47 | 5 |
| **Width(W)in mm** | 3.02 | 3.02 | 0.8 | 0.8 | 3.05 |

**Table 2-13: Dimensions of Feeding Lines of Transmitter Antenna**

### 2.6.8.1 Simulated Results of the Transmitter Antenna

#### 2.6.8.1.1 Simulated S11 Parameter of Transmitter Antenna

The S11 of the two feeding points is found by connecting the power divider with the antenna so that the feeding point will become only one and the return loss can be found out easily. The simulated S11 parameter is found to be -43.709dB. Given below:

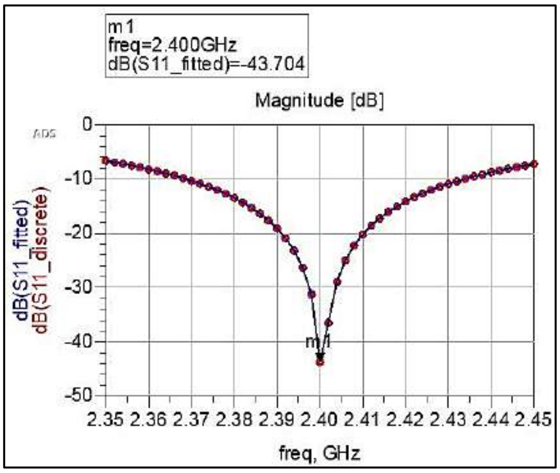



**Figure 2-66: Simulated S11-parameter of Transmitter Antenna**

#### 2.6.8.1.2 Simulated Smith Chart of the Transmitter Antenna

The simulated smith chart impedance normalized at 50Ω is found to be 1.008+j0.01Ω and shown below:

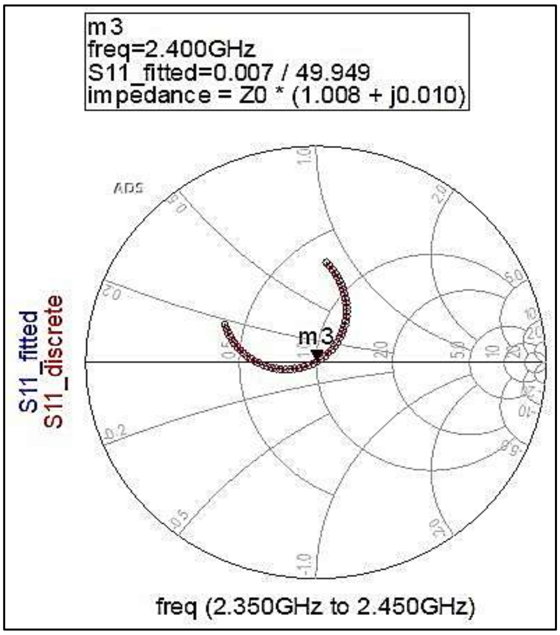



**Figure 2-67: Simulated Smith Chart of Transmitter Antenna**

#### 2.6.8.1.3 Simulated Gain, Directivity and Efficiency of Transmitter Antenna

The simulated gain, directivity and efficiency is found out to be 10.92dBi, 12.93dBi and 62.91% respectively. Given below:

| Antenna Parameters | |
|---|---|
| Frequency (GHz) | 2.4 |
| Input power (Watts) | 0.00499673 |
| Radiated power (Watts) | 0.00314376 |
| Directivity(dBi) | 12.9366 |
| Gain (dBi) | 10.9242 |
| Radiation efficiency (%) | 62.9165 |

**Figure 2-68: Simulated Gain, Directivity and Efficiency of Transmitter Antenna**

#### 2.6.8.1.4 Simulated 2D and 3D Radiation Patterns of the Transmitter Antenna

The simulated 2D and 3D radiation patterns of the transmitter antenna is found to be:

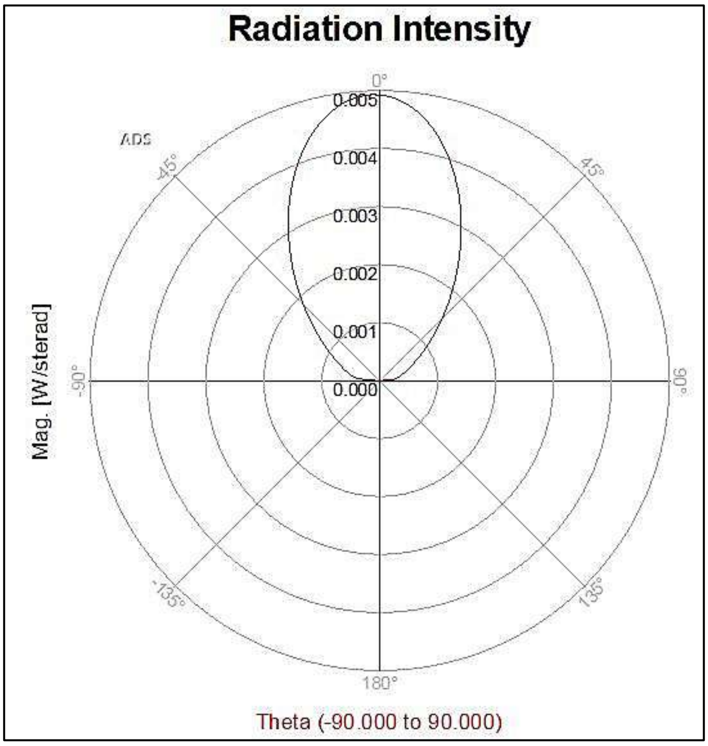



**Figure 2-69: Simulated 2D Radiation Pattern of Transmitter Antenna**

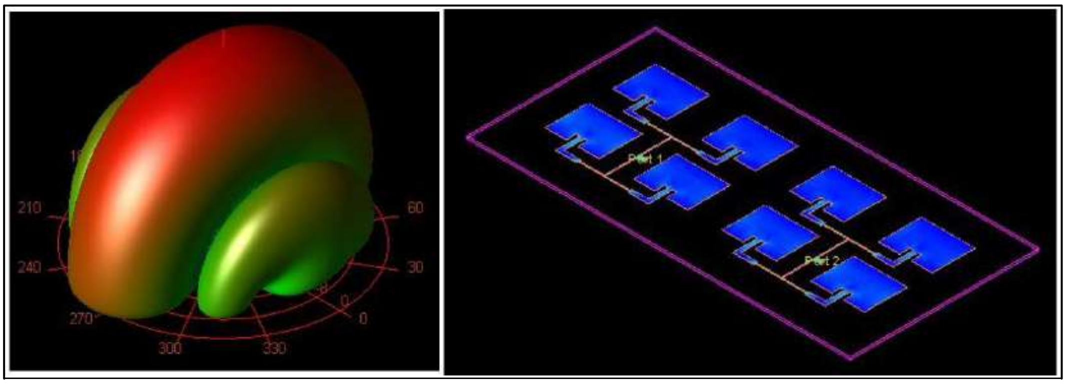



**Figure 2-70: Simulated 3D Radiation Pattern of Transmitter Antenna**

### 2.6.8.2 Fabricated Two 2x2 Elements Transmitter Antenna

The transmitter antenna is fabricated on an FR-4 substrate having thickness of 1.6mm. The fabricated antenna is given below:

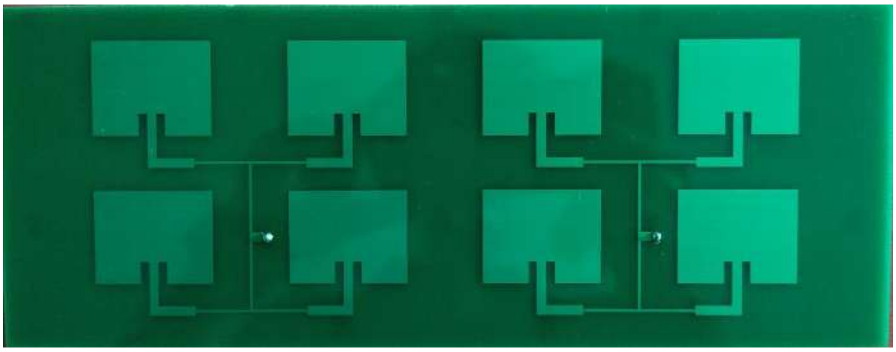


**Figure 2-71: Fabricated Transmitter Antenna**

#### 2.6.8.2.1 Measured S11 of the Transmitter Antenna

The S11 of the fabricated transmitter antenna is found by connecting the power divider board with the two feeding points of the antenna so that a resulting one feeding point will be used for finding the return loss. The S11 of the antenna is analyzed using a Vector Network Analyzer and found to be -25.66dB.

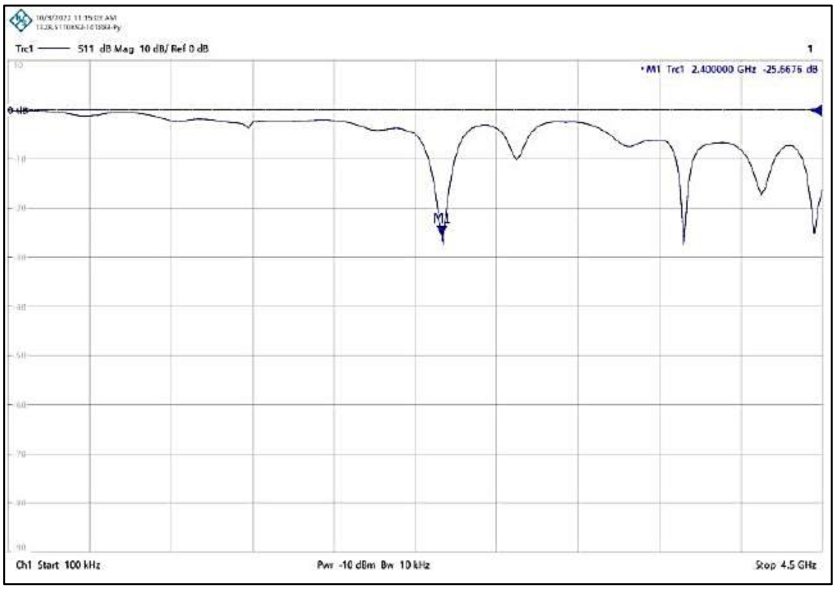



**Figure 2-72: Measured S11 Parameter of Transmitter Antenna**

#### 2.6.8.2.2 Measured Smith Chart of the Transmitter Antenna

The measured smith chart normalized impedance at 50Ω of the transmitter antenna is analyzed using Vector Network Analyzer and found to be 1.053+j0.106Ω. Given below:

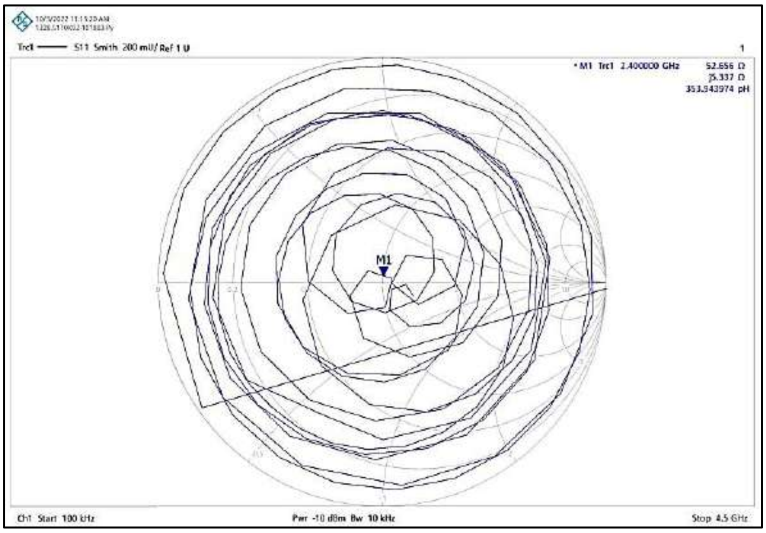



**Figure 2-73: Measured Smith Chart of the Transmitter Antenna**

#### 2.6.8.2.3 Measured VSWR of the Transmitter Antenna

The SWR of the transmitter antenna is also measured using VNA and found to be 1.117U.

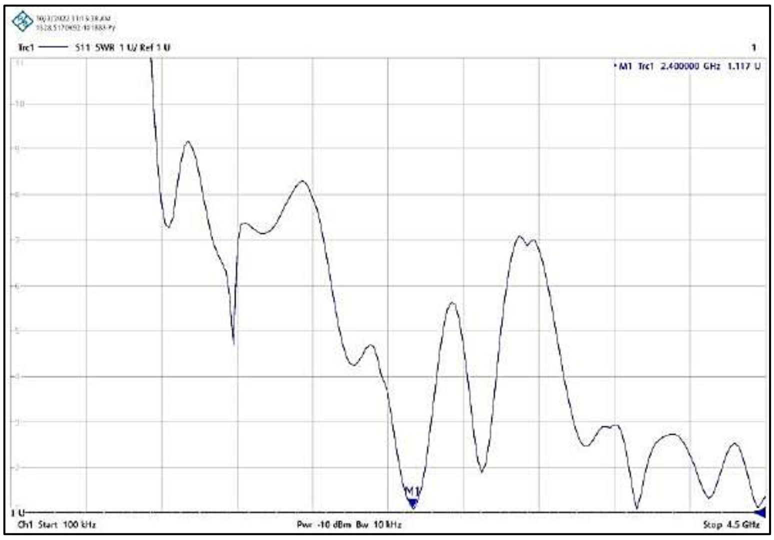



**Figure 2-74: Measured VSWR of the Transmitter Antenna**

#### 2.6.8.2.4 Measured Radiation Pattern and Gain of the Transmitter Antenna

The radiation pattern of the transmitter antenna is drawn by using a monopole antenna of 2-3dBi gain and giving 0dBm power to the monopole antenna. Since the monopole antenna transmits the power in all directions with same power values therefore for radiation patterns, this antenna is used. On the other hand, the transmitter antenna is connected to the spectrum analyzer to receive the power transmitted from the monopole antenna and the power levels by rotating the antenna at different angles are observed. The radiation pattern is drawn for Near (Fresnel) and Far Field (Fraunhofer) distances. The distances is found by using the below formulas:

$$Near\ Field \leq \frac{2D^2}{\lambda}$$

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

Where,

*D = Maximum Dimension of the Antenna*

*λ = Wavelength of 2.4GHz*

The maximum dimension of the fabricated antenna is 28.82cm. So by calculations, we found out the Near Field distance < 133cm and the Far Field distance > 133cm.

The gain of the fabricated antenna is found by observing the power level received by the transmitter antenna at 0 degrees of angle from the monopole antenna at a Far Field Distance selected to be 150 cm. The power level which should be received by the antenna with a simulated gain of 10.92dBi is found out by calculating using the Friis Transmission Equation.

$$P_r = P_t + G_t + G_r + 20log_{10}\left(\frac{\lambda}{4\pi d}\right)$$

Where,

*$P_r$ = Power received by the receiver antenna (two 2x2 Transmitter Antenna)*

*$P_t$ = Power transmitted by the transmitter antenna (Monopole Antenna)*

*$G_t$ = Gain of the transmitting antenna*

*$G_r$ = Gain of the receiving antenna*

*$\lambda$ = Wavelength of 2.4GHz*

*d = distance between Tx and Rx antennas*

Power level that should be observed at the receiving end is calculated using this equation is -30.65dBm.

So, a power level of -30.65dBm should be observed by the antenna if we claim (simulated) gain to be 10.92dBi. However, there is always a 2-3 dBm power loss due to SMA connectors. So, by subtracting this 2dBm, the required observed power should be -32.65dBm. The power levels received at different degrees or the radiation pattern is given below:

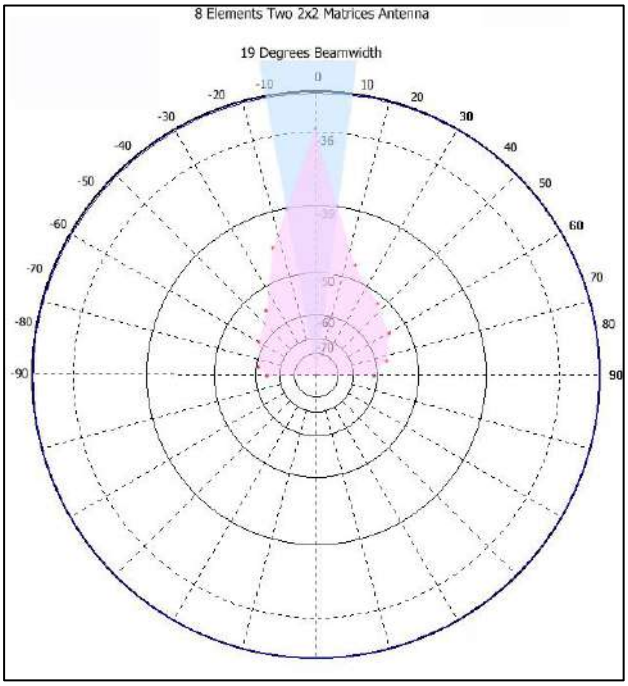



**Figure 2-75: Measured Far Field Radiation Pattern of Transmitter Antenna**

From the above graph, the Power level received at 0 degrees is -35.9dBm. So by taking the difference of the observed and calculated power, we can get the gain loss or the dBi loss.

Loss = Power should be observed - Power Observed

Loss = -32.65 - (-35.9)

Loss = 3.25dBm

So by subtracting the Loss from the simulated gain, we can have the measured gain of the transmitter antenna.

Measured Gain = Simulated Gain - Loss

Measured Gain = 10.92 - 3.25

**Measured Gain = 7.67dBi**

From the above results, we can conclude that the transmitter antenna is having a measured gain of 7.67dBi. And the beamwidth of the antenna is found by plotting the half power points (-3dB) and finding out the angle. So from the measured graph, the beam width is found out to be 19 degrees.

The Near Field Radiation Pattern is measured at 100cm distance and is given below:

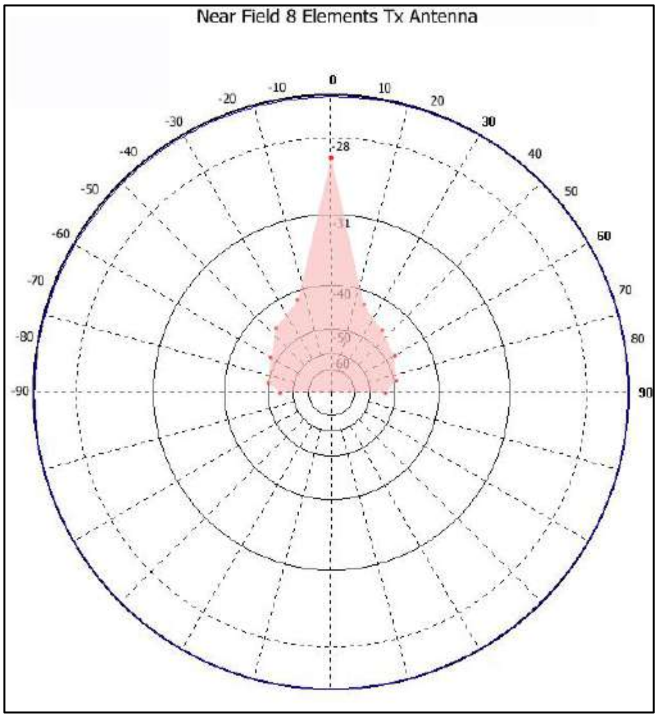



**Figure 2-76: Measured Near Field Radiation Pattern of Transmitter Antenna**

### 2.6.8.3 Comparing Simulated and Measured Results of Transmitter Antenna

| | S11 (dB) | Gain (dBi) | Normalized Smith Chart Impedance (Ω) |
|---|---|---|---|
| **Simulated Results** | -43.7 | 10.92 | 1.008+j0.010 |
| **Measured Results** | -25.66 | 7.67 | 1.053+j0.106 |

**Table 2-14: Comparison between Measured and Simulated results of Transmitter Antenna**

By comparing the simulated and measured results, we can conclude that the antenna is having very small return loss and having a good gain. Therefore we can use this antenna in our project.

# CHAPTER 3: DESIGNING AND TESTING OF RECEIVER MODULE COMPONENTS

## 3.1 Overview of the receiver module components

The receiver module consists of a receiving antenna which can convert the EM radiation into electrical signals. These signals are then rectified and amplified into DC voltages by an in-house designed Charge Pump and Rectifier circuit. The charge pump will provide constant DC voltages, the charges will be stored in a capacitor bank which will then power up the loads connected to the receiver module. The load can be any Mobile Phone, Laptop, Tablet etc. which can be powered up by DC voltages.

## 3.2 Selection of receiving antenna

There are various types of antennas available, however for our application, it is necessary to choose a suitable one which could perform well in this project. Major antenna types are:

### 3.2.1 Omni-directional Antenna

An Omni-directional antenna is a type of antenna which receives signals with the same power from every direction [17]. In this case, the receiver antenna will catch the signals of different Wi-Fi devices or mobile phones which are using 2.4GHz frequency for communication. Therefore, there will be noise from the signals due to these devices. The radiation pattern of these types of antennas consists of 360 degrees.

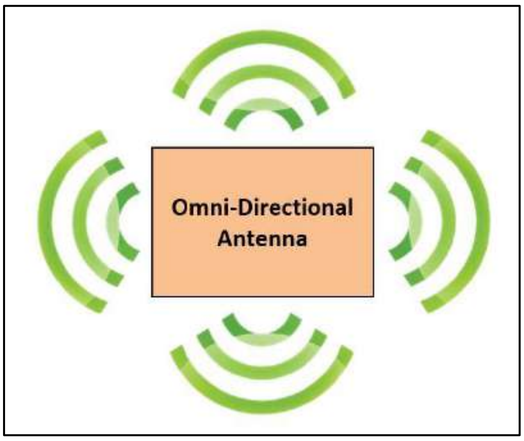



**Figure 3-1: Omni-directional Antenna Radiation Pattern**

### 3.2.2 Uni-directional Antenna

A unidirectional antenna is a type of antenna which can receive the EM radiation from a specific direction, which eventually makes the signal strong enough and reduces the noise effect in the signal [17]. It can also reduce the interference from other directions.

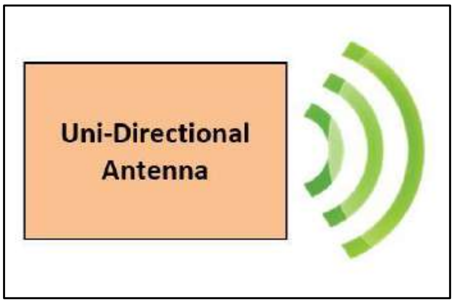



**Figure 3-2: Uni-directional Antenna Radiation Pattern**

### 3.2.3 Antenna Selected

Since, we need more power at long distance and a directional antenna is able to pull in a signal from greater distance, therefore a unidirectional antenna is chosen for this project. Unidirectional antennas are also in large numbers. However, we have chosen Microstrip Patch Antennas due to their low cost, light weight and they are easy to fabricate.

## 3.3 Rectangular Microstrip Patch Antenna Designing

The receiving side power is tested by incorporating the single element, 4 element 2x2 matrix form, 4 element array form and 8 elements of two 2x2 matrices. The antennas designed and tested in the transmitter module are the same as the receiver module. However, the 4 element array form is designed and tested for the receiver module separately. A four element is designed so that the receiving side will have more area and will get the signal from far distances. The antenna design is given below.

### 3.3.1 Four Elements Array Antenna Designing for Receiver

The four element inset feed antenna is designed using the calculated values of the patch element calculated above in the transmitter side. However the physical dimensions of the patch vary according to the application. In this antenna, the two element antenna designed in the transmitter module is connected. The antenna is designed by merging the 2 two elements antenna by means of impedance matching [12]. The input is taken as a 50Ω line and it is divided into two 100Ω parallel lines so that the equivalent resistance will become 50Ω. The 100Ω line is connected with the 50Ω line using the quarter wave line of 70Ω for impedance matching between 100Ω and 50Ω lines. Each 50Ω line is connected to the two element antenna designed in the transmitter module. The distance from the center of two elements must be ≥$\lambda/2$ distance to minimize the effects of side lobes and loss of signal [9] [11]. The antenna is given below with its dimensions:

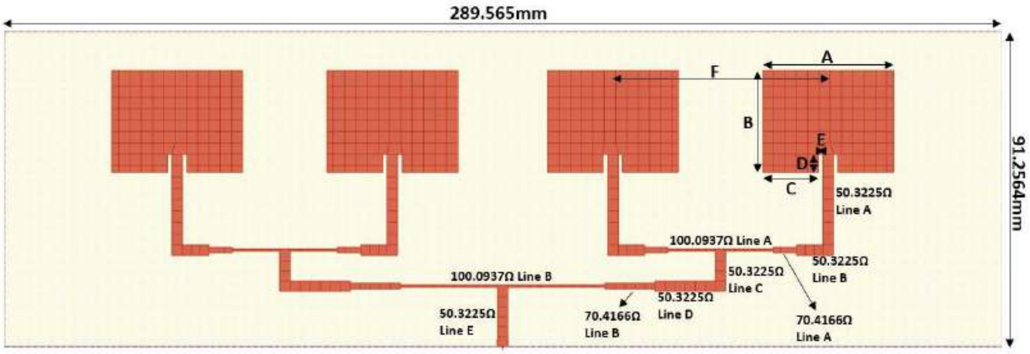



**Figure 3-3: Simulated 4 Elements Array Form Antenna**

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| **Length in mm** | 38.04 | 29.59 | 16.23 | 5.2226 | 1.265 | 62.5 |

**Table 3-1: Dimensions of 4 Elements Array Form Antenna**

| 50.3225Ω Lines | | | | | |
|---|---|---|---|---|---|
| **Lines** | **A** | **B** | **C** | **D** | **E** |
| **Length(L) in mm** | 29.25 | 7.7175 | 11.61 | 17.4875 | 17.12 |
| **Width(W) in mm** | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 |

**Table 3-2: Dimensions of Feeding Lines of 4 Elements Array Form Antenna**

| | 70.4166Ω Lines | | 100.0937Ω Lines | |
|---|---|---|---|---|
| **Lines** | **A** | **B** | **A** | **B** |
| **Length(L) in mm** | 6.7675 | 14.5375 | 30.48 | 59.425 |
| **Width(W) in mm** | 1.62 | 1.62 | 0.709 | 0.709 |

**Table 3-3: Dimensions of Feeding Lines of 4 Elements Array Form Antenna**

#### 3.3.1.1 Simulated Results of the Receiving Antenna

##### 3.3.1.1.1 Simulated S11 Parameter of Receiving Antenna

The simulated S11 parameter of the receiving antenna is found to be -31.12dB. Given below:

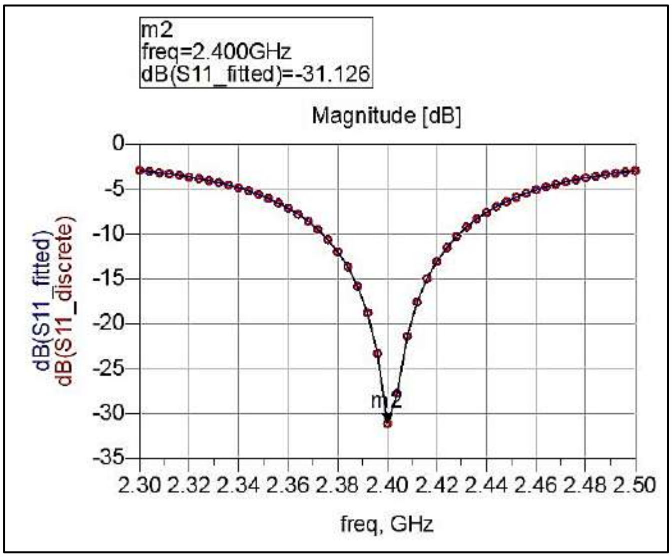



**Figure 3-4: Simulated S11 Parameter of Receiving Antenna**

##### 3.3.1.1.2 Simulated Smith Chart of the Receiving Antenna

The simulated results of smith chart impedance normalized at 50Ω are found to be 1.003+j0.056Ω. Shown below:

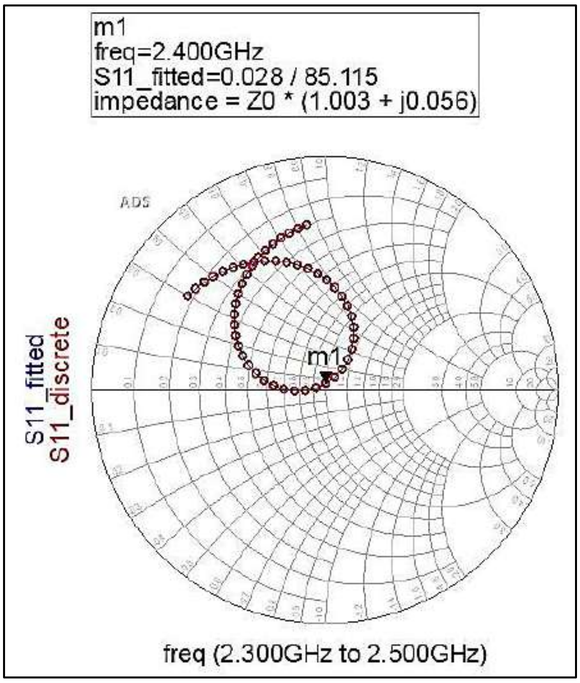
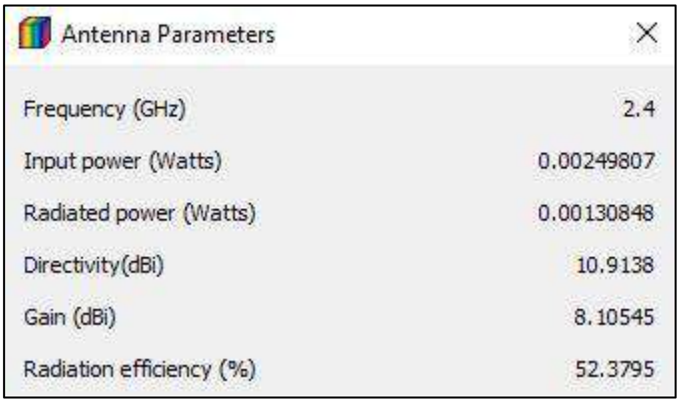



**Figure 3-5: Simulated Smith Chart of Receiving Antenna**

#### 3.3.1.1.3 Simulated Gain, Directivity and Efficiency of Receiving Antenna

The simulated gain, directivity and efficiency is found to be 8.1dBi, 10.91dBi and 52.37% respectively. Given below:



Antenna Parameters

| | |
|---|---|
| Frequency (GHz) | 2.4 |
| Input power (Watts) | 0.00249807 |
| Radiated power (Watts) | 0.00130848 |
| Directivity(dBi) | 10.9138 |
| Gain (dBi) | 8.10545 |
| Radiation efficiency (%) | 52.3795 |

**Figure 3-6: Simulated Gain, Directivity and Efficiency of Receiving Antenna**

#### 3.3.1.1.4 Simulated 2D and 3D Radiation Pattern of the Receiving Antenna

The simulated 2D and 3D radiation pattern of the transmitter antenna is found to be:

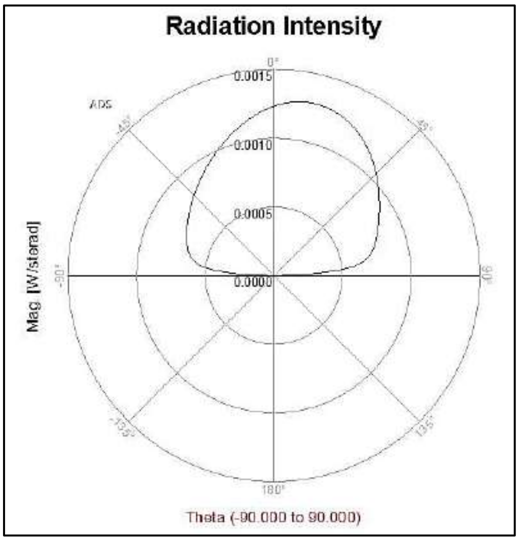



**Figure 3-7: Simulated 2D Radiation Pattern of Receiving Antenna**

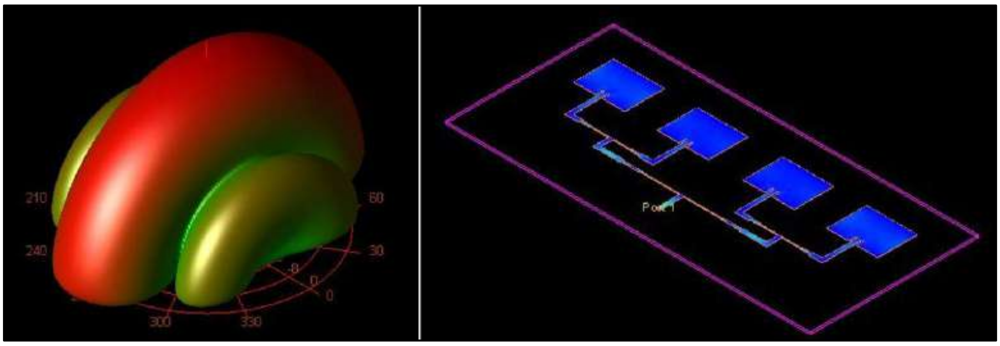



**Figure 3-8: Simulated 3D Radiation Pattern of Receiving Antenna**

From the radiation pattern, we can have an idea that the antenna is designed very efficiently so that the antenna will not catch the signals from unwanted directions and eventually there will be no noise in the signal. The whole signal is converged from the transmitter antenna into one direction and will be received efficiently by the receiving antenna.

### 3.3.1.2 Fabricated four Elements array Receiver Antenna

The receiver antenna is fabricated on an FR-4 substrate having thickness of 1.6mm. The fabricated antenna is given below:

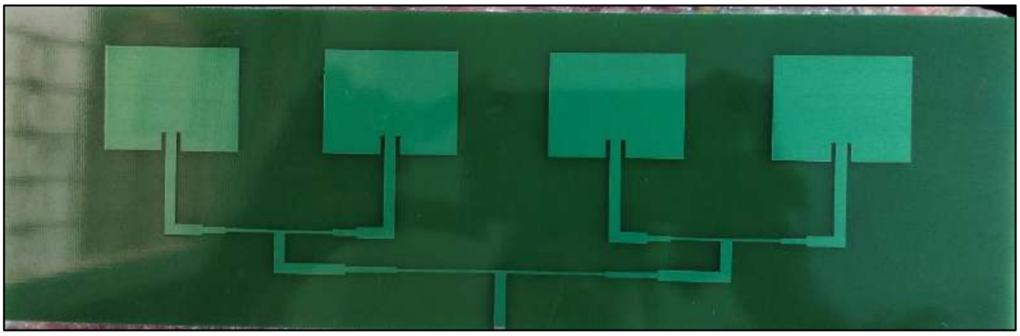


**Figure 3-9: Fabricated 4 Elements Receiving Antenna**

#### 3.3.1.2.1 Measured S11 of the Receiver Antenna

The S11 of the fabricated receiver antenna is analyzed using Vector Network Analyzer and found to be -7.43dB. Given below:

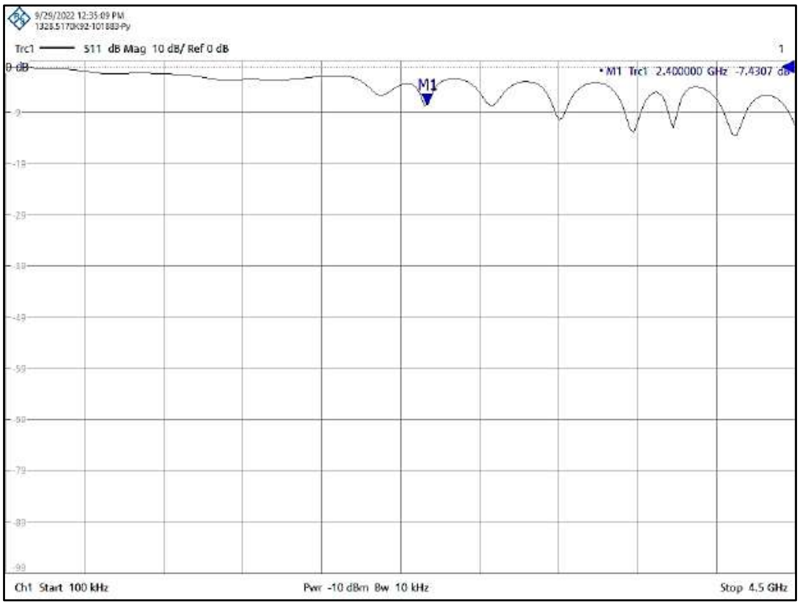



**Figure 3-10: Measured S11 Parameter of Receiving Antenna**

#### 3.3.1.2.2 Measured Smith Chart of the Receiver Antenna

The measured smith chart normalized impedance at 50Ω of the receiver antenna is analyzed using Vector Network Analyzer and found to be 1.575+j0.995Ω. Given below:

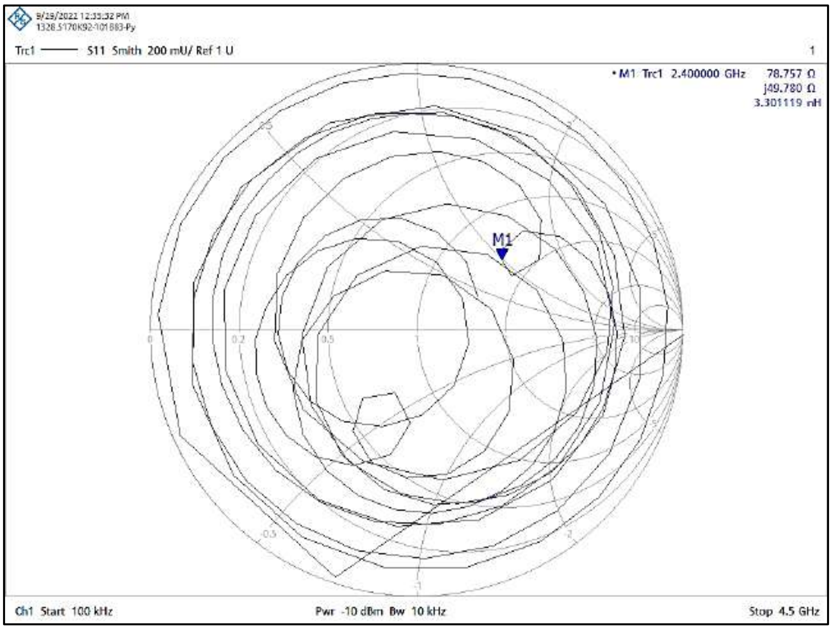



**Figure 3-11: Measured Smith Chart of Receiving Antenna**

#### 2.6.8.2.3 Measured VSWR of the Receiver Antenna

The SWR of the receiver antenna is also measured using VNA and found to be 2.429U. Given below:

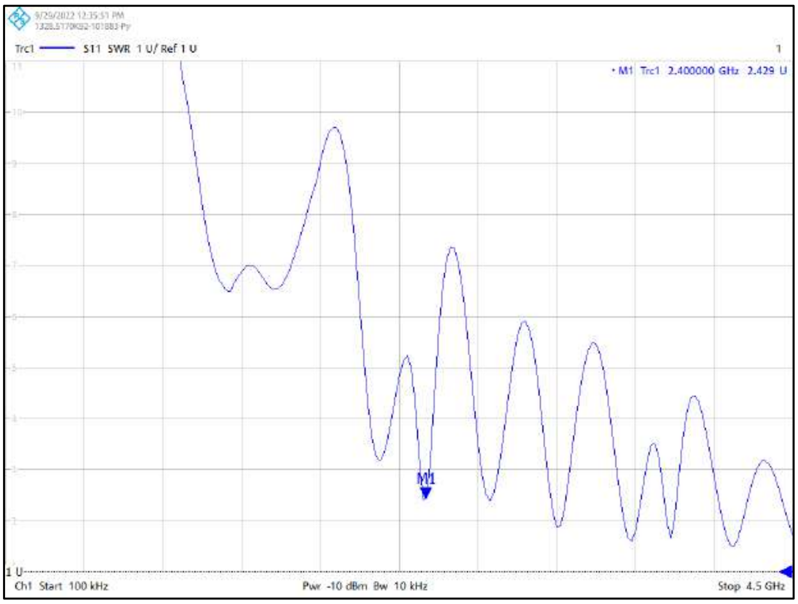



**Figure 3-12: Measured VSWR of Receiving Antenna**

#### 2.6.8.2.4 Measured Radiation Pattern and Gain of the Receiver Antenna

The radiation pattern of the receiving antenna is drawn by using a monopole antenna of 2-3 dBi gain and giving 0dBm power to the monopole antenna. Since the monopole antenna transmits the power in all directions with same power values therefore for radiation patterns, this antenna is used. On the other hand, the receiving antenna is connected to the spectrum analyzer to receive the power transmitted from the monopole antenna and the power levels by rotating the antenna at different angles are observed. The radiation pattern is drawn for Near (Fresnel) and Far Field (Fraunhofer) distances. The distances is found by using the below formulas:

$$Near\ Field \leq \frac{2D^2}{\lambda}$$

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

Where,

*D = Maximum Dimension of the Antenna*

*λ = Wavelength of 2.4GHz*

The maximum dimension of the fabricated antenna is 28.956cm. So by calculations, we found out the Near Field distance < 134cm and the Far Field distance > 134cm.

The gain of the fabricated antenna is found by observing the power level received by the transmitter antenna at 0 degrees of angle from the monopole antenna at a Far Field Distance selected to be 150 cm. The power level which should be received by the antenna with a simulated gain of 8.1dBi is found out by calculating using the Friis Transmission Equation.

$$P_r = P_t + G_t + G_r + 20log_{10}\left(\frac{\lambda}{4\pi d}\right)$$

Where,

$P_r$ = *Power received by the receiver antenna (Four Elements Array Antenna)*

$P_t$ = *Power transmitted by the transmitter antenna (Monopole Antenna)*

$G_t$ = *Gain of the transmitting antenna*

$G_r$ = *Gain of the receiving antenna*

*λ = Wavelength of 2.4GHz*

*d = distance between Tx and Rx antennas*

Power level that should be observed at the receiving end is calculated using this equation is -33.47dBm.

So, a power level of -33.47dBm should be observed by the antenna if we claim (simulated) gain to be 8.1dBi. However, there is always a 2-3 dBm power loss due to SMA connectors. So, by subtracting 2dBm, the required observed power should be -35.47dBm. The power levels received at different degrees or the radiation pattern is given below:

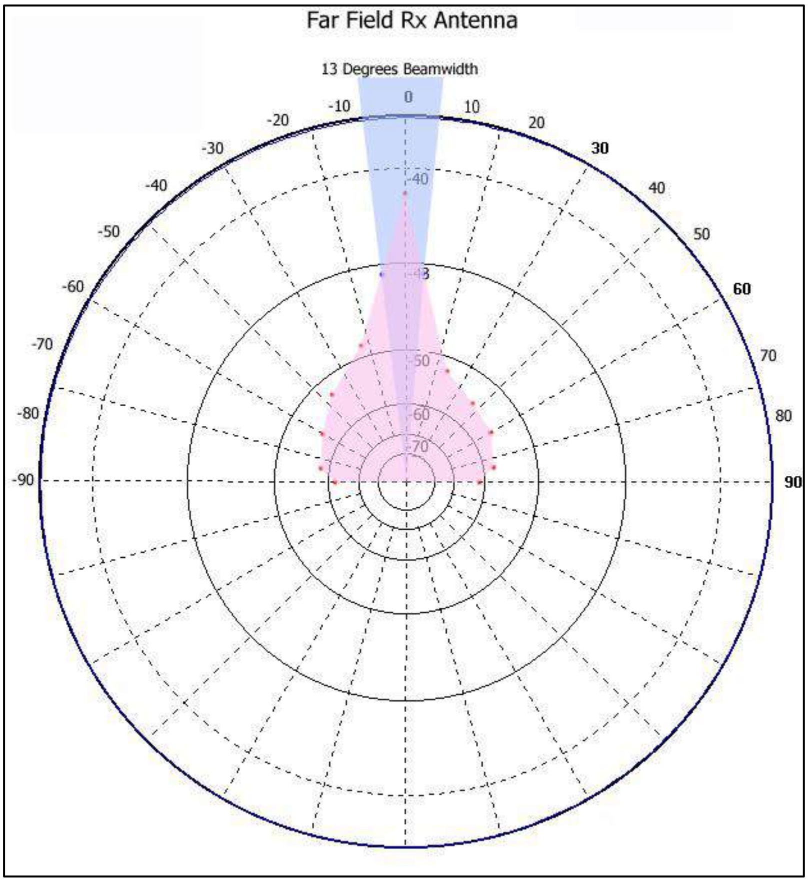



**Figure 3-13: Measured Far Field Radiation Pattern of Receiving Antenna**

From the above graph, the Power level received at 0 degrees is -40.8dBm. So, by taking the difference of the observed and calculated power, we can get the gain loss or the dBi loss.

Loss = Power should be observed - Power Observed

Loss = -35.47 - (-40.8)

Loss = 5.33dBm

So by subtracting the Loss from the simulated gain, we can have the measured gain of the transmitter antenna.

Measured Gain = Simulated Gain - Loss

Measured Gain = 8.1 - 5.33

**Measured Gain = 2.77dBi**

From the above results, we can conclude that the transmitter antenna is having a measured gain of 2.77dBi. And the beamwidth of the antenna is found by plotting the half power points (-3dB) and finding out the angle. So from the measured graph, the beam width is found out to be 13 degrees.

The Near Field Radiation Pattern is measured at a distance of 50cm. Given below:

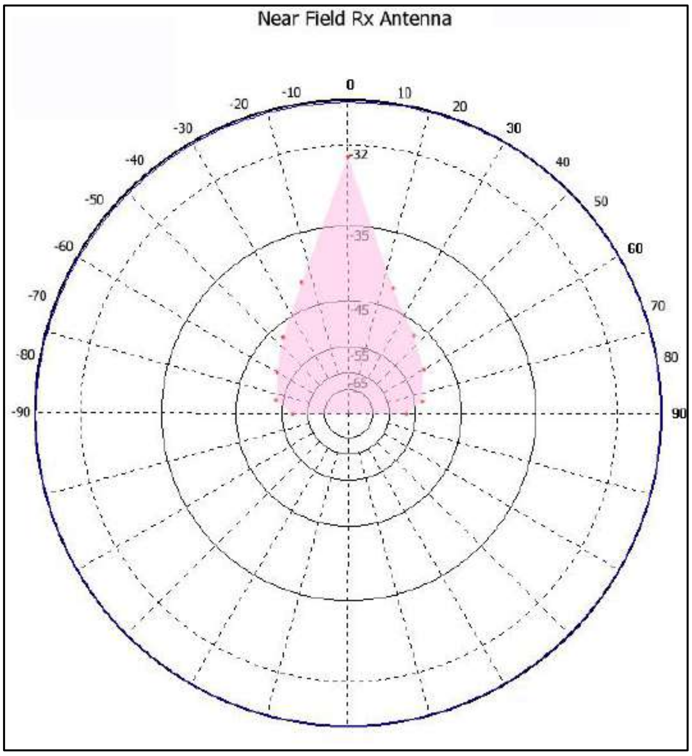



**Figure 3-14: Measured Near Field Radiation Pattern of Receiving Antenna**

## 3.4 Charge Pump & rectifier circuit and its working

A charge pump and rectifier circuit is an AC to DC converter with the property of amplifying the voltages of the input to the output. It is a circuit which incorporates only passive components such as capacitors and diodes for this purpose. The capacitor works as a charge storing element while the diode is used for switching purposes. This circuit is mostly used in the applications where high voltages with low current are required. Since the circuit works by amplifying the voltages while reducing the current. The circuit comprises different stages in which each stage amplifies the peak input voltages by the factor of 2. The circuit diagram for the single stage is given below:

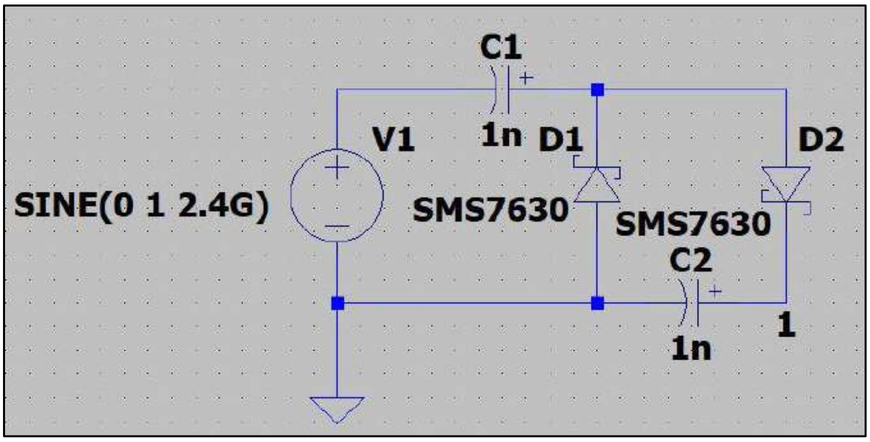



**Figure 3-15: Single Stage Charge Pump & Rectifier Circuit**

For input sinusoidal signal of 2.4GHz with peak value of 1V, the output voltage waveform is given below:

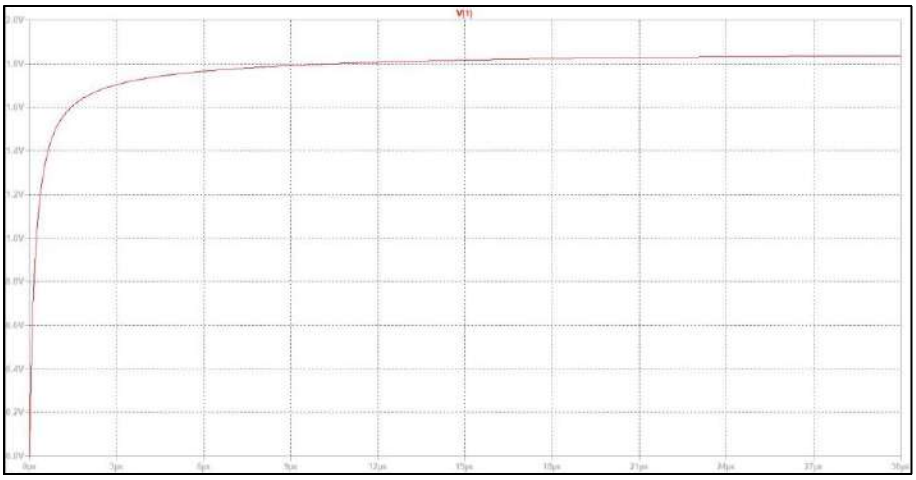


**Figure 3-16: Output Voltage Waveform of Single Stage**

This circuit output is amplified as well as rectified to DC voltages. The working of this circuit is as follows:

Consider the negative cycle of the sine wave first, in which the diode D1 will become forward biased and will start to charge the capacitor C1. For the whole negative cycle the capacitor will charge up to the peak voltages of the input source. Now for the positive half cycle of the sine wave, the diode D2 will become forward biased and now the capacitor C2 will start to charge and the Capacitor C1 will become discharged and the charges of C1 will be stored in the C2. In this way, the C2 is charged to 2 times the input voltages, one of source and one of the C1. In this way, for the 1st stage of the circuit, the output voltages will be equal to two times the input peak voltages, $V_{out} = 2V_p$.

In this way, if we increase the stages of this circuit, the output voltages will be amplified according to the stages of the circuit. Each capacitor in each stage will first store the charge and then will give its charge to the other capacitor and eventually amplifies the voltages at the output terminal. The selection of capacitor and diode is the most crucial task of this circuit. Therefore, an analysis takes place for the selection of these components.

### 3.4.1 Diode Selection

The circuit is comprised of diodes, which will also drop some of the voltages for becoming forward biased. Therefore, it is necessary to choose a diode which is having very small forward bias voltages, as the power which will be received through wireless means will be very small to make the ordinary diodes even on. For this specific purpose, schottky diodes are used. These diodes have very small forward voltage drops in the range of 0.1 to 0.4 V, and they are used for low power applications. For our application, the diode SMS7630 is chosen due to its low forward voltage drop which is in the range of (120-240mV). The diode I-V curve is illustrated below:

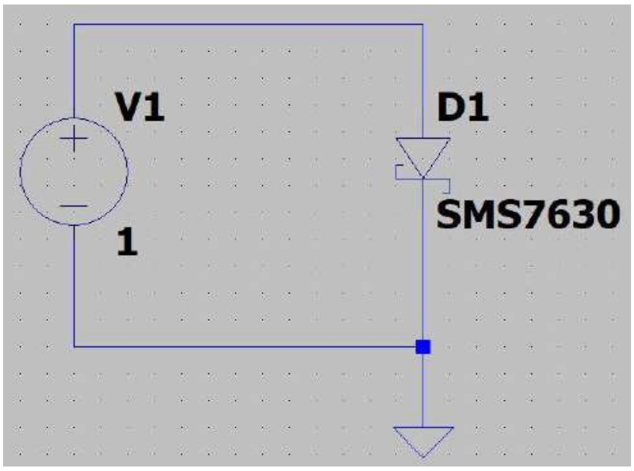



**Figure 3-17: Circuit for SMS7630 Diode**

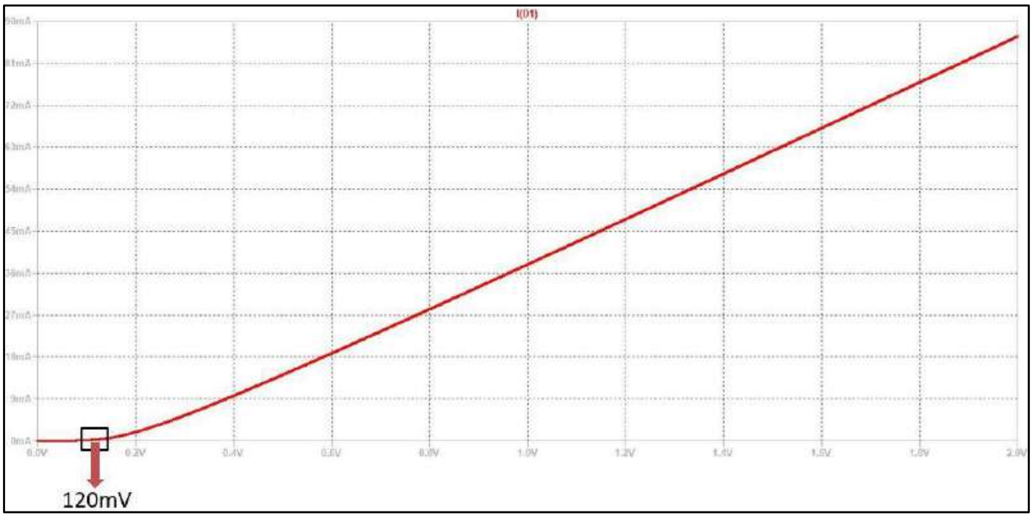



**Figure 3-18: IV Curve of SMS7630 Diode**

### 3.4.2 Capacitor Value Selection

Another crucial task of the circuit is selecting the capacitor. In our case, since the frequency is very high in GHz therefore, large value capacitors of milli or micro farads cannot be used because, and in this way the capacitor will take too much time to charge fully. Therefore, a small value of capacitor should be chosen. In this case, capacitors of capacitance in nano-farads are chosen. But still the problem comes to the exact value of the capacitance, therefore some tests were taken place to select a suitable value.

#### 3.4.2.1 0.1nF Capacitor Simulation result

The circuit is simulated with capacitors of value 0.1nF. The input of the circuit is taken as 1 V peak sinusoidal signal with a frequency of 2.4GHz. Charge pump & rectifier circuit with 8 levels is designed and analyzed.

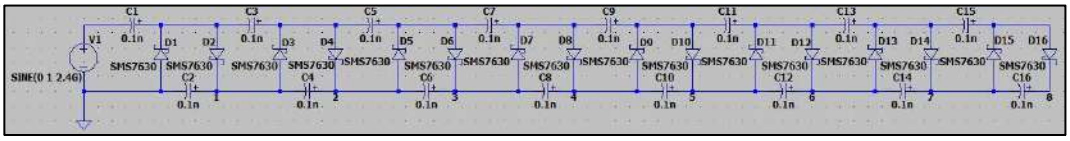


**Figure 3-19: 8 Stages Charge Pump & Rectifier with 0.1nF Capacitor**

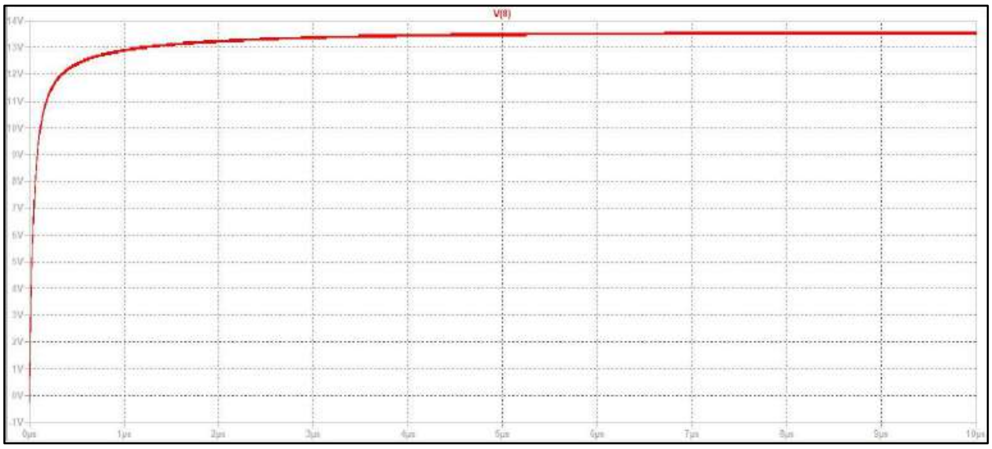


**Figure 3-20: Output at 8th Stage of Charge Pump with 0.1nF Capacitor**

The output of this circuit comes to a steady state after a span of about 3.5 µsec. While there are ripples in the steady state voltages of the output. The output voltage of this circuit is around 11-12V for 8 levels.

### 3.4.2.2 1nF Capacitor Simulation result

The circuit is simulated with capacitors of value 1nF. The input of the circuit is taken as 1 V peak sinusoidal signal with a frequency of 2.4GHz. Charge pump & rectifier circuit with 8 levels is designed and analyzed.

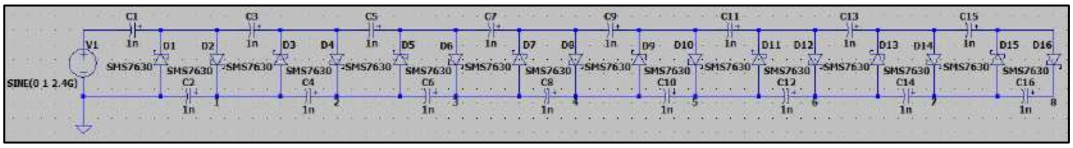


**Figure 3-21: 8 Stages Charge Pump & Rectifier with 1nF Capacitor**

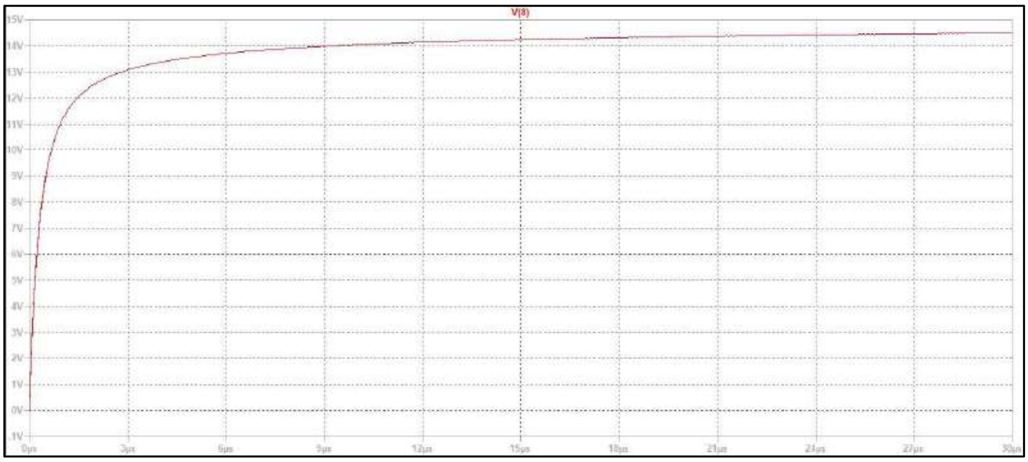



**Figure 3-22: Output at8th Stage of Charge Pump with 1nF Capacitor**

The output of this circuit comes to a steady state after a span of about 18 µsec. While there are no ripples in the steady state voltages of the output. The output voltage of this circuit is around 13-14V for 8 levels.

### 3.4.2.3 10nF Capacitor Simulation Result

The circuit is simulated with capacitors of value 10nF. The input of the circuit is taken as 1 V peak sinusoidal signal with a frequency of 2.4GHz. Charge pump & rectifier circuit with 8 levels is designed and analyzed.

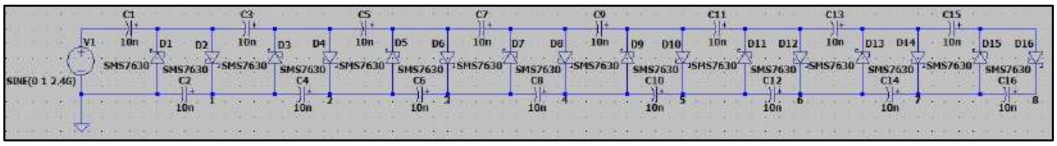


**Figure 3-23: 8 Stages Charge Pump & Rectifier with 10nF Capacitor**

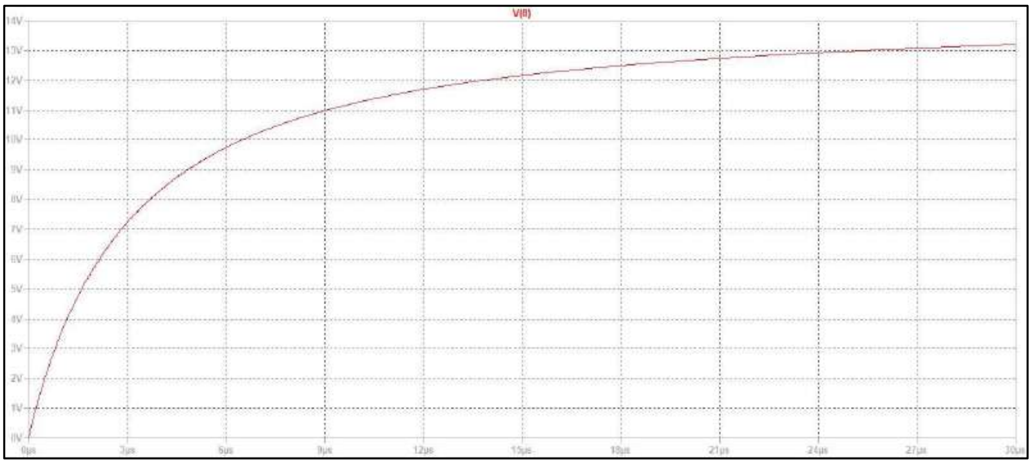



**Figure 3-24: Output at 8th Stage of Charge Pump with 10nF Capacitor**

The output of this circuit comes to a steady state after a span of about 27 µsec. While there are small ripples in the steady state voltages of the output. The output voltage of this circuit is around 12-13V for 8 levels.

#### 3.4.2.4 Capacitor Selected

| Capacitance | Output Voltage at 8th Level | Ripple in Output Voltage | Steady State Time |
|---|---|---|---|
| **0.1nF** | 11 - 12 V | High Ripples | 3.5 µsec |
| **1nF** | 13 - 14 V | No Ripples | 18 µsec |
| **10nF** | 12 - 13 V | Small Ripples | 27 µsec |

**Table 3-4: Comparison between Different Capacitors Output**

From the above results, we can come to a conclusion of capacitor value. The capacitor with lower ripples, lower steady state time and high output voltages is chosen. So the final decision is 1nF capacitor.

### 3.4.3 Fabricated Charge Pump & Rectifier

Charge pump & rectifier circuit is fabricated for 32 stages with capacitance value of 1nF and diodes of SMS7630. The circuit is simulated on LTSpice and the PCB board was designed on Altium Designer software. The fabricated PCB is given below:

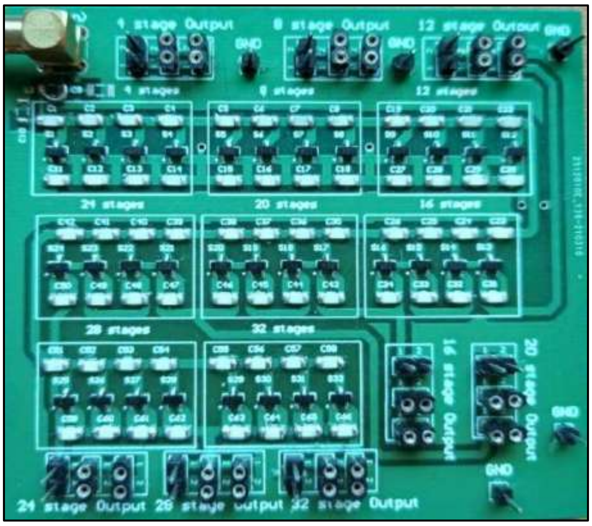



**Figure 3-25: Fabricated Charge Pump & Rectifier Circuit**

## 3.5 Super Capacitors

The output from charge pump circuit is having some ripples and the current at the output is not enough to directly connect a load to it. Therefore, there is a need of an intermediate system which can store the current and will release it slowly to the load connected at the receiving end. There comes two options, one is battery and the second one is capacitor. A battery cannot be used as it is having very large charging time and require a good amount of current. While a capacitor can charge in less time and can be discharged slowly by means of some external circuitry. Due to this, capacitor is chosen.

However, there comes another problem that, a standard value capacitor can discharge instantly when connected to the load. Therefore, we will need to use a super capacitor for our application. A super capacitor is a type of capacitor with high capacitance value and having slow discharging time. The super capacitor is given below:


**Figure 3-26: Super Capacitor**

# CHAPTER 4: INTEGRATING TRANSMITTER AND RECEIVER MODULES AND ANALYZING THE RESULTS

## 4.1 Integrated Transmitter and Receiver Modules

The transmitter and receiver modules are integrated and the results of the power received at the receiving end is analyzed. The prime purpose of all these components and devices is to efficiently transmit a favorable amount of power to the receiver module so that, a load can be powered up wirelessly. The integrated modules are illustrated below:

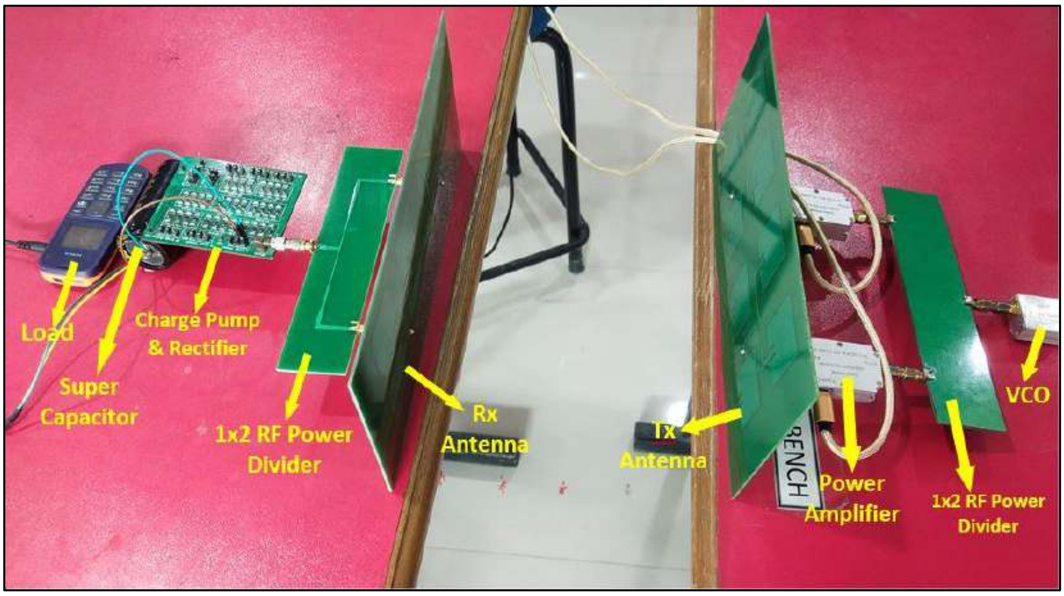



**Figure 4-1: Integrated Transmitter and Receiver Modules**

The results are analyzed using all of the antennas which are fabricated in the previous chapters such as, single element inset feed, 4 elements array form, 2x2 matrix form and two 2x2 matrices form of antennas. These antennas are used at the receiver end while the transmitting antenna which is used is only the two 2x2 matrices form antenna.

## 4.2 Test Results Distance vs. dBm

The results of power received at the receiving antenna in dBm, are taken for each combination of antennas and by varying the distance between the transmitter and receiver modules. The test results are discussed below:

### 4.2.1 Distance vs. dBm Results of Single Element Inset Feed Rx Antenna

The power level is analyzed at the receiving antenna. The results are taken by incorporating the single element inset feed antenna at the receiving end and the two 2x2 matrices form antenna at the transmitting end.

**Figure 4-2: Integrated two 2x2 matrices form at Tx and Single Element Inset Feed at Rx end**

| Distance in cm | Power Level in dBm |
|---|---|
| 10 | 10.8 |
| 20 | 10 |
| 30 | 9.2 |
| 40 | 5.9 |
| 50 | 4.4 |
| 60 | 2.4 |
| 70 | 1.1 |
| 80 | -0.4 |
| 90 | -1 |
| 100 | -3.9 |
| 110 | -5 |
| 120 | -4.5 |
| 130 | -6.8 |
| 140 | -6.6 |
| 150 | -6.4 |
| 160 | -8.3 |
| 170 | -9.7 |
| 180 | -9.7 |
| 190 | -8.6 |
| 200 | -9.2 |

**Table 4-1: Distance vs. dBm by incorporating Single Element Inset Feed Antenna at Rx End**

### 4.2.2 Distance vs. dBm Results of Four Elements Array Form Rx Antenna

The power level is analyzed at the receiving antenna. The results are taken by incorporating the four elements array form antenna at the receiving end and the two 2x2 matrices form antenna at the transmitting end.

**Figure 4-3: Integrated two 2x2 matrices form at Tx and Four Elements Array Form at Rx end**

| Distance in cm | Power Level in dBm |
|---|---|
| 10 | 17.1 |
| 20 | 15.7 |
| 30 | 13.1 |
| 40 | 12.1 |
| 50 | 10.1 |
| 60 | 9.7 |
| 70 | 8.4 |
| 80 | 7.2 |
| 90 | 6 |
| 100 | 5.5 |
| 110 | 3.5 |
| 120 | 3.6 |
| 130 | 3.7 |
| 140 | 1.5 |
| 150 | 1.5 |
| 160 | 2.4 |
| 170 | 0.6 |
| 180 | -0.4 |
| 190 | -0.1 |
| 200 | 0.4 |

**Table 4-2: Distance vs. dBm by incorporating Four Elements Array Form Antenna at Rx End**

### 4.2.3 Distance vs. dBm Results of 2x2 Matrix Form Rx Antenna

The power level is analyzed at the receiving antenna. The results are taken by incorporating the 2x2 matrix form antenna at the receiving end and the two 2x2 matrices form antenna at the transmitting end.

**Figure 4-4: Integrated two 2x2 matrices form at Tx and 2x2 Matrix Form at Rx end**

| Distance in cm | Power Level in dBm |
|---|---|
| 10 | 17.9 |
| 20 | 17.7 |
| 30 | 17.7 |
| 40 | 15.4 |
| 50 | 14.4 |
| 60 | 12 |
| 70 | 11.2 |
| 80 | 9.6 |
| 90 | 8.6 |
| 100 | 7.5 |
| 110 | 6.9 |
| 120 | 5.8 |
| 130 | 5.3 |
| 140 | 4.8 |
| 150 | 3.5 |
| 160 | 3.3 |
| 170 | 3.2 |
| 180 | 2.4 |
| 190 | 1.5 |
| 200 | 1.6 |

**Table 4-3: Distance vs. dBm by incorporating 2x2 Matrix Form Antenna at Rx End**

### 4.2.4 Distance vs. dBm Results of two 2x2 Matrices Form Rx Antenna

The power level is analyzed at the receiving antenna. The results are taken by incorporating the two 2x2 matrices form antenna at both transmitting and receiving ends.

**Figure 4-5: Integrated two 2x2 matrices form at both Tx and Rx ends**

| Distance in cm | Power Level in dBm |
|---|---|
| 10 | 21 |
| 20 | 18 |
| 30 | 17.3 |
| 40 | 14.4 |
| 50 | 13.6 |
| 60 | 12.7 |
| 70 | 11.1 |
| 80 | 10.3 |
| 90 | 9.2 |
| 100 | 8.2 |
| 110 | 7.6 |
| 120 | 6.3 |
| 130 | 6.3 |
| 140 | 5.6 |
| 150 | 4.4 |
| 160 | 4.1 |
| 170 | 4.3 |
| 180 | 3.4 |
| 190 | 2 |
| 200 | 1.6 |

**Table 4-4: Distance vs. dBm by incorporating two 2x2 Matrices Form Antenna at Rx End**

## 4.3 Test Results Distance vs. Voltages

The results of voltages made at 4th stage of charge pump and rectifier circuit are taken for each combination of antennas and by varying the distance between the transmitter and receiver modules. The test results are discussed below:

### 4.3.1 Distance vs. Voltages Results of Single Element Inset Feed Rx Antenna

The results are taken by incorporating the single element inset feed antenna at the receiving end and the two 2x2 matrices form antenna at the transmitting end.

| Distance in cm | Voltages (V) at 4th Stage of Charge Pump |
|---|---|
| 10 | 11.54 |
| 20 | 10.89 |
| 30 | 8.34 |
| 40 | 7.04 |
| 50 | 4.77 |
| 60 | 2.98 |
| 70 | 2.4 |
| 80 | 1.99 |
| 90 | 1.75 |
| 100 | 1.32 |
| 110 | 1.21 |
| 120 | 1.19 |
| 130 | 0.77 |
| 140 | 0.79 |
| 150 | 0.76 |
| 160 | 0.6 |
| 170 | 0.49 |
| 180 | 0.56 |
| 190 | 0.6 |
| 200 | 0.44 |

**Table 4-5: Distance vs. Voltage by incorporating Single Element Inset Feed Antenna at Rx End**

### 4.3.2 Distance vs. Voltages Results of 4 Elements Array Form Rx Antenna

The results are taken by incorporating the 4 elements array form antenna at the receiving end and the two 2x2 matrices form antenna at the transmitting end.

| Distance in cm | Voltages (V) at $4^{th}$ Stage of Charge Pump |
|---|---|
| 10 | 13.55 |
| 20 | 10.76 |
| 30 | 10.02 |
| 40 | 8.78 |
| 50 | 8.38 |
| 60 | 5.31 |
| 70 | 4.65 |
| 80 | 3 |
| 90 | 2.71 |
| 100 | 2.31 |
| 110 | 2.28 |
| 120 | 2.16 |
| 130 | 1.55 |
| 140 | 1.67 |
| 150 | 1.8 |
| 160 | 1.26 |
| 170 | 1.12 |
| 180 | 1.18 |
| 190 | 1.29 |
| 200 | 1.23 |

**Table 4-6: Distance vs. Voltage by incorporating 4 Elements Array Form Antenna at Rx End**

### 4.3.3 Distance vs. Voltages Results of 2x2 Matrix Form Antenna

The results are taken by incorporating the 2x2 matrix form antenna at the receiving end and the two 2x2 matrices form antenna at the transmitting end.

| Distance in cm | Voltages (V) at 4$^{th}$ Stage of Charge Pump |
|---|---|
| 10 | 16.17 |
| 20 | 15.07 |
| 30 | 13.58 |
| 40 | 11.33 |
| 50 | 10.57 |
| 60 | 9.91 |
| 70 | 8.74 |
| 80 | 7.83 |
| 90 | 6.57 |
| 100 | 5.05 |
| 110 | 4.24 |
| 120 | 3.81 |
| 130 | 2.91 |
| 140 | 2.98 |
| 150 | 2.65 |
| 160 | 2.04 |
| 170 | 2.03 |
| 180 | 2.07 |
| 190 | 2.08 |
| 200 | 1.76 |

**Table 4-7: Distance vs. Voltage by incorporating 2x2 Matrix Form Antenna at Rx End**

### 4.3.4 Distance vs. Voltages Results of two 2x2 Matrices Form Rx Antenna

The results are taken by incorporating the two 2x2 matrices form antenna at both the transmitting and receiving ends.

| Distance in cm | Voltages (V) at $4^{th}$ Stage of Charge Pump |
|---|---|
| 10 | 18.49 |
| 20 | 13.76 |
| 30 | 13.47 |
| 40 | 11.35 |
| 50 | 10.55 |
| 60 | 10.35 |
| 70 | 9.52 |
| 80 | 8.81 |
| 90 | 8.23 |
| 100 | 6.9 |
| 110 | 6.66 |
| 120 | 5.22 |
| 130 | 4.25 |
| 140 | 4.43 |
| 150 | 3.43 |
| 160 | 2.68 |
| 170 | 2.6 |
| 180 | 2.2 |
| 190 | 2.7 |
| 200 | 2.18 |

**Table 4-8: Distance vs. Voltage by incorporating two 2x2 Matrices Form Antenna at Rx End**

## 4.4 Comparing Each Antenna Results

The results of the power and voltages recorded at each of the receiver antenna is compared with each other by simulating the results in the form of graph. The graph is plotted between distance and power, and distance and voltage (at $4^{th}$ stage of charge pump).

### 4.4.1 Comparing Power of each Antenna

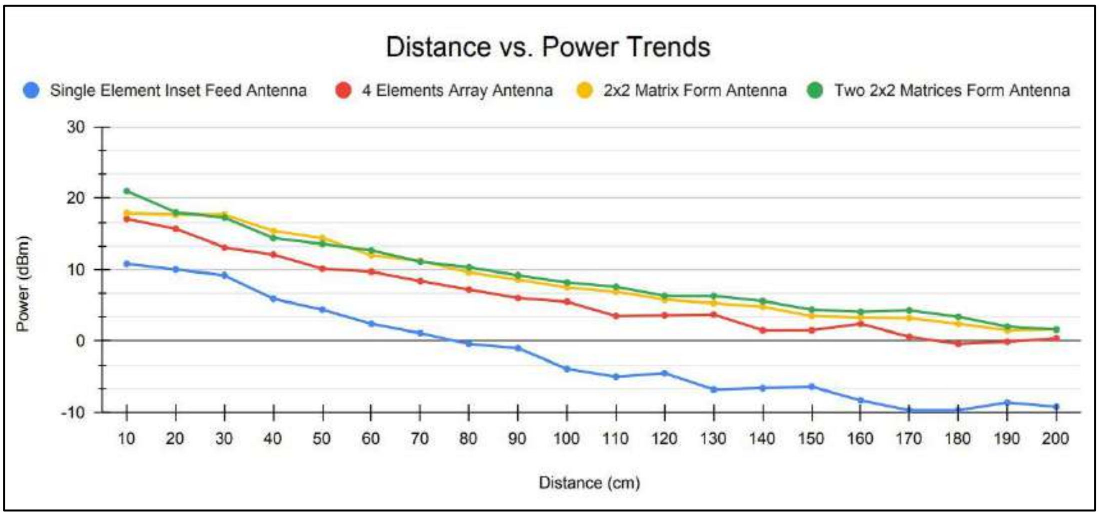



**Figure 4-6: Distance vs. Power Trend of different Rx Antennas**

From the graph plotted, we can conclude that the two 2x2 matrices Antenna is working so well that the power received by this antenna is maximum from all of the other antennas.

### 4.4.2 Comparing Voltages of each Antenna

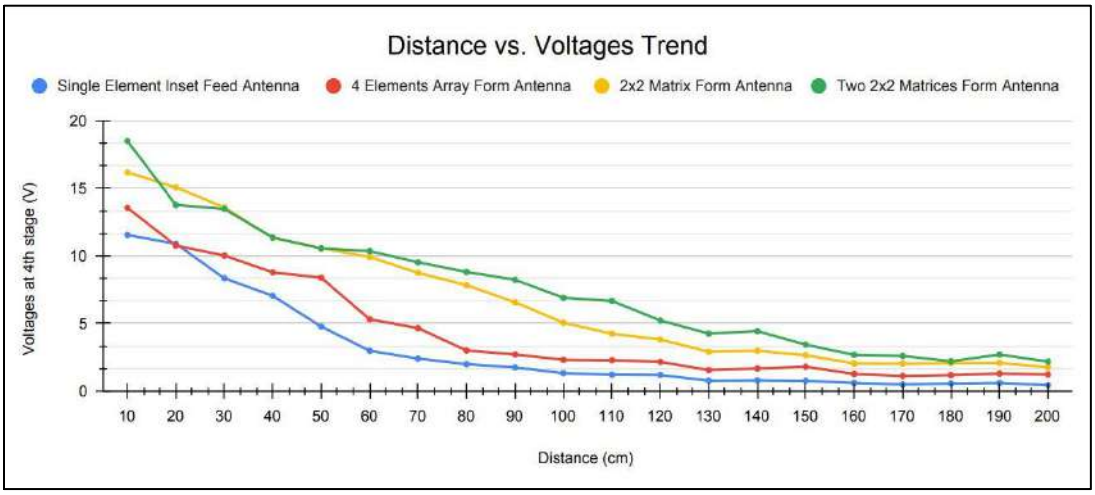



**Figure 4-7: Distance vs. Voltage Trend of different Rx Antennas**

From the graph plotted, we can conclude that the two 2x2 matrices Antenna is working so well that the Voltages recorded at the $4^{th}$ stage of charge pump received by this antenna is maximum from all of the other antennas.

# CHAPTER 5: CONCLUSION AND FUTURE DIRECTIONS

## 5.1 Conclusion

A vast amount of research is conducted to ensure maximum power is transmitted and received by the system. The transmitter module is designed in such a way that the gain and directivity of the antennas are maximum enough so that, all the power is transmitted into the direction of the receiver module. The antennas are designed on the substrate FR-4 with dielectric constant of 4.4F/m. The receiver module is also consist of antennas with high gain and directivity so that, all the power coming from the transmitter module is being received by the receiver module. By using the designed and fabricated transmitter and receiver module prototypes, 1 Watt of power is successfully transmitted from Transmitter to Receiver module at a distance of 2 meters. The Receiver module then processed the power and generated DC 5V and 0.6mA of current by using charge pump and rectifier circuit at the receiver end, which is then used to power up the loads, such as Mobile Phones.

## 5.2 Future Directions

We have successfully designed and tested efficient transmitter and receiver modules. However, there could be some improvements in the system such as:

- There can be a communication between Transmitter and Receiver module by which the transmitter module will direct its beam of power to the receiver modules position automatically.
- The beam can be electronically shifted to the position of receiver by using phase shifter ICs.
- Procuring or designing an amplifier which can give output power of greater than or equal to 40dBm. So that, an optimum amount of power will be received by the receiver module.
- The antennas are designed in such a manner that their gain, and directivity is more improved while keeping the return loss as small as possible to transmit the power at far distances.

# COST ANALYSIS

| S No. | Product Name | In Number | Price in PKR |
|---|---|---|---|
| **1** | Tx Rx Antennas and Divider Board | 1 | 18,000/- |
| **2** | Power Amplifiers | 2 | 8,000/- |
| **3** | Voltage Controlled Oscillator | 1 | 7,500/- |
| **4** | Capacitor, Diodes, Wires and SMA Connectors | 1 | 15,000/- |
| **5** | PCB Boards and Etching Solutions | 1 | 1,100/- |
| **Total Amount** | | | **49,600/-** |

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