INKJET-PRINTED BROADBAND ENERGY HARVESTERS, RECTIFIERS FOR 5G AND IOT APPLICATIONS FEATURING BROAD RANGE MATCHING CAPABILITIES

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Presented to
The Academic Faculty

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LEHARIKA PRAKASH

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INKJET-PRINTED BROADBAND ENERGY HARVESTERS, RECTIFIERS FOR 5G AND IOT APPLICATIONS FEATURING BROAD RANGE MATCHING CAPABILITIES

Approved by:

Dr. Emmanouil M. Tentzeris, Advisor
School of Electrical and Computer Engineering
Georgia Institute of Technology

Dr. Andrew F. Peterson
School of Electrical and Computer Engineering
Georgia Institute of Technology

Dr. Gregory G. Durgin
School of Electrical and Computer Engineering
Georgia Institute of Technology

Date Approved: [December 10, 2022]

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SUMMARY

The need for 5G and the constant improvement in connecting broadband networks to devices has been a research area which has been advancing since recent times. With its ability to support millions of devices along with connecting them and providing mission-based applications such as health monitoring, collecting data etc., it has set a pathway for IoT devices to be used and connected with ultra-efficiency. Apart from this, since the inception of 5G, a lot many researchers have been working on a technique that can harvest power through this network for wireless and wearable devices. This is implemented by designing energy harvesters and rectifiers to harvest energy from the 5G network. This is done by converting the radio frequency waves from the network to usable power. Since this method also comes under wireless charging, it has been one of the most anticipated and prominent technologies for the present and the future of Electromagnetics.

With the increase of designing rectifiers, rectennas (rectifying antennas) and energy harvesters, this method has been effective due to its capability of achieving high transmittable power which can be used as a replaceable battery for many electronic devices. Hence many efforts have been taken to work on providing the best power deliverability via the wireless approach, and one solution was to increase or widen the bandwidth of the reception of radio waves. Popularly known as broadband energy harvesting it has been a desired feature in the implementation of providing better power facility for a lot of microelectronic and other devices, mainly because using narrow bandwidths for energy harvesting can prove to be an issue where there can be a high possibility of sudden drop of power due to a variety of factors affecting it such as excitation level etc. Hence this thesis provides many approaches and results which can act as a basis for the design, modeling, and simulation of multiple rectifiers and energy harvesters for 5G and IoT

applications. The proposed research focuses on using the solution of designing broadband energy harvesters and rectifiers.

The focus would be on developing the antenna gain, bandwidth, size along with a comparison of which type of antenna can be used for this application to understand which antenna can have the capability to radiate as well as receive the RF energy with minimum loss. Methods and solutions to improve the bandwidth of the antenna will also be proposed. The design of a rectifier will be an essential factor in the energy harvesting circuit, since the target of receiving the best RF to DC conversion with less loss would be determined. The energy leakage in the system due to power leakage during transmission due to narrow bandwidth will be addressed by designing a good impedance matching network between the antenna and the load. Matching circuits also come into picture, as due to the presence of large input signal, the rectifier can operate in different regions, which can result in impedance variation leading to variable input power and other issues. This thesis will hence propose the solutions for these issues by using broadband frequency range in wide band and will compare, deduce, design, model and simulate the output of these energy harvester circuits and rectifiers.

This thesis will hence prove to be an effort to focus on designing wide band energy harvesters and through the process, also discovering which application can be a better option for this kind of design. This will not only help in providing guidance but also understand the new issues faced with this kind of approach. We should also make note that the overall power conversion efficiency can be obtained by maximizing the efficiency of the individual component of the circuit. As a result, major attention will be given to understand which substrate or component can be used to design a circuit to obtain wide range and large bandwidth along with great power efficiency in each step of designing the circuit network.

CHAPTER 1

INTRODUCTION

Wireless technology has been one of the most prominent technologies in this era with many applications pertaining especially in 5G, mobile phones and smart applications such as IoT, involving health and sensor networks. Primarily, this technology's motive was to replace the current batteries in these devices with wireless batteries. The focus is made on wireless charging techniques, one of which relates to Radio Frequency Energy Harvesting, also known as RF Energy Harvesting. Many research teams are working on the autonomy of the batteries by reducing the consumption of the devices. Other teams have chosen to recycle ambient energy like in MEMS [1]. The charging of multiple applications is easy because the user can do it easily, like for mobile phones. But for other applications, like wireless sensor nodes located in difficult access environments, the charging of the batteries remains a major problem [2]. Hence, Wireless Radio Frequency energy harvesting seems to be one of the solutions for both 5G and IoT based applications.

This thesis projects the need for RF energy harvesting in wireless technology, introducing broadband behavior, the various design steps involved as well as result comparison and analysis for 5G and IoT. RF harvesting differs from traditional power sources because it can pull energy out of the air, precisely from the frequency band, reducing or eliminating the need for a battery charge to power devices that always require energy to run [3]. With different power harvesting technologies that have been in use for a long time, radio frequency energy harvesting seems to be an efficient, cost-cutting solution to replace the current batteries, which can prove to offer unlimited life span and hence be rechargeable wirelessly, thereby making a lot of smart technologies involving batteries – including sensing with IoT, a lot more convenient to design as well as to use depending on the required application. In near future, this technology will be able to harvest power for small and smart devices offering good efficiency in parallel, which is its biggest advantage. Following this page, further description is made regarding the need for broadband rf energy harvesters, the corresponding designs, and results, as well as summary and future enhancements.

1.1 Radio Frequency Energy Harvesting

RF Energy Harvesting uses antennas to capture the Electromagnetic waves from air and convert it into DC power using rectifiers. The frequency range and operating power range of an RF harvester depends on the transmitting source available. The common wireless sources include 2G/3G/4G/5G cellular towers or BSs (Base Stations), radio signal transmitting stations, TV signal broadcasting stations, Satellites, Wi-Fi kiosks/routers, satellites, NFC transmitter, RFID readers, BLE (Bluetooth Low Energy) transmitter, UHF transmitter etc. [5].

1.1.1 DIFFERENT BLOCKS OF AN RF ENERGY HARVESTER

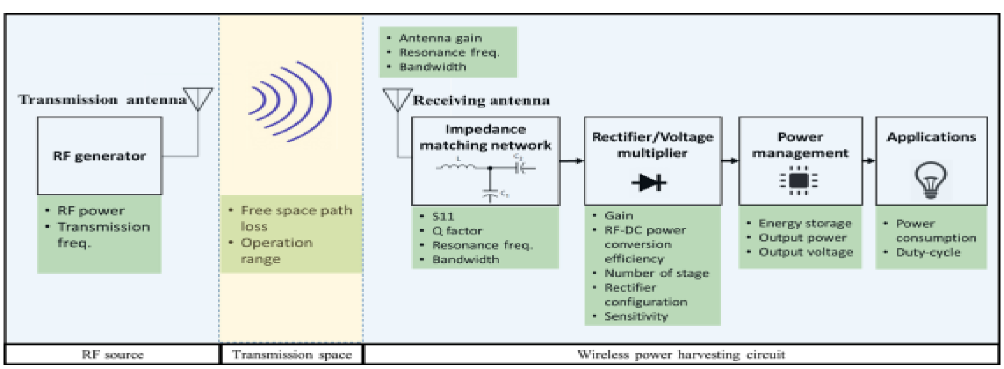

Figure 1 – Block Diagram of an RF Energy Harvester

A typical RF Energy Harvester receives the EM waves from a transmission antenna at a particular frequency, which travels along a free space path at its operational range. The primary block is the receiving antenna. This receiving antenna can be designed based on numerous factors, such as the application it can be used in, the operating frequency and the frequency band it can receive the EM waves from the transmission antenna. Effort needs to be put on choosing an antenna for an RF energy harvester, since compared to other antennas, this antenna needs to be the desired size, cost and yield satisfactory results depending on the use, in this case, IoT or smart implementation. Another factor to be considered is the S parameter results also whether it captures the EM waves at a single frequency or, in our case, a wide range of frequencies. Achieving good gain and resonance in both cases is crucial to achieve good RF-to-DC efficiency.

The next design block is an impedance matching circuit, which optimizes the performance of the entire harvester. To do so, effort should be put in designing circuits that can input signals of large frequencies and boost the impedance between the receiving antenna and the rectifier. One point to be noted here is that this circuit is accompanied with a voltage boosting circuit or a voltage doubler along with a rectifier, which converts the RF frequency received by the receiving antenna to DC voltage. In many cases, we need to match the impedance obtained from the antenna and the rectifier, and hence the impedance matching circuit takes effect in getting the desired result.

The third component of the RF Energy Harvester is the rectifier, which converts the EM waves to DC power/voltage, which then can be used to charge or be used as a voltage/power supply to the desired device. Again, although RF energy harvesting itself can be classified into Far Field

Radio Frequency Energy Harvesting and Near Field RF Energy Harvesting, in this thesis, our focus is

on near field, since most of the smart applications involve near field, meaning, the device, the transmission antenna and the user are in a close to one another. This rectifier usually contains a diode to perform the rectification, and the design can be modified into achieving best power conversion efficiency. Since the impedance matching circuit tries to maximize the power transfer between the source and the load, the rectifier, then takes this input, and converts into a DC power/ voltage. This process is known as rectification.

The power management block acts as an add on block which acts as an AC block to block any unwanted altering AC voltages obtained after rectification in case there is a significant percentage of unsuccessful rectification. It also manages the output DC power, for example, it can contain voltage boost and buck convertors, designed according to the desired output voltage depending on the application.

1.2 Broad Band RF Energy Harvesting

The primary difference between an RF energy harvester and a broad band RF energy harvester is that a Broadband RF energy harvester is capable of harvesting energy from a wide range of frequencies, not only a single frequency. While the general harvester is designed at one frequency, in this harvester the distinguishable feature is that the receiving antenna is designed to capture EM waves at a broad range, depending on the application, this range can vary between a few MHz to GHz.

1.2.1 Advantages of Broadband RF Energy Harvesting

The main advantage of a Broadband RF Energy Harvester is that it has more choices in frequencies to harvest energy power from, meaning, it can cover one or more of the frequencies covered by different existing frequency bands such as WIFI, GSM, 4G, sub 6 5G, 5G and MM wave frequencies Also, since this method proves to get minimum wastage, it can also be tagged as a provider for sustainable/green energy. Lastly, since it provides a wide band of frequencies to harvest energy from, the power dissipation and the obtained power is also comparably more than that of the energy harvester with receiver antenna at a single/ narrow band of frequencies.

1.2.2 Types of Broadband RF Energy Harvester systems

There are two types of Broadband RF Energy Harvester systems – namely, dedicated broadband RF Energy Harvester System and Ambient Broadband RF Energy Harvester System. Dedicated RF Energy Harvester Systems have dedicated RF sources and the energy supplier is predictable. However, with Ambient RF Energy Harvesting, the RF sources are not dedicated, and it is not controllable. One major disadvantage with ambient/ubiquitous RF Energy Harvesting is that they provide low power densities since the RF source power is not assigned particularly.

Figure 2 – Ambient RF Energy Harvesting [6]

1.3 Applications of RF Energy Harvesting

1.3.1 Wireless Sensor Networks

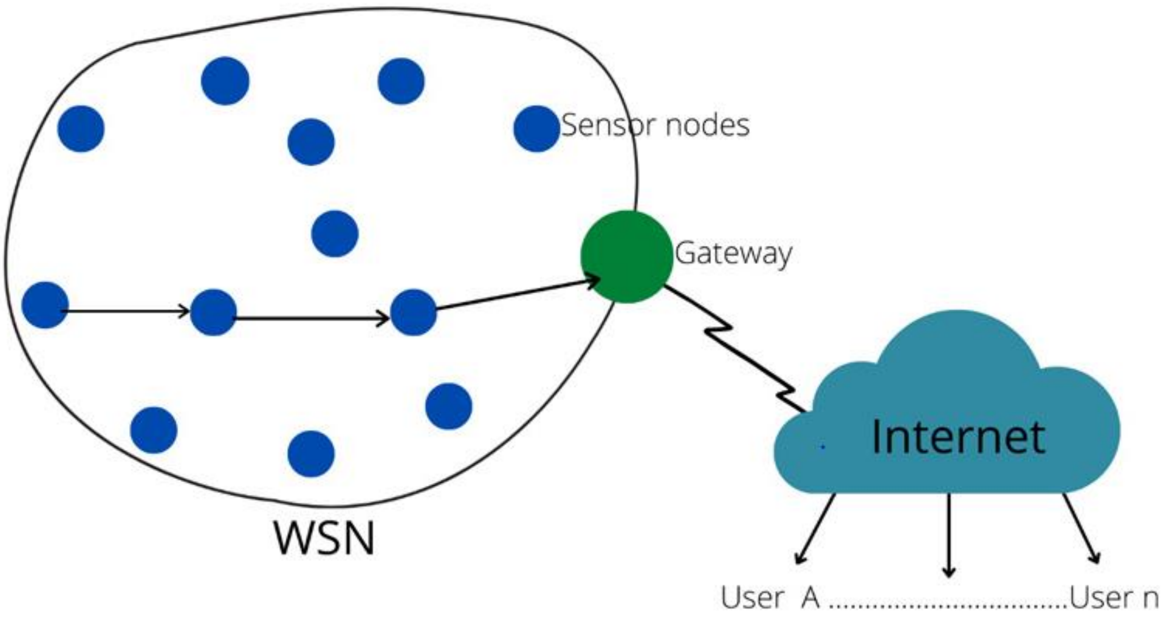

Figure 3 – Wireless Sensor Network architecture [8]

RF Energy Harvesting offers a crucial advantage in providing wireless connections or any replacements in batteries for Wireless Sensor Networks, where primarily these sensors are embedded in a network, providing, and transmitting data continuously, thereby offering great functionality by self-powering batteries of the sensors, which leads to a lower cost architecture [8].

1.3.2 Versatility

The major reason RF energy harvesting is better than other harvesting techniques, is that it provides a cost-efficient way to replace batteries. We know that batteries used in devices, especially in smart devices such as mobile phones are not only expensive, but also need to be charged on a daily or at least once in two or three days. Some devices even need continuous power, which brings up a need for RF Energy Harvesting – this technology offers continuous supply of power to the devices, hence ensuring versatility, not only in conserving a tremendously large amount of power, but also providing a green solution to consume sustainable energy in the most efficient way. In fact, the energy present in Radio Frequencies in the air, was not in consideration for a long time, until in the 20th Century, scientists realized that we have a ubiquitous amount of power present that can be harvested continuously. Another point that can be made here is that batteries come in varied sizes and shapes, however most of the near field rf energy harvesters can be designed with a far more reduced battery size and weight, offering an additional advantage of portability. RF Energy Harvesters can also be integrated in many of the smart IoT devices and sensors too.

1.3.3 IoT

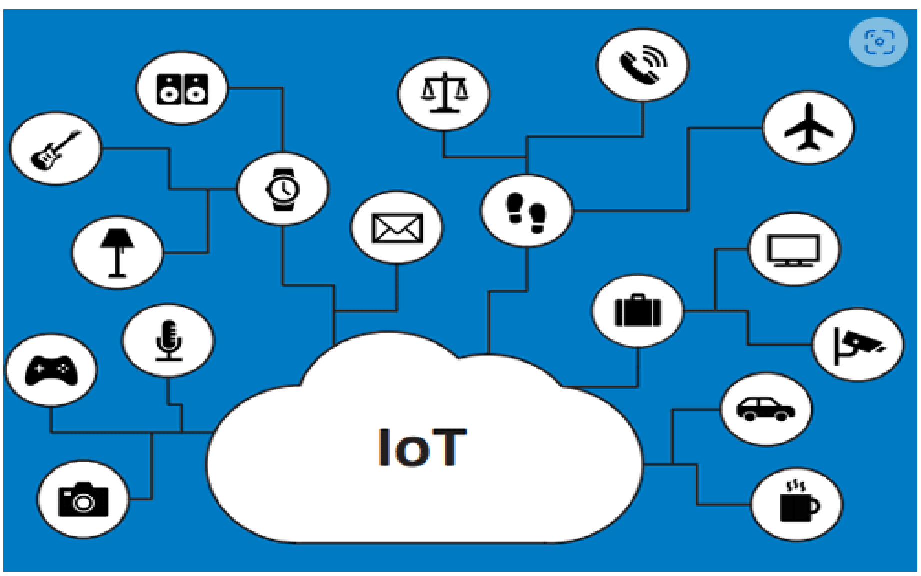

Figure 4 – Applications of IoT [8]

IoT, also known as Internet of Things, provides a wide range of applications such as gaming, emails, audio, video, sensor, heat, health, time, accessibility etc. With all these smart applications comes the need of designing complex devices with low power consumption, less weight, and less cost for people to use it conveniently. RF Energy Harvester can be an add on solution to charge the batteries present in the IoT devices for more flexibility in various applications. For example, for wearable IoT devices, an RF Energy Harvester can be implemented with flexible substrates, which can not only make the device light weight, but also give efficient power. In some cases, in other harvesting techniques such as solar energy harvesting, where the device does not receive enough Solar power, an RF energy Harvester can come into picture offering better accessibility to the device, thereby offering better performance capabilities. In this thesis, we have designed the harvester with the IoT frequency band in consideration.

CHAPTER 2

ANTENNA DESIGN

2.1 Antennas – an overview

Antennas are devices which can send and receive signals. They convert electromagnetic waves to electrical waves. Depending on different requirements, we have several types of antennas supporting different frequencies, either a single frequency or multiple frequencies. With time, there came a need of designing an antenna for an ultra-wide range of frequencies, to achieve different applications at once. For instance, by including the ISM frequency band, Wi-Fi and IoT frequency bands into consideration while designing a broad band antenna, we can achieve flexibility as well as a broad bandwidth to cover all wireless services [9].

2.1.1 Broadband Antennas

Ultra-wideband (UWB) is a radio transmission technology which occupies an extremely wide bandwidth exceeding the minimum of 500MHz or at least 20% of the center frequency [10]. Not only do we get to operate different applications through broadband, but in case of RF Energy Harvesting, we also can achieve good RF to DC power conversion efficiency through the band which can help charge most smart devices operating through those frequencies. Hence, broadband antennas form an important design block in designing a rectenna or an RF Energy Harvester. One major factor to consider while designing a broadband antenna is choosing the bandwidth for the antenna to achieve the desired return loss as well as the application.

2.2. Criteria for broadband antenna design

2.2.1 Wide Impedance Bandwidth

While there are different applications and different frequency bands that a broadband antenna can operate, close attention should be given when designing antenna and choosing the frequency band, which highly depends on many factors, such as cost, weight, size, and use. In terms of harvesting RF energy, in the case of broadband, we need to make sure we achieve good resonance mostly throughout the band – about less than -10dB, which ensures good wide impedance bandwidth.

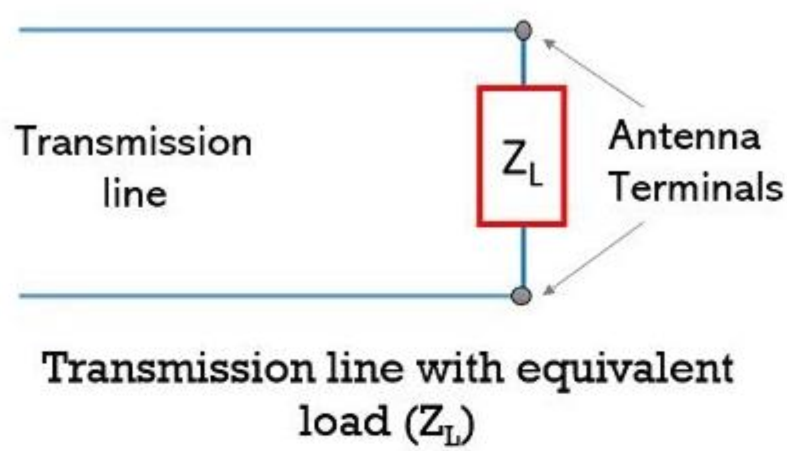

Figure 5 – Impedance across antenna terminals [11]

To calculate the impedance of the antenna, it is given by the below formula:

$$Z_{11} = R_{11} + jX_{11} \tag{1}$$

Where Z denotes the self-impedance of the antenna, R denotes the radiation resistance and X denotes the radiation reactance of the antenna [11].

2.2.2 Polarization

Antenna Polarization is the term used in correspondence with the electromagnetic wave radiated through it. It is defined as the orientation of the electric field vector of the radiated electromagnetic wave by the antenna with a negligible number of losses [12]. It is important to choose an antenna based on the type of polarization, since distinct types yield different results. Since polarization of an antenna is determined by the Electric Field Vector of the Electromagnetic wave, a linear polarized antenna would radiate waves involving either horizontal or vertically polarized electric field vector. Usually for a wideband antenna, circular polarization has been proven to yield effective results in achieving and improving the impedance of the antenna, the axial ratio, as well as the gain of the antenna throughout the bandwidth. Axial ratio is the ratio of major and minor axis of a circularly polarized antenna pattern. It gives us the measure of deviation from the best case.

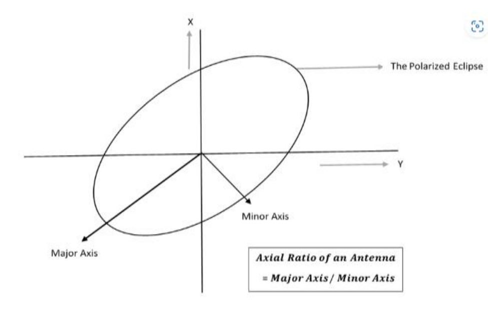

Figure 6 – Determining Axial Ratio of an Elliptical Antenna [13]

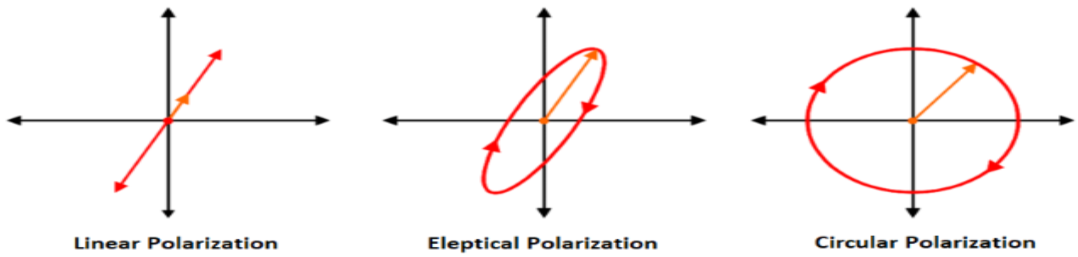

Figure 7– Different types of polarization [13]

2.2.3 Size, cost, and application

Broadband antennas, when chosen by material and application, can vary in sizes. However, since the thesis covers 5G and IoT as the main technologies in focus, the antennas have been designed accordingly. Compactness, light weight, and good gain values are to be achieved when choosing to design a broadband antenna for 5G and IoT, since most of the antennas designed for these applications are not only flexible but also achieve a high data rate in these frequency ranges. One additional frequency band included is the mm wave frequency band, which typically lie between the frequency range 30-300GHz. The thesis covers up to 80GHz. The band from 3-30GHz is known as the microwave band, which is used for telecommunication. The terahertz band is just above the millimeter-wave band and is typically defined to cover the 300 GHz to 3 + THz range. The wavelength of electromagnetic radiation is given by $\lambda = c/f$, where $c = 3 \times 10^8\ m/s$ is the speed of light and f is the frequency (in Hz)[14].

2.3 Design 1 – Elliptical Edge Slot Antenna

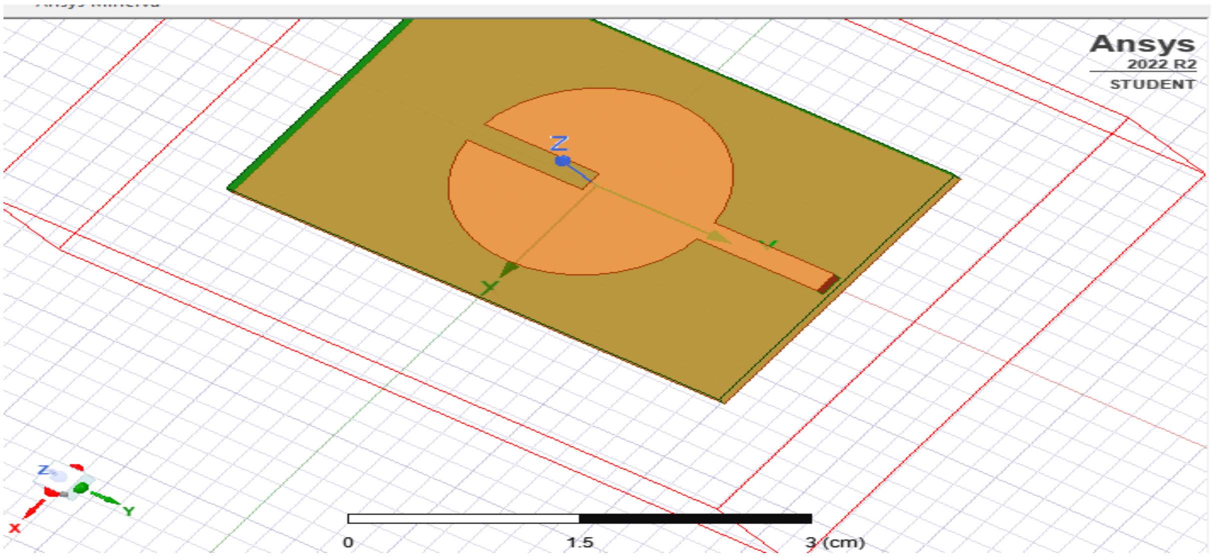

Figure 8 -Elliptical edge patch antenna with slot

2.3.1 Design motivation and overview

The first antenna design is an elliptical edge patch antenna with a vertical slot from the center of the ellipse of the antenna. The main difference between this patch antenna and the other antennas which would be included in this thesis below is that this antenna has a slot, which is designed to achieve wider bandwidth, less radiation loss and low dispersion. For the antenna to demonstrate broadband behavior, the antenna should project return loss less than -10dB and consistent or higher gain over the frequency range.

Babinet's principle relates the radiated fields and impedance of an aperture or slot antenna to that of the field of its dual antenna.[15]. Hence when a slot is introduced in an antenna, the electric field travels all around the circumference or the perimeter of the slot (depending on if it is a circular or polygon in shape). It is to be noted that slots can hold different shapes, depending on where we want to achieve the highest gain, which frequency band we choose and what materials we use to design our antennas. With slot antennas, we also need to consider the principle of duality, which means that when the slot is introduced, the polarization of the antenna can be reversed.

2.3.2 Design Equations

In an elliptical patch antenna, the semi-major axis, semi minor axis, and effective semi-major axis are designated as a, b and $aeff$ respectively [16]. We can determine the dual resonance frequency of the elliptical edge slot antenna using the below mentioned Mathieu functions [16].

$$a_{eff} = a[1 + \frac{2h}{\pi \varepsilon_r a}\{ \ln(\frac{a}{2h}) + (1.41\varepsilon_r + 1.71) + h\alpha 0.268\varepsilon_r + 1.6512 \tag{2}$$

$$f_{11}^{e,0} = \frac{15}{\pi e a_{eff}}\sqrt{\frac{q_{11}^{e,0}}{\varepsilon_r}} \tag{3}$$

$$q_{11}^{e} = -0.0049e + 3.7888e^2 - 0.7278e^3 + 2.314e^4 \tag{4}$$

$$q_{11}^{0} = -0.0063e + 3.8316e^2 - 1.1351e^3 + 5.2229e^4 \tag{5}$$

where, a = length of semi-major axis; h = height of dielectric substrate; $aeff$ = effective length of semi-major axis; εr =permittivity of dielectric substrate; e = eccentricity of elliptical patch [16]. It should be noted that f11(e,0) is known as dual resonance frequency and q11(e,0) is the approximated Matthieu function of the TM 11 e,0 mode, which is the dominant mode [16].The size of the patch dimensions (width and length) can be calculated via the following equations:

$$f_L = \frac{7.2}{(L+r+P)*k}\ GHz \tag{6}$$

$$L = 2B \tag{7}$$

r = A/4 (8)

Here fL is known as lower edge frequency, h is the substrate thickness which has been taken 1.575mm as a typical value for the ROGER DUROID 5870 TM Substrate. Similarly, the patch length and the microstrip line width and the effective dielectric constant calculated with the below mentioned formula:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \quad (9)$$

Table 1 – Design parameters of the antenna

PARAMETER	VALUE
Operating Frequency	22.5GHz
Substrate	ROGER DUROID 5870 TM
Major Radius	0.952cm
Elliptical ratio	1(circle)
Edge feed width	0.192cm
Edge Feed Length	0.562cm
Feed Width	0.1972cm
Feed Length	0.914cm
Height	0.1575cm
Substrate length	4.05cm
Substrate width	2.7cm

The materials for antenna and ground plane are copper, and the ground plane is the same size as that of the substrate.

2.4 Simulated Results

2.4.1 Gain plots

This antenna has been designed at the operating frequency of 22.5GHz and shows broadband behavior from 22.5GHz to 40GHz. The gain plots are simulated in ANSYS HFSS at frequencies 10GHz, 22.5GHz, 28GHz and 32GHz with the obtained gain as follows:

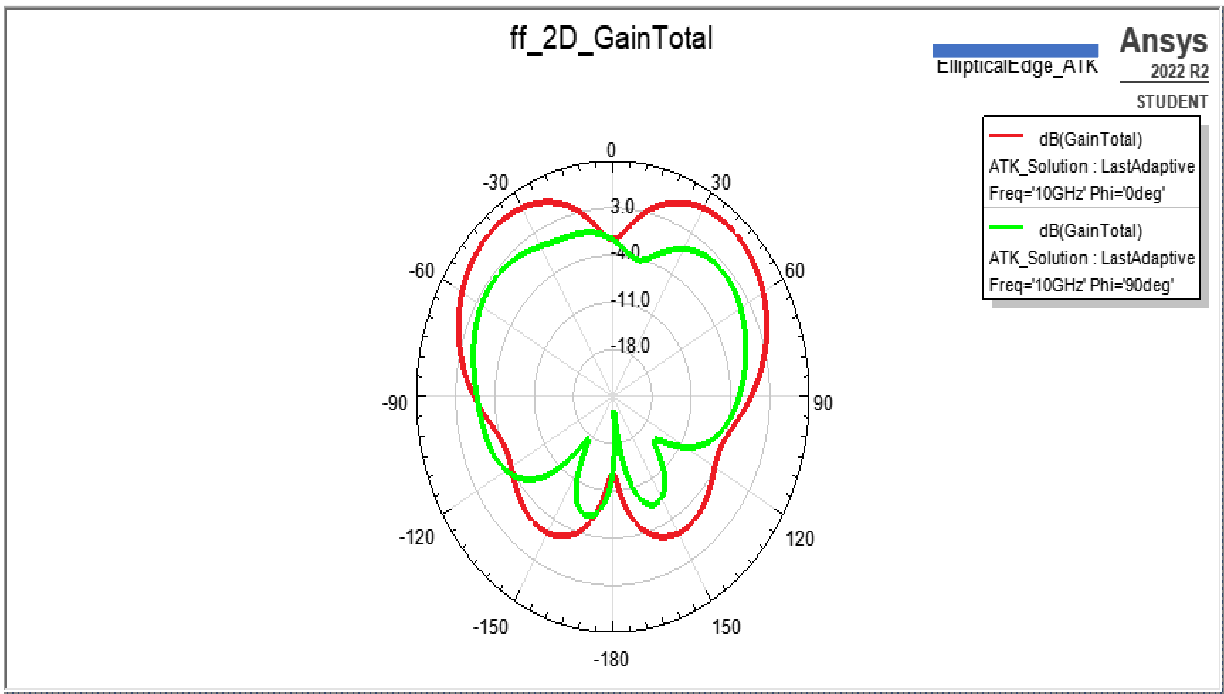

Figure 9 – 2D Gain and directivity plot at 10GHz

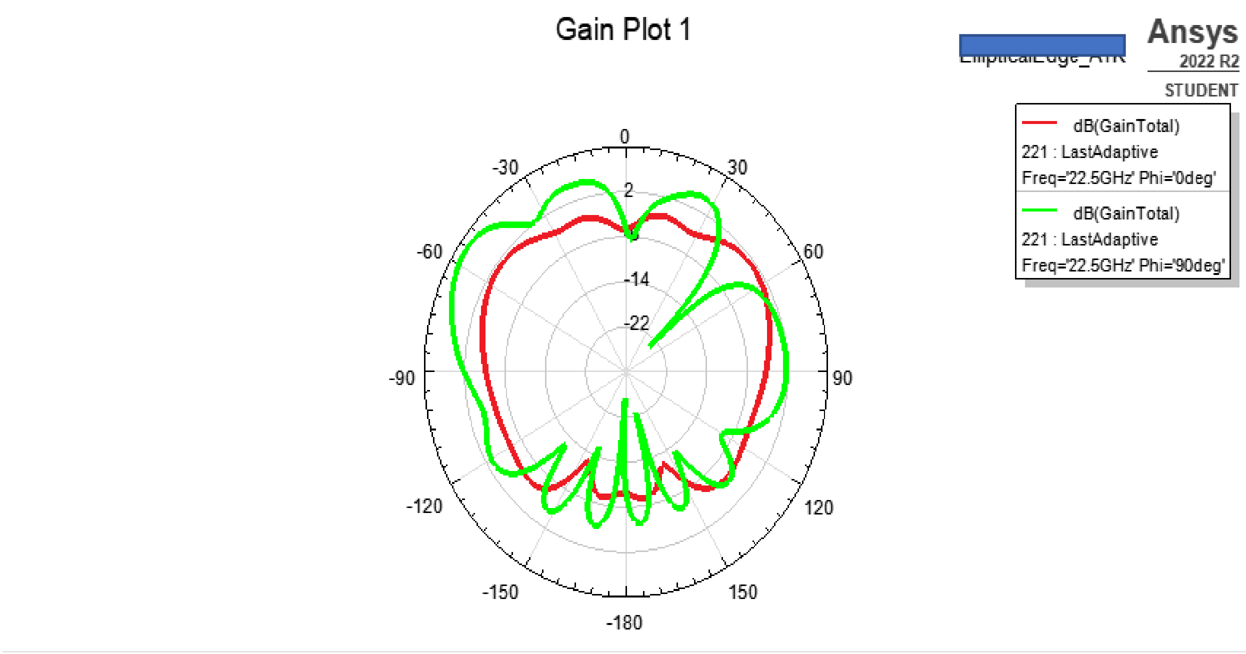

Figure 10 – 2D Gain and directivity plot at 22.5 GHz

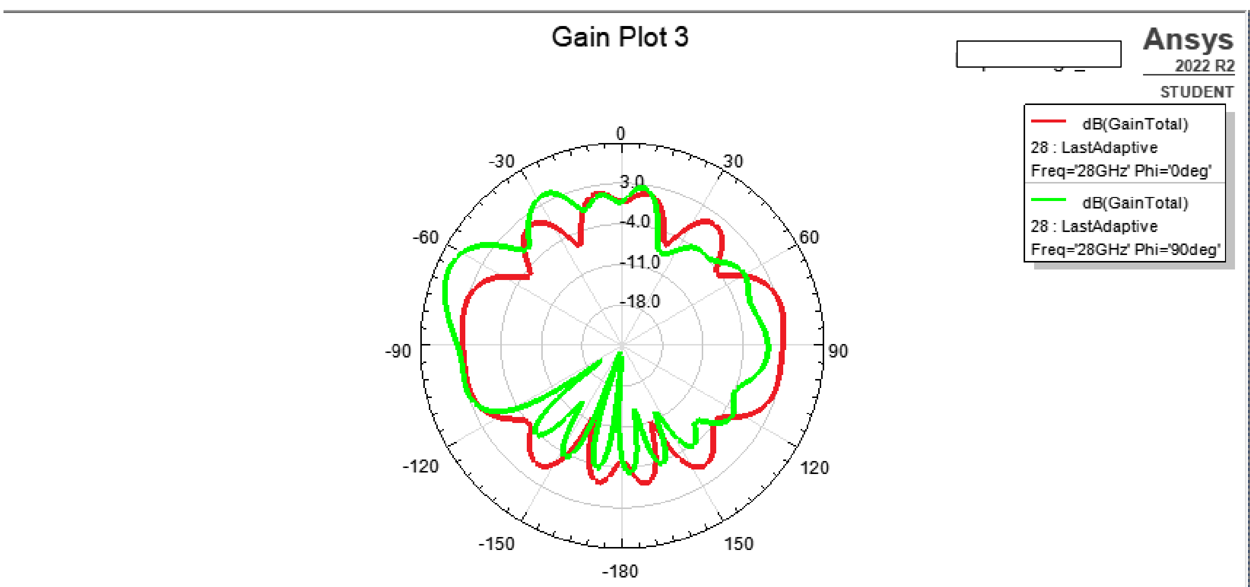

Figure 11 – 2D Gain and directivity plot at 28GHz

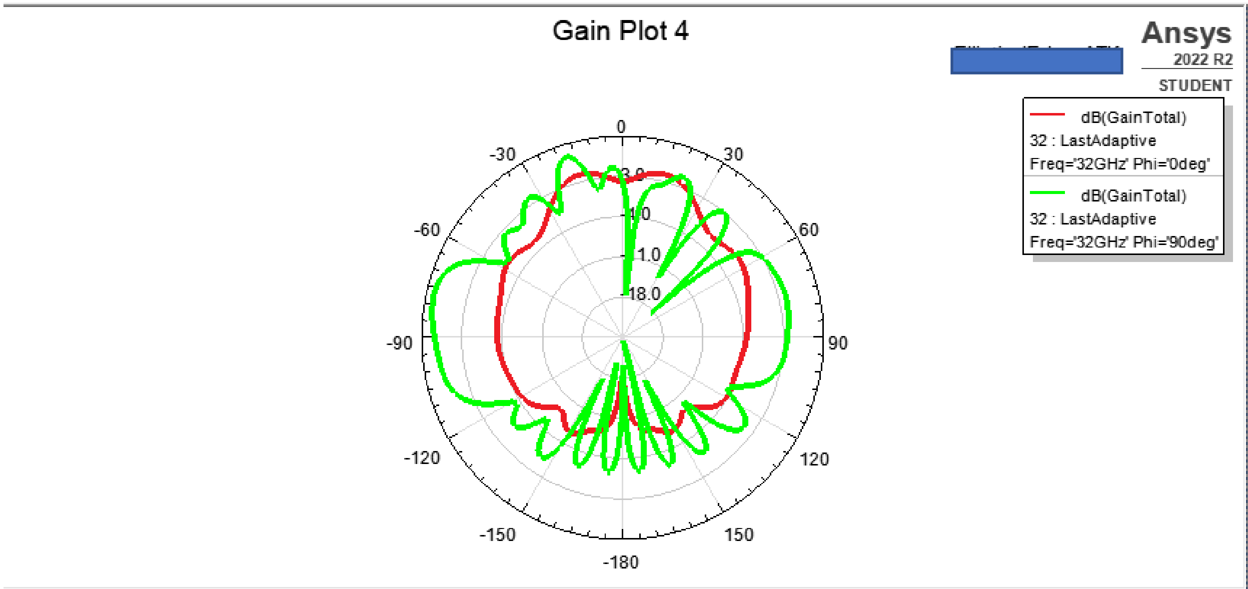

Figure 12 – 2D Gain and directivity plot at 32GHz

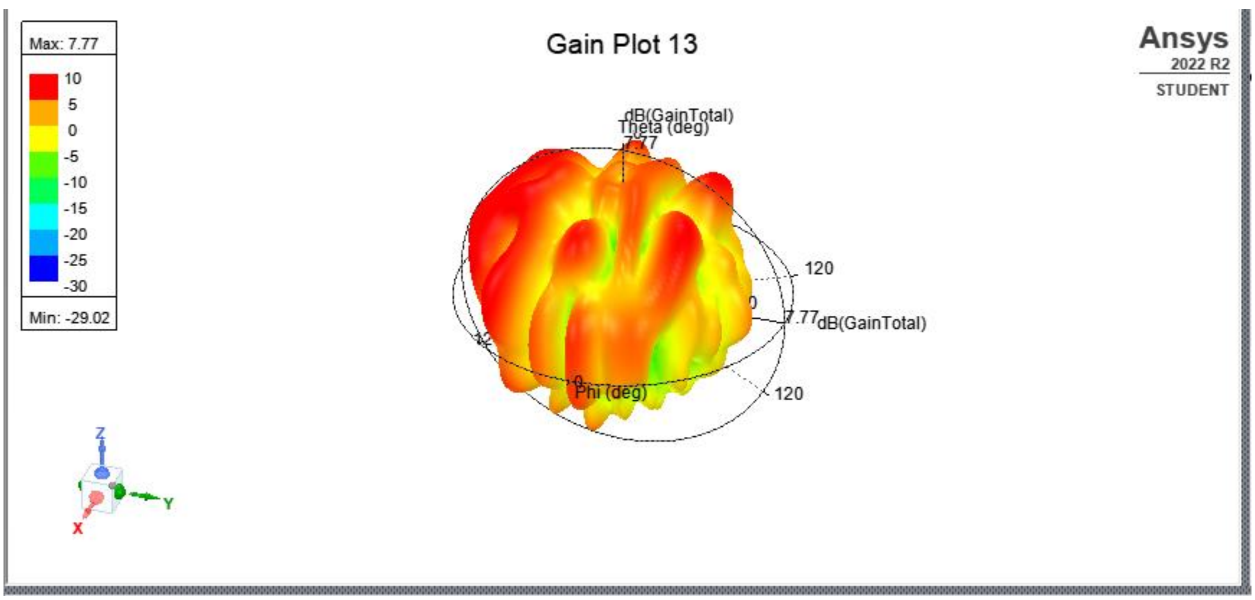

Figure 13 – 3D Gain plot at 10GHz

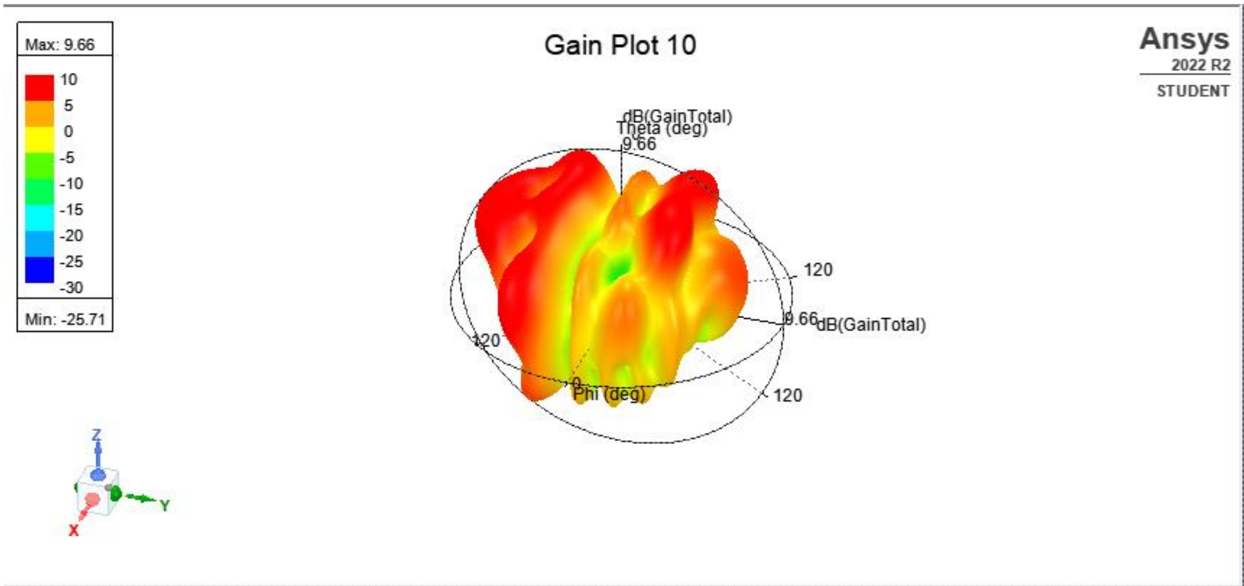

Figure 14 – 3D Gain plot at 22.5GHz

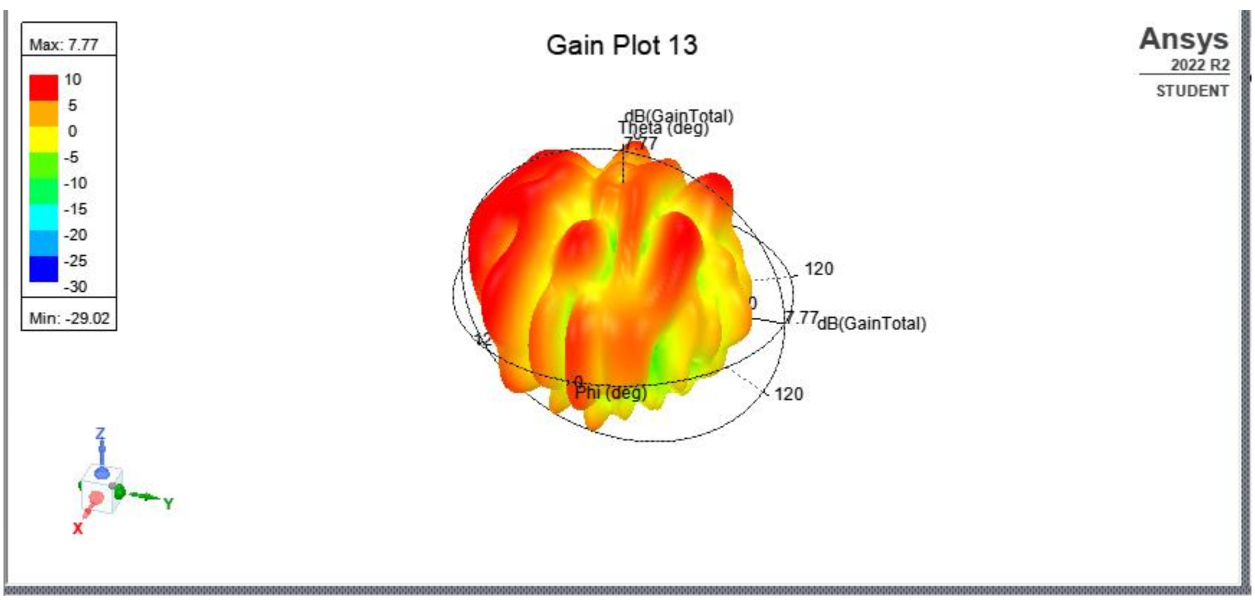

Figure 15 – 3D Gain plot at 28GHz

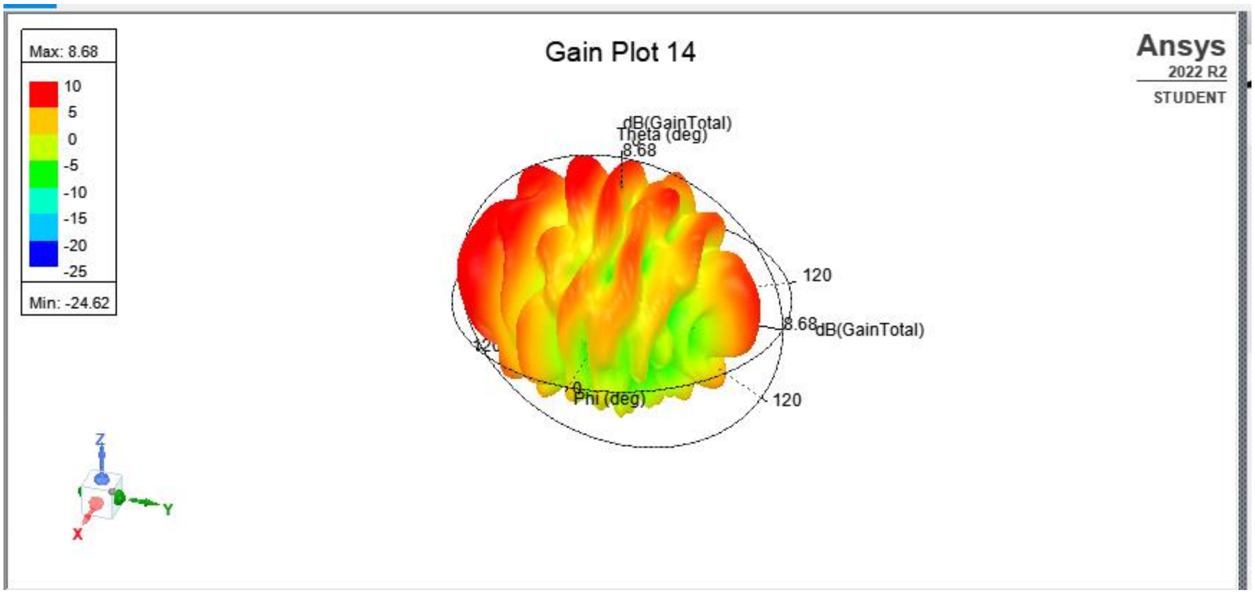

Figure 16 – 3D Gain plot at 32GHz

The obtained gain plots show good gain consistently throughout the frequency band. The directivity and elevation plots also show consistent broadband behavior, which is demonstrated.

2.4.2 S – PARAMETER PLOT

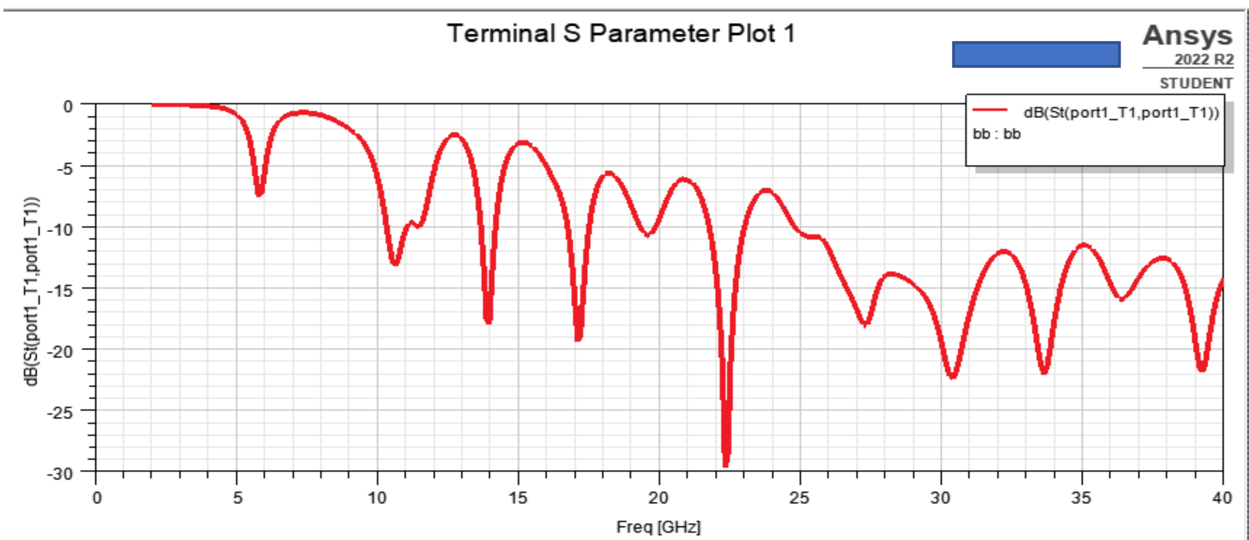

Figure 17 – S Parameter Plot

Here we see that the highest resonance of the antenna is at 22.5GHz, with the broadband behavior starting from 22.5GHz until 40GHz. Close consideration needs to be put at frequency 5.8GHz, we see a good resonance, hence this antenna can be used even for IoT, Wi-Fi and Bluetooth applications from the frequency band 2.4GHz onwards. This antenna shows good impedance and gain over an ultra-broad range of frequency band, including microwave bands, 5G and mm wave frequencies, hence can be used in applications pertinent to these frequency bands.

2.5 Design 2 – Elliptical Edge Antenna

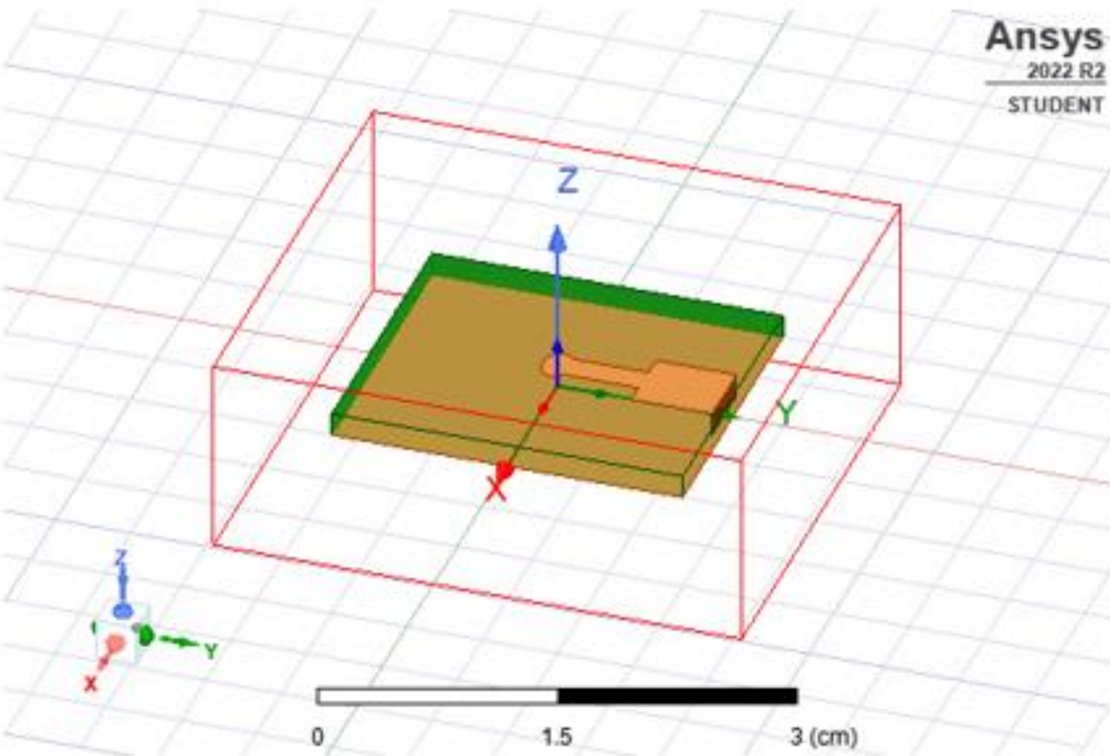

Figure 18 – Elliptical Edge Patch Antenna

This antenna, like the design of previous antenna, is an elliptical edge patch antenna designed at an operating frequency of 17GHz. However, this antenna has a smaller elliptical radius. The main idea behind simulating this antenna was to obtain good resonance and broadband behavior over a large frequency range. The design parameters used for this antenna are in the following table below.

Table 2 – Design Parameters of Antenna

DESIGN PARAMETERS	VALUES
Operating Frequency	17GHz
Substrate	ROGER DUROID 5870 TM
Patch Radius	0.14cm
Patch Ratio	0.6857cm
Substrate height	0.1575cm
Substrate Length	2.33cm
Substrate width	2cm
Edge feed width	0.192cm
Edge feed length	0.331cm
Feed width	0.493cm
Feed Length	0.538cm

The antenna was designed in ANSYS HFSS software version 2022, with the substrate Roger Duroid 5870 TM, having a dielectric constant of 2.2. This antenna was simulated from 0 to 60GHz, and the antenna material used for the antenna and ground plane is copper.

2.6 Simulated Results

2.6.1 Gain at Different Frequencies

The gain parameters of the antenna are simulated at 17,28,30,32 and 34GHz as seen below:

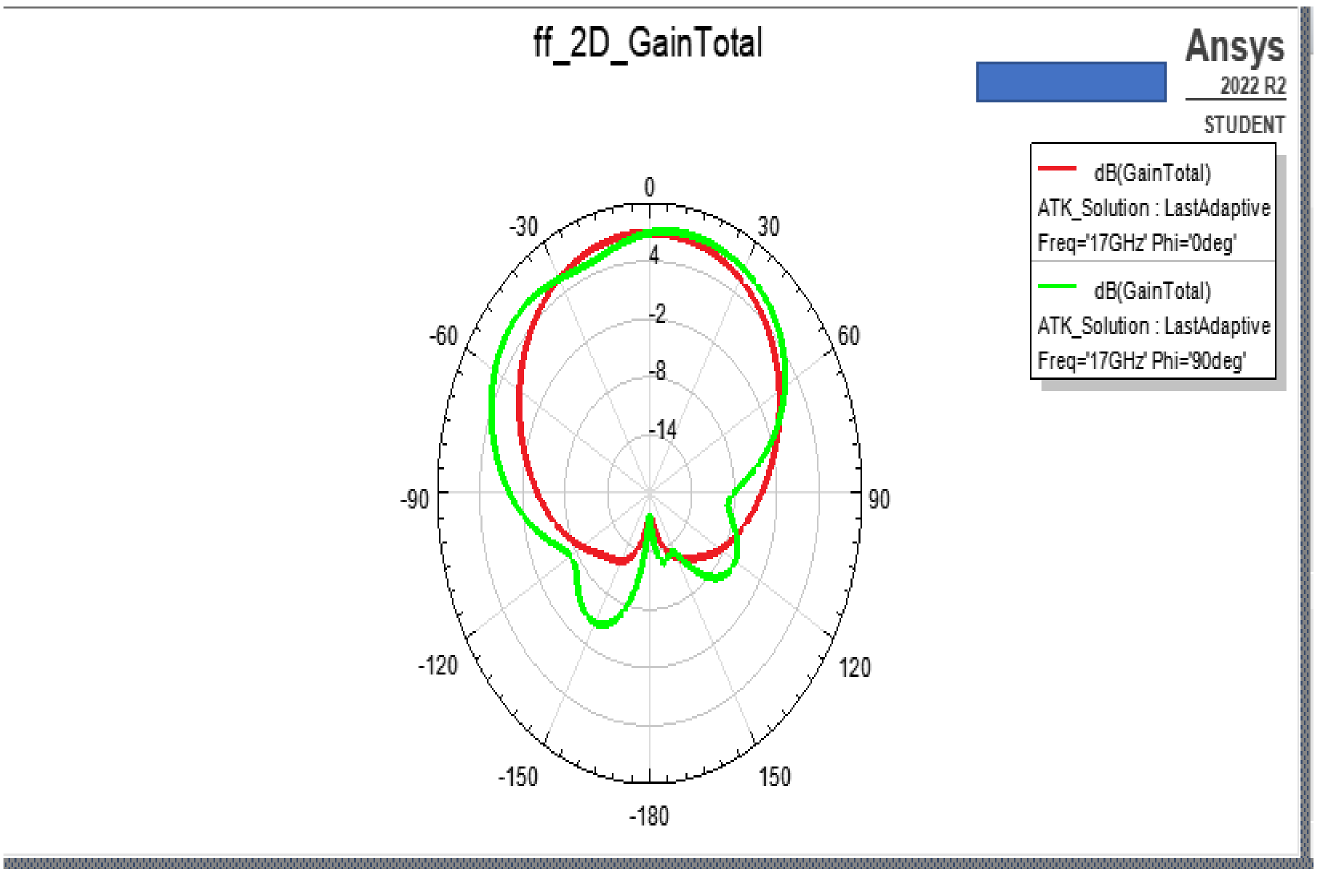

Figure 19 – 2D Gain and directivity plot at 17GHz

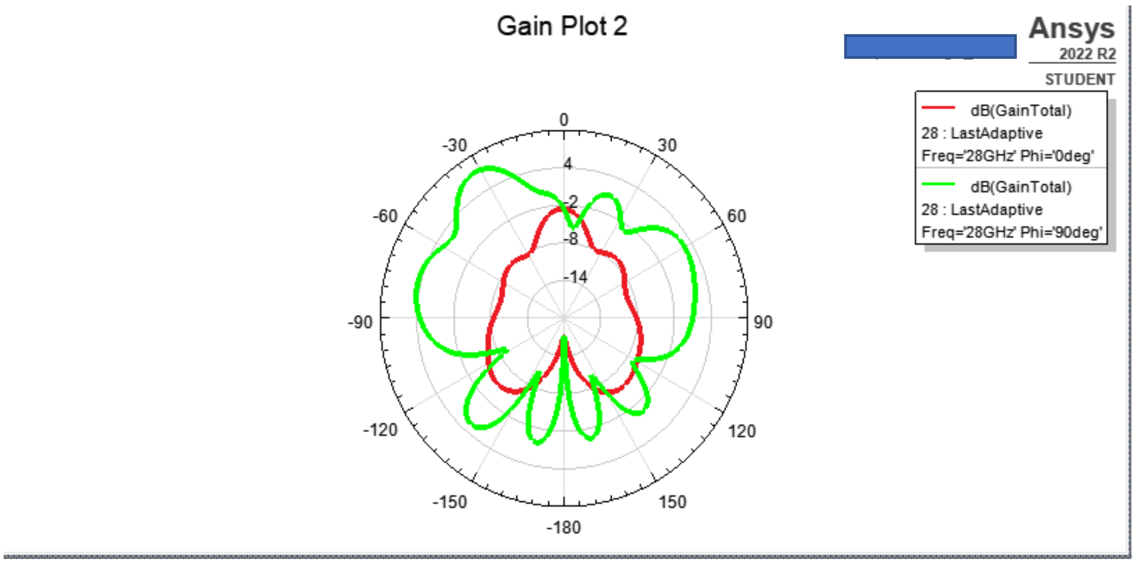

Figure 20 – 2D Gain and directivity plot at 28GHz

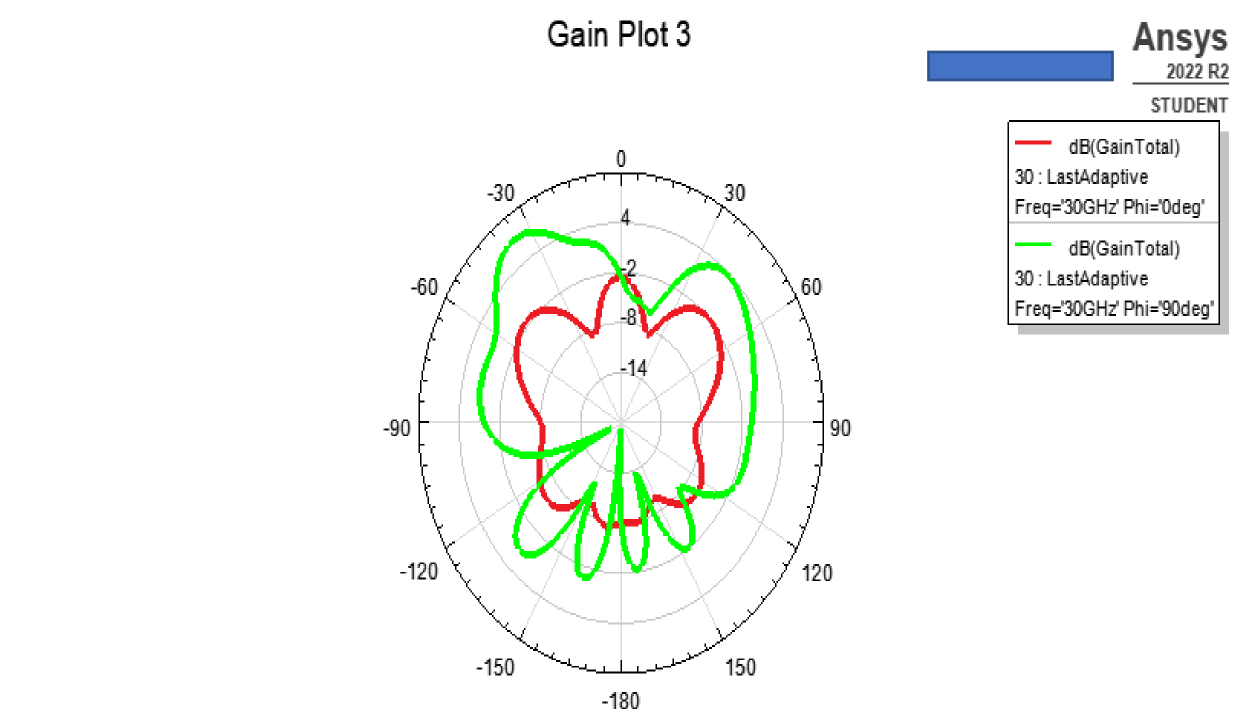

Figure 21 – 2D Gain and directivity plot at 30GHz

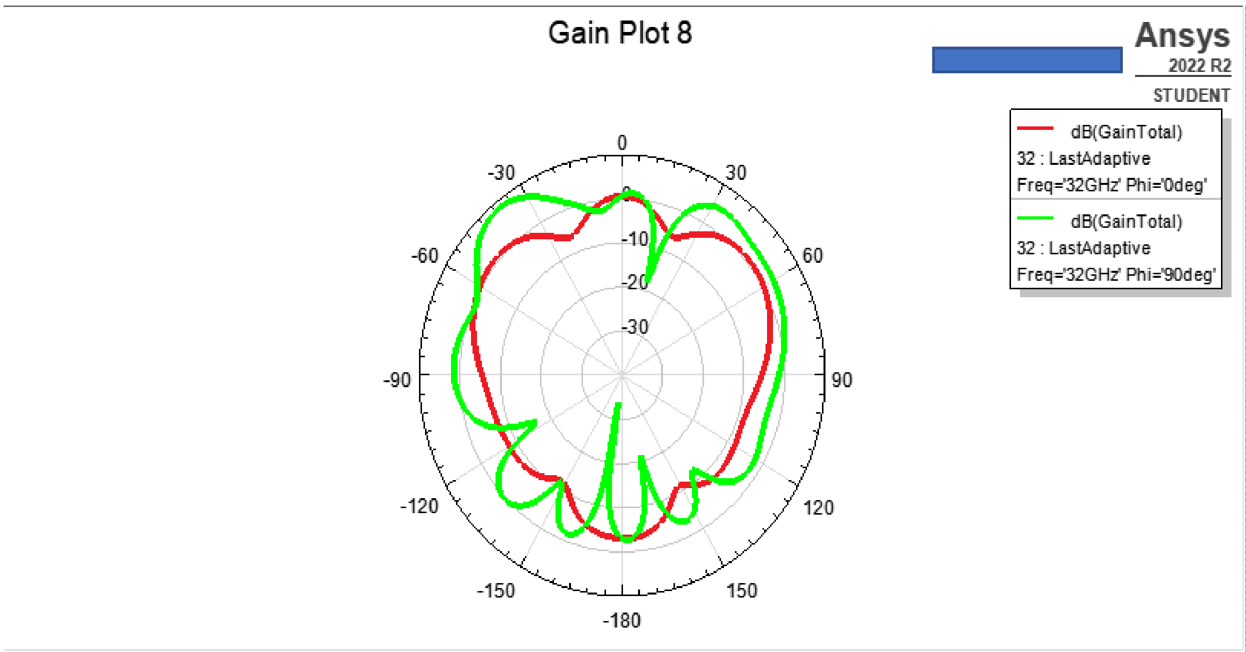

Figure 22– 2D Gain and directivity plot at 32GHz

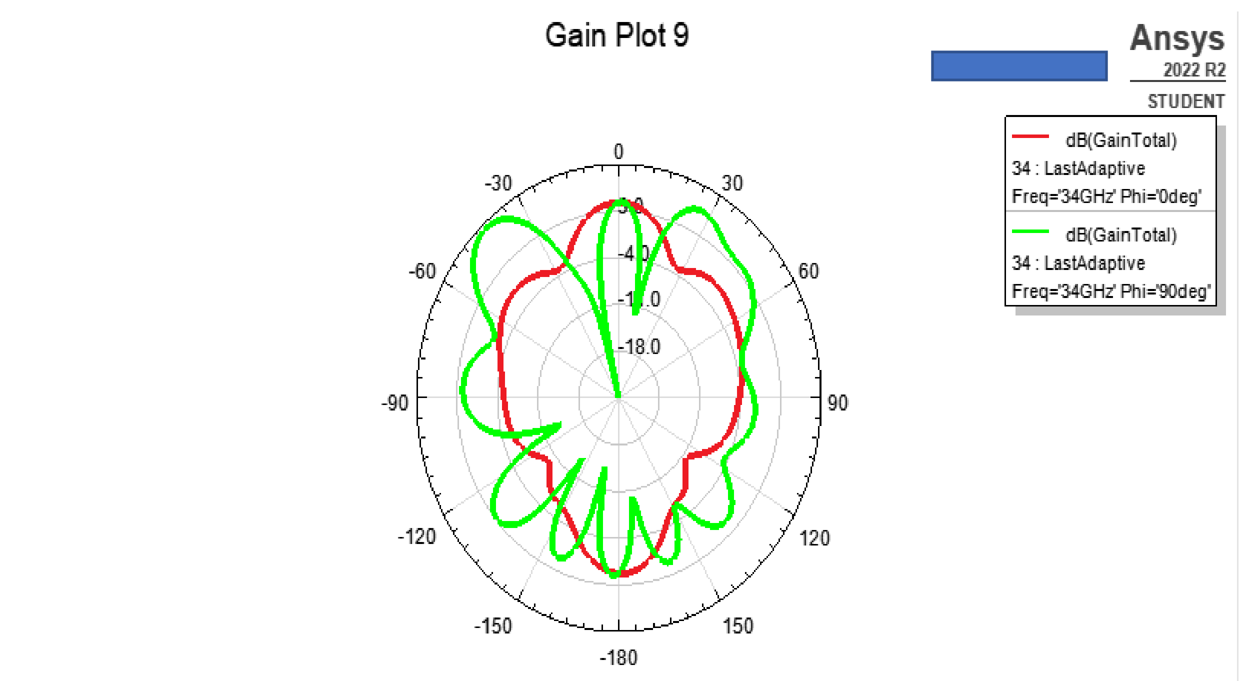

Figure 23 – 2D Gain and directivity plot at 34GHz

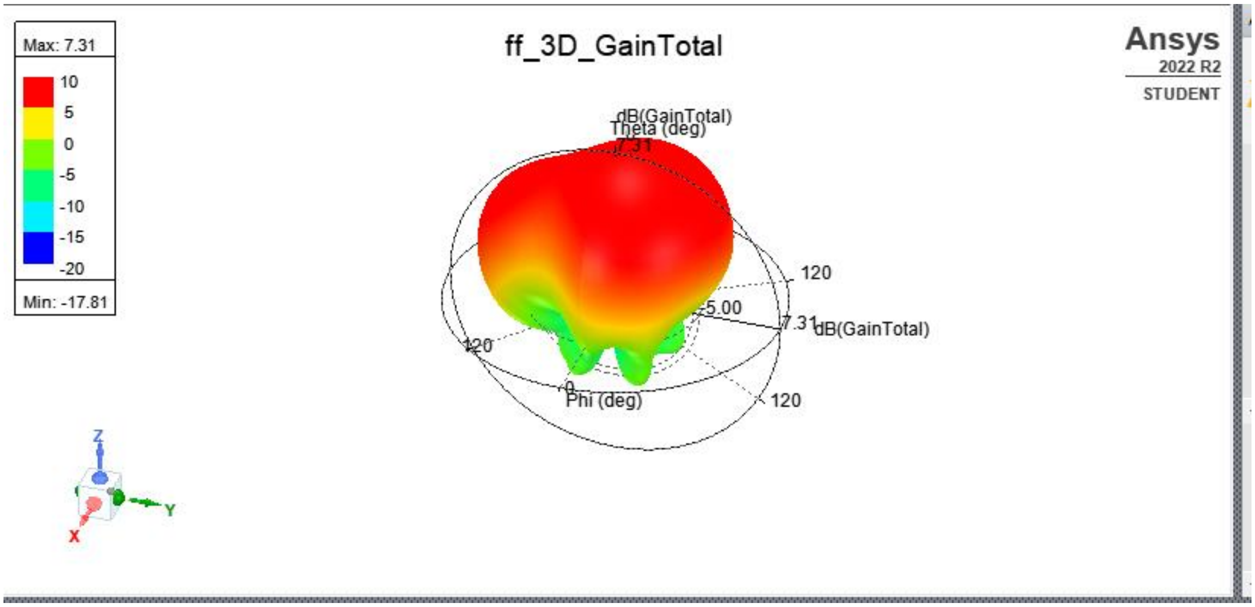

Figure 24 – 3D Gain plot at 17GHz

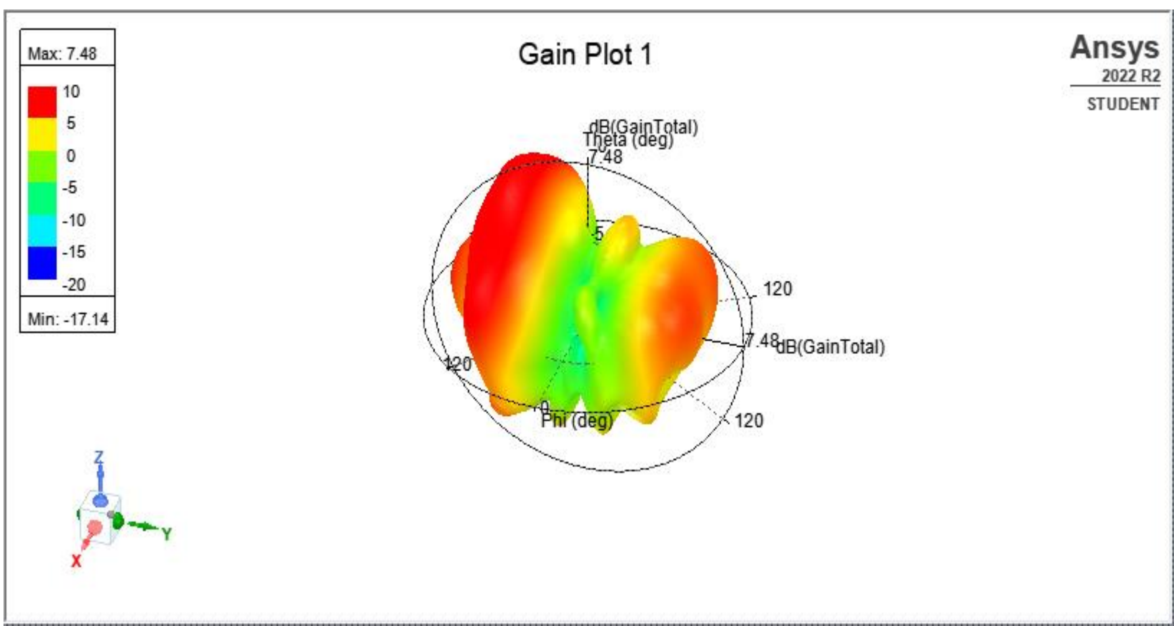

Figure 25 – 3D Gain plot at 28GHz

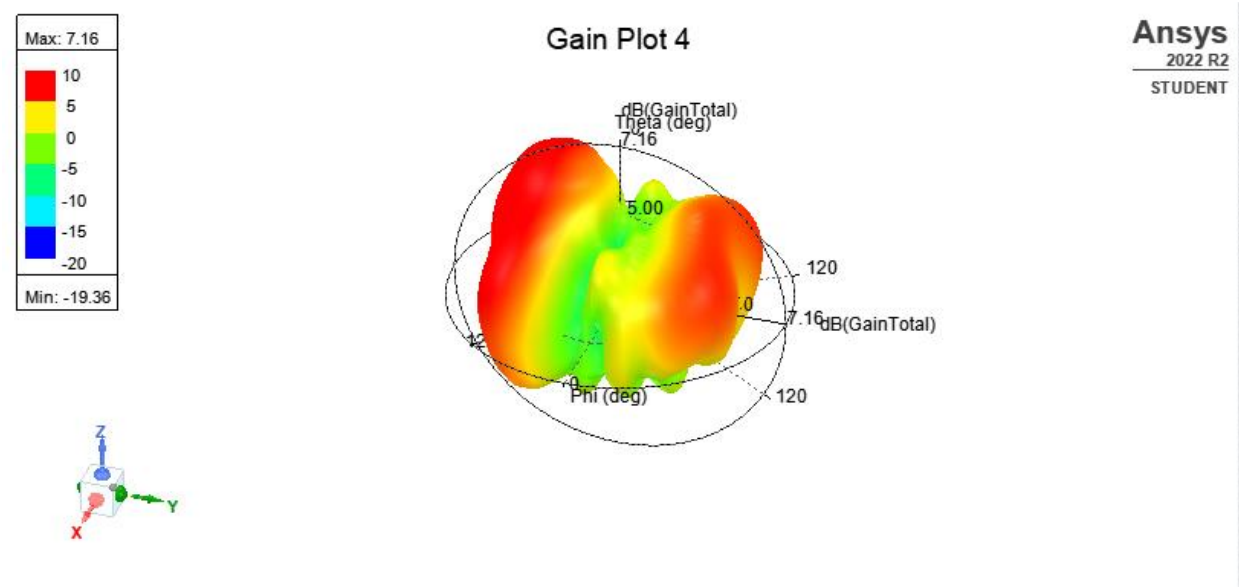

Figure 26 –3D gain plot at 30GHz

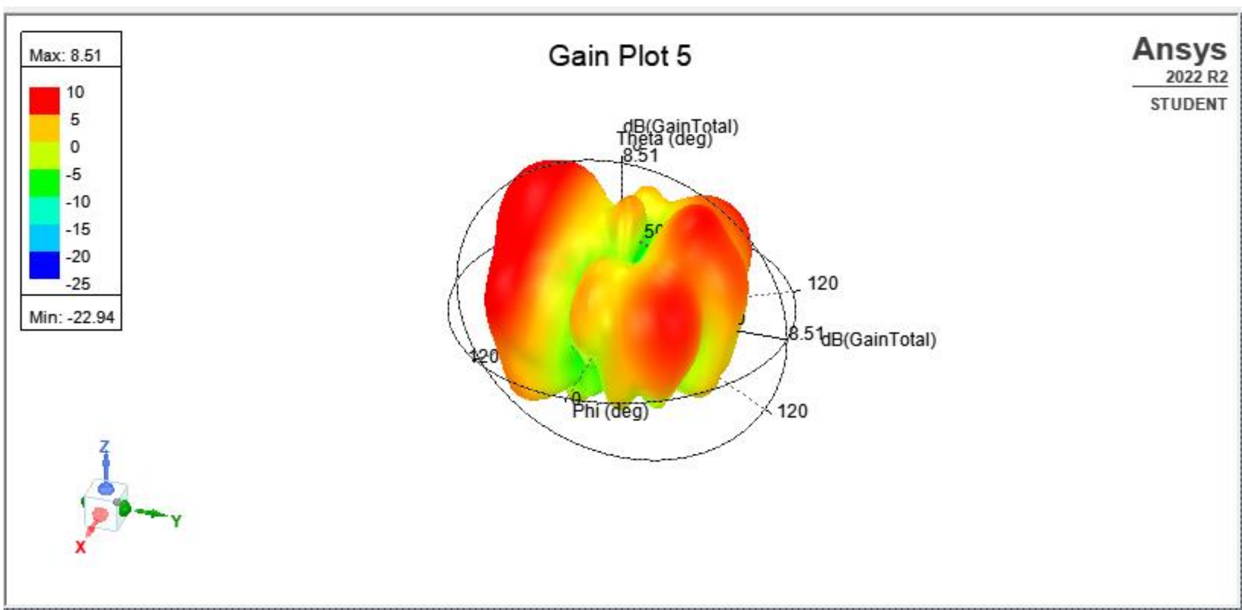

Figure 27 – 3D Gain Plot at 32GHz

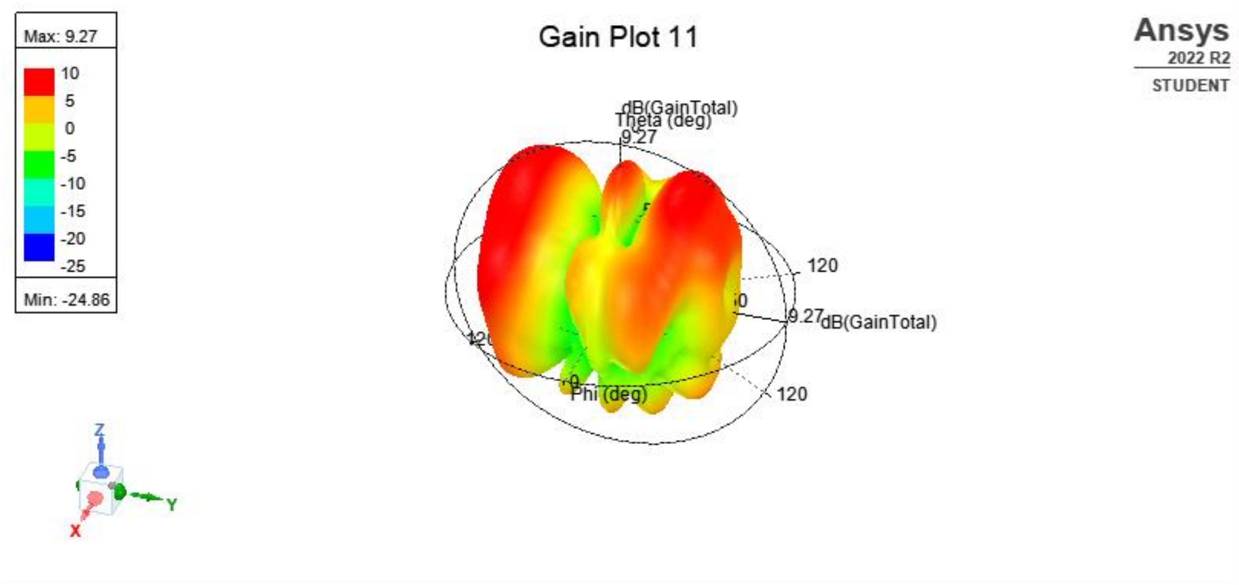

Figure 28 – 3D Gain Plot at 34 GHz

2.6.2 S – PARAMETER PLOT

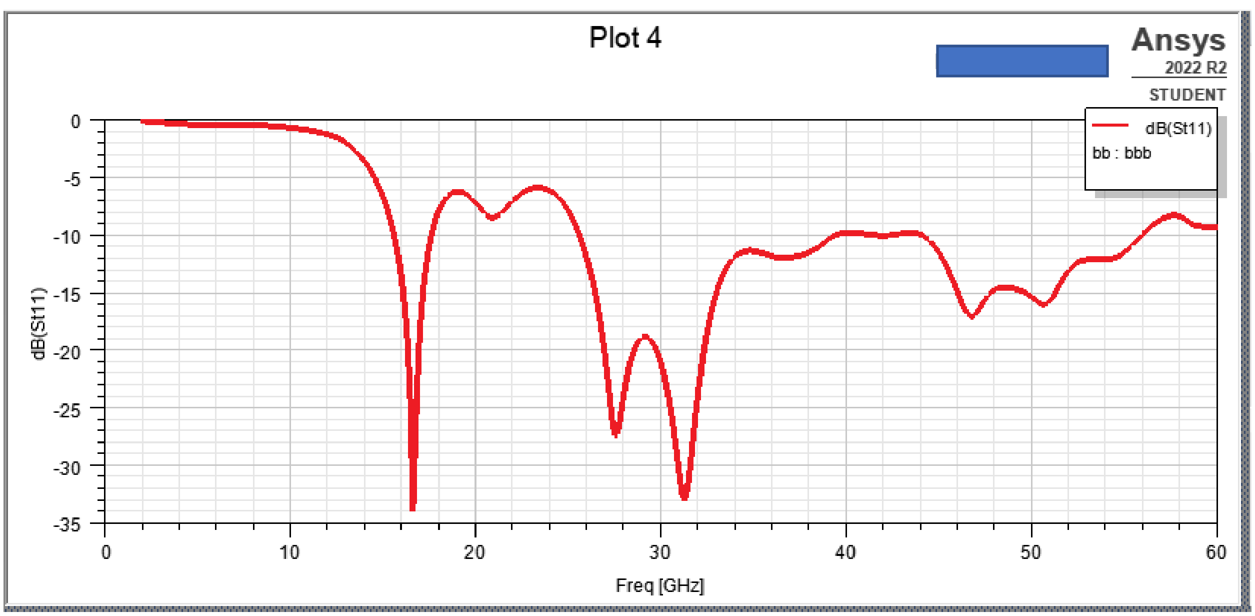

Figure 29 – S Parameter Plot

This S parameter plot shows good resonance and broadband behavior from 17GHz to 60GHz, which is an ultra-wide range of frequency band. Hence this antenna can be claimed as a broadband antenna and can primarily be used in 5G and mm wave-based applications.

2.7 Design 3 – Rectangular Patch Antenna

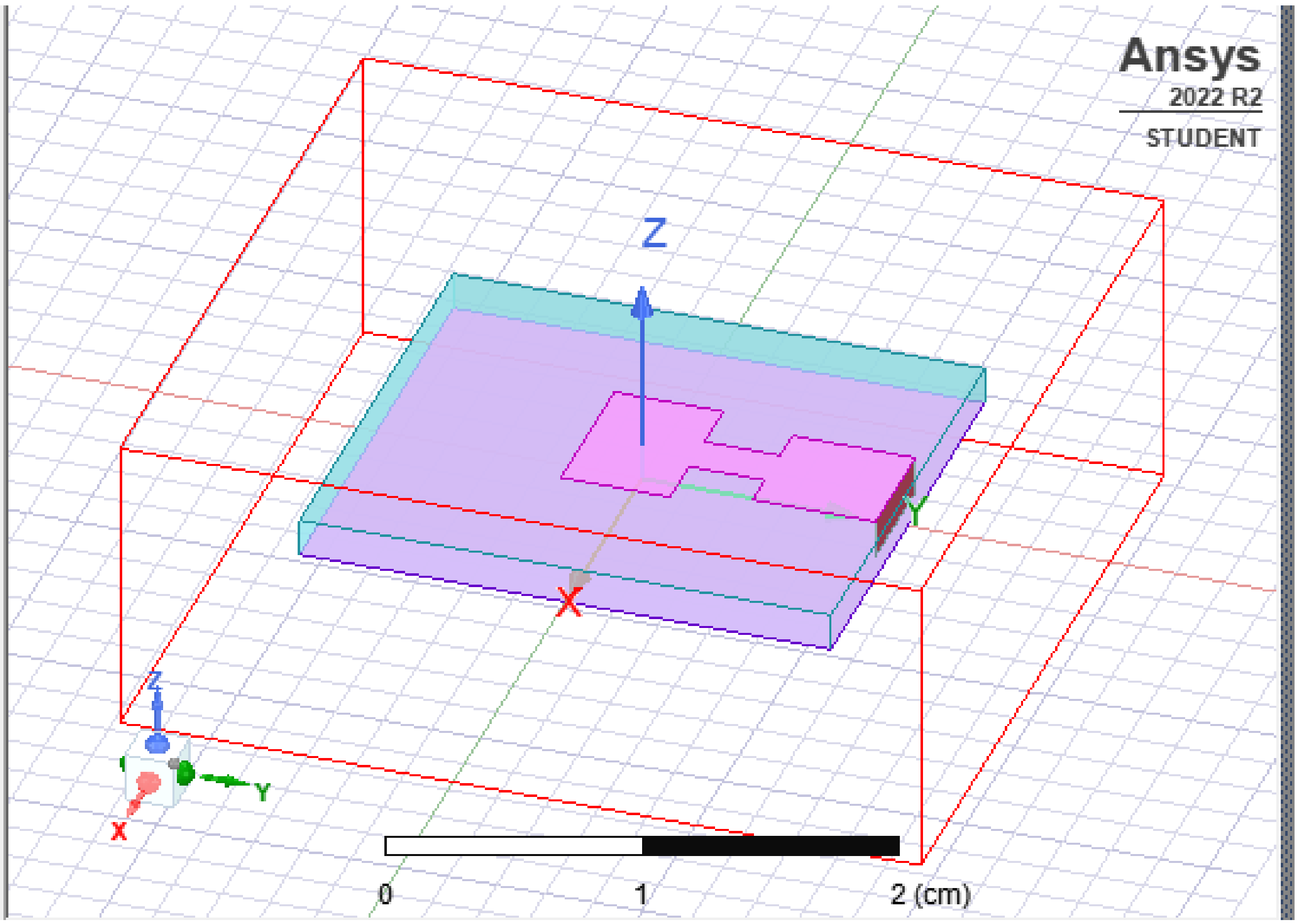

Figure 30 – Rectangular Patch Microstrip Antenna

Table 3 – Design Parameters of Antenna

DESIGN PARAMETERS	VALUES
Operating Frequency	18GHz
Patch length	1.19cm
Patch width	0.91cm
Substrate length	2.19cm
Substrate width	1.9cm
Substrate height	0.1575cm
Material	ROGER DUROID 5870 TM
Edge Feed width	0.45cm
Edge Feed Length	0.66cm
Feed length	0.508cm
Feed Width	0.493cm

This design is a rectangular microstrip patch antenna with operating frequency of 18GHz, designed and simulated in ANSYS HFSS version 2022. The design parameters are mentioned in the table above. The material used for the antenna and ground plane is copper. The equations for calculating the design parameters are as follows. The width of the patch can be calculated with the below mentioned equation:

$$W = C/2f_o\sqrt{(\varepsilon_r + 1)/2} \tag{10}$$

Then we calculate the effective dielectric constant with height, width of the antenna patch and the dielectric constant of the substrate as follows.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + (\varepsilon_r - 1) * [1 + 12h/W]^{-1/2}/2 \tag{11}$$

Similarly, we calculate the effective length of the antenna along with the length extension with the general equations of designing a microstrip patch. Finally, the length of the patch is calculated with the below described equation:

$$L = L_{eff} - 2\Delta L \tag{12}$$

Here, W is the Width of the Patch, L is the Length of the Patch, h is the thickness, ε_r is the relative Permittivity of the dielectric substrate and c is the Speed of light: 3×10^8 m/sec.

2.8 Simulated Results

2.8.1 Gain

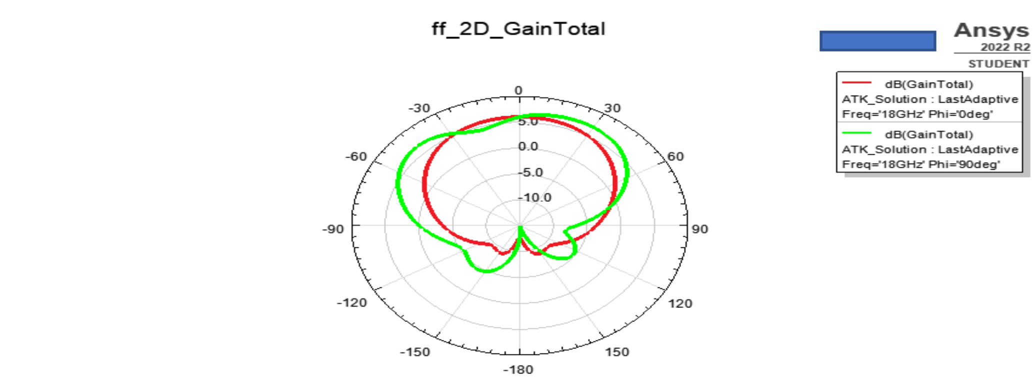

Figure 31 – 2D Gain and directivity plot at 18GHz

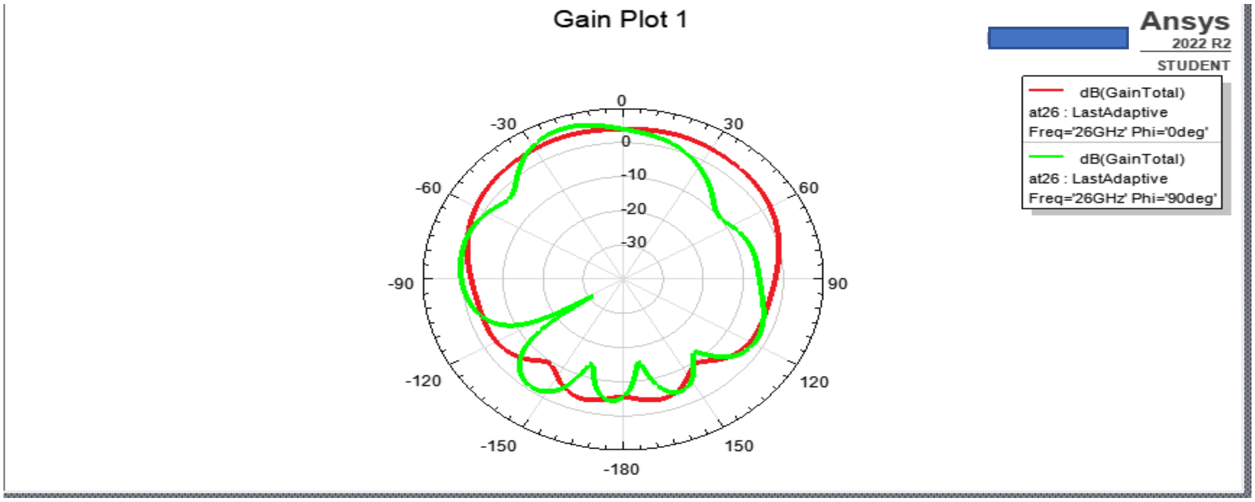

Figure 32 – 2D Gain and directivity plot at 26GHz

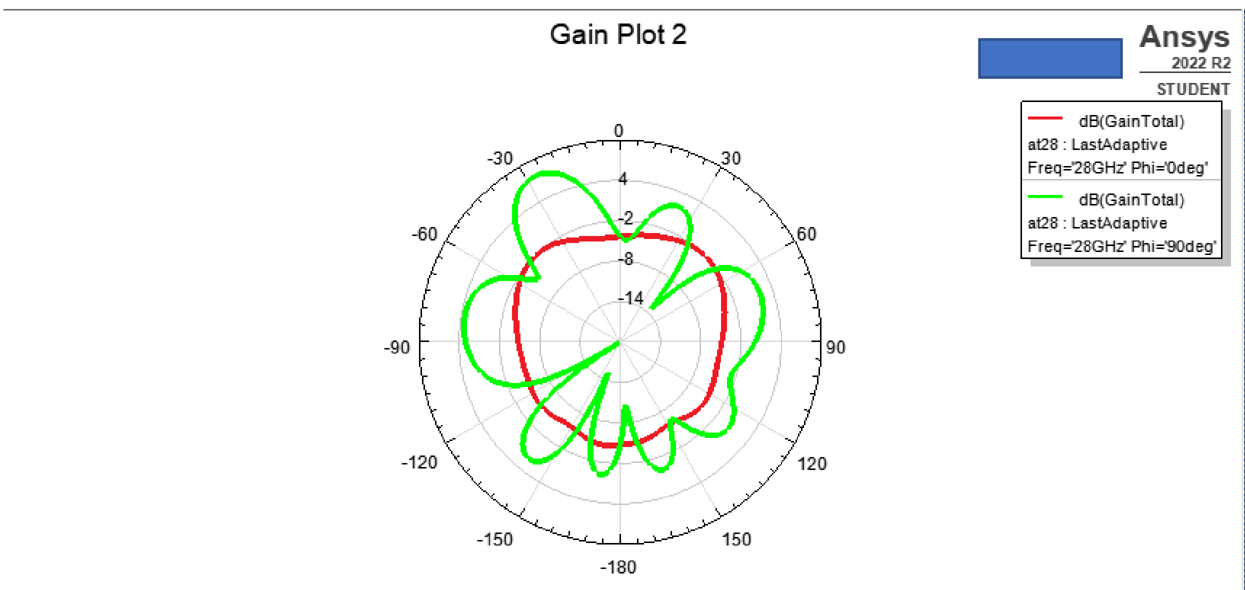

Figure 33 – 2D Gain and directivity plot at 28GHz

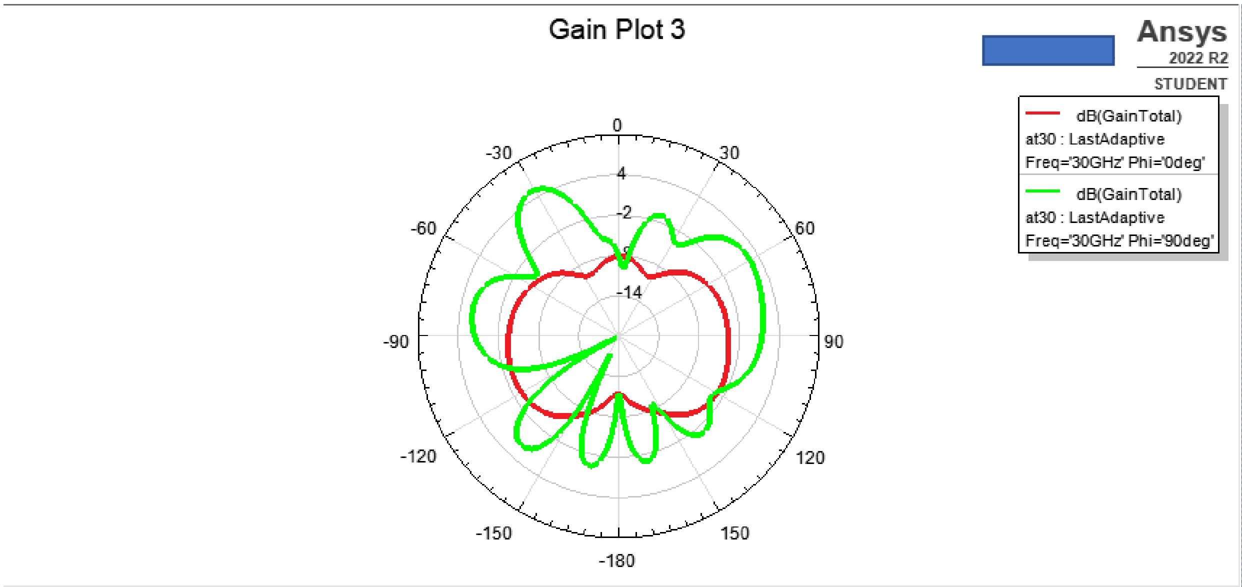

Figure 34 – 2D Gain and directivity plot at 30GHz

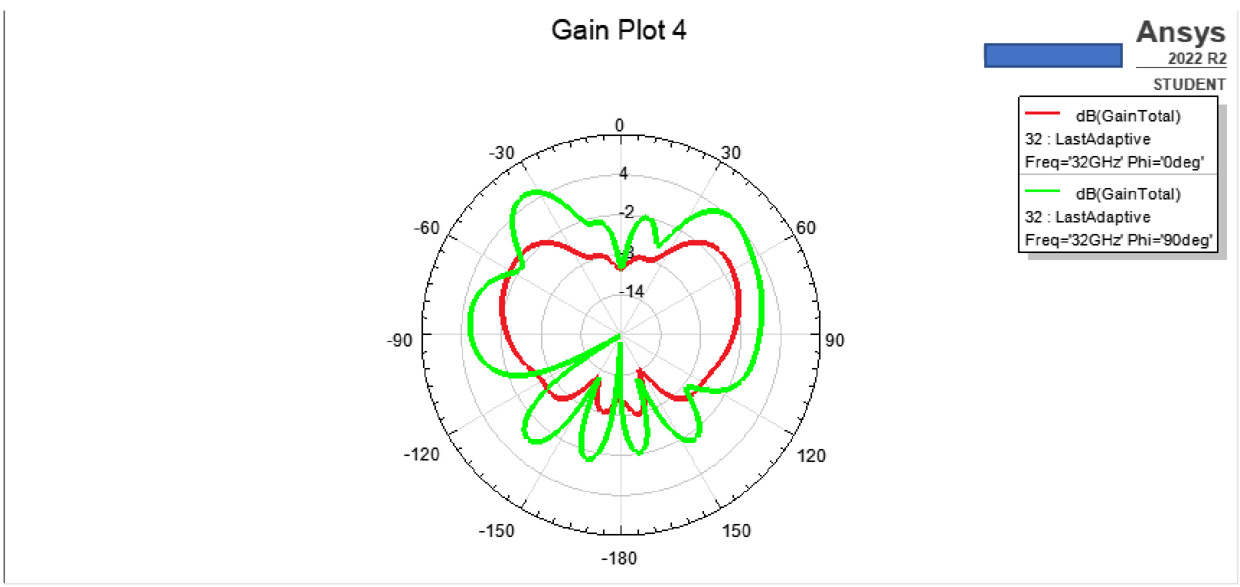

Figure 35 – 2D Gain and directivity plot at 32GHz

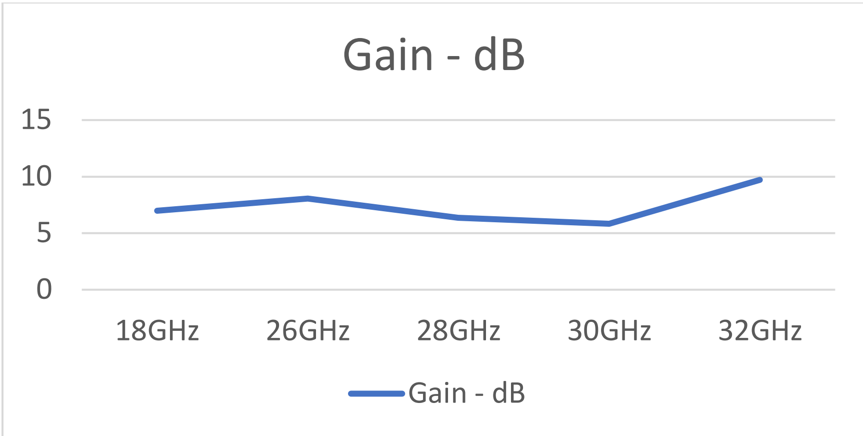

Figure 36 – Gain vs Frequency plot

2.8.2 S – PARAMETER

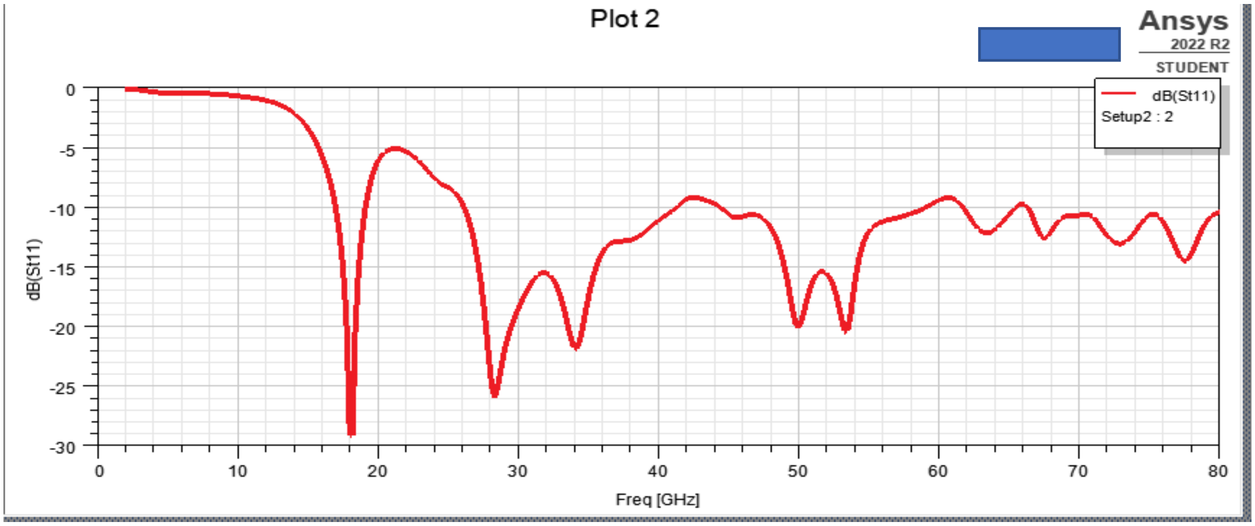

Figure 37 – S Parameter Plot

As observed in the above plot, this antenna shows broadband behavior from 18GHz to 80GHz, also showing good gain at different frequencies. This antenna proves to be a low cost, efficient antenna for 5G and mm wave applications.

CHAPTER 3

RECTIFIER IN RF ENERGY HARVESTING

3.1 Rectifier

3.1.1 Rectifiers – an overview:

A rectifier is a circuit which converts Electromagnetic waves to DC Power. This is usually through a device known as the diode, which performs or has a non-linear junction. There are some cases where we use a transistor for rectification of RF to DC power, however, to achieve a good conversion efficiency in an RF Energy Harvester, the diode is a better choice. It acts as a crucial component in the RF energy Harvester, since it performs this conversion mentioned above. Usually, a rectifier block contains the rectifier, the impedance matching network and the power management circuit all together. One more point to add is that in simple terms, a Rectenna – Rectifier + Antenna - is also a combined circuit device that converts electromagnetic waves to DC power. In this case, we aim to get good DC power to make use of it for different 5G and IoT based applications.

3.1.2 RECTIFIER DESIGN

There must be good amount of work and consideration offered towards choosing a rectifier to perform the broadband behavior in RF energy harvesting. With an ultra-wide band antenna, having a rectifier that fetched DC output only for a single frequency is not worthwhile at all, since to compensate and harvest power from such a large bandwidth, we need to also design the rectifier in such a way that it can support a wide range of frequency bandwidth rectification.

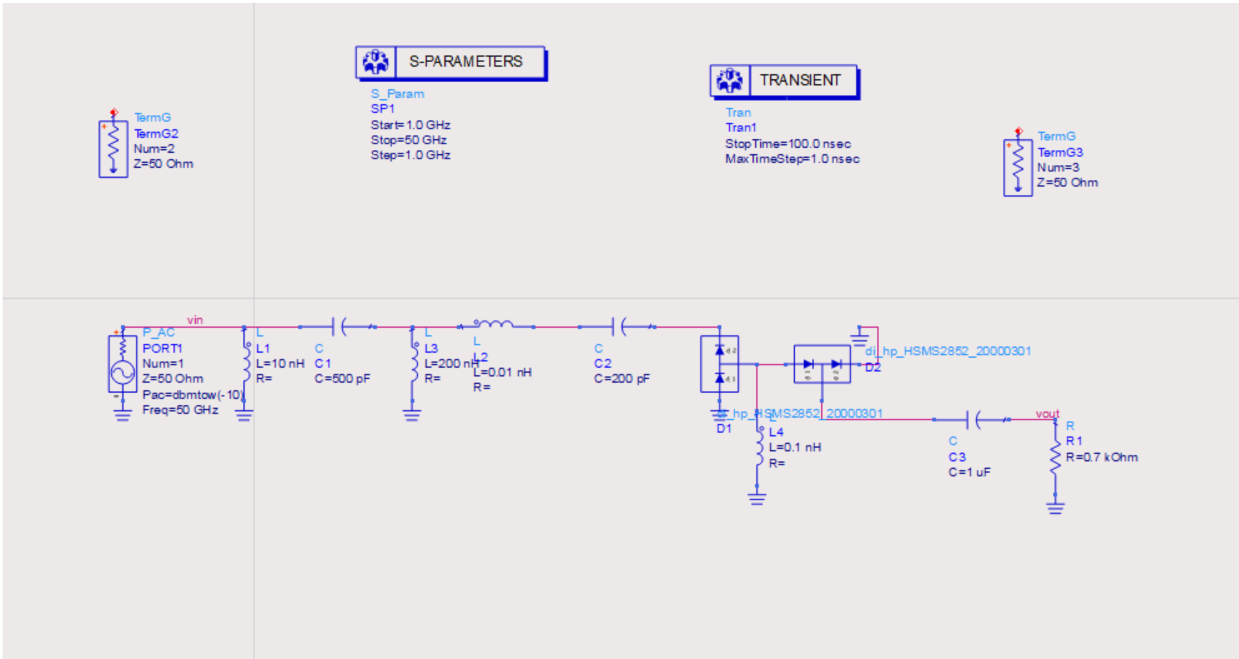

Figure 38 – Rectifier Design

The above figure shows the designed wideband rectifier in ADS simulation software version 2023. The maximum input frequency is 50GHz, which is in consideration with the antenna frequency bands simulated in the antenna designs, to achieve best results. If we look closely, this rectifier has three stages – it consists of a voltage doubler, a load resistor in the end to extract the DC Power from the Antenna, and a highly efficient impedance matching network.

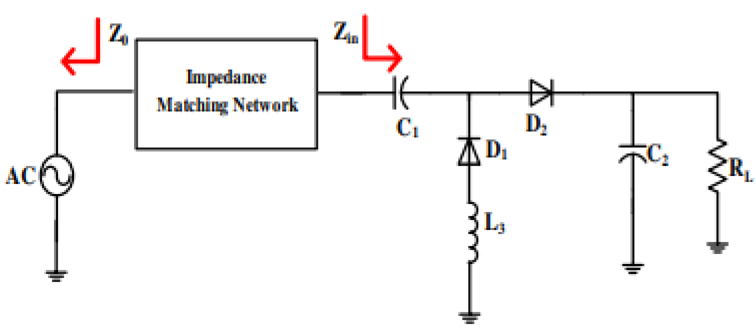

Figure 39 – Layout of rectifier circuit [17]

3.2 Impedance matching network and voltage doubler

In the block diagram above, we can see that the rectifier has been designed with an impedance matching network followed by a full wave voltage doubler circuit that performs the rectification. The diodes D1 and D2 used in the voltage doubler are HSMS 2852 diodes, which prove to give better results in wideband rectifications. In the end of the circuit, we find a load resistor RL, that, for now, is fixed to be 0.7kohm. The idea behind the functionality of this voltage doubler is that since it is a full wave rectifier, both the negative and the positive half of the RF signal received from the antenna is rectified. Diode D1 rectifies the negative part of the wave and Diode D2, the positive part.

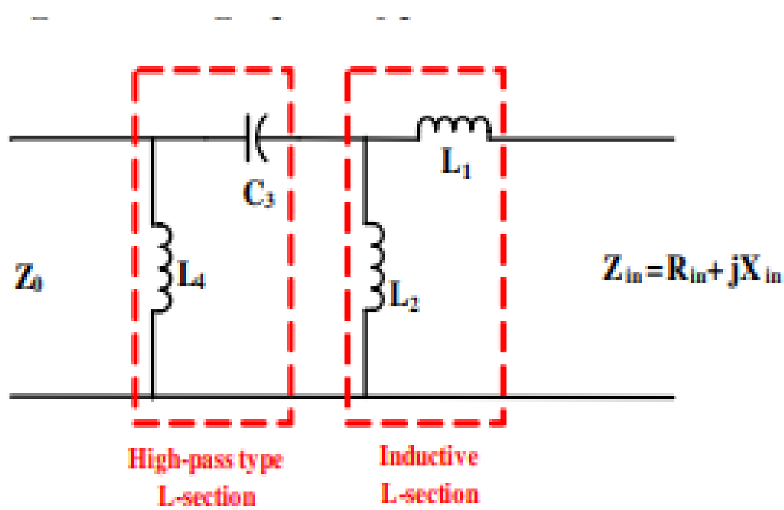

Figure 40 – Two Stage Impedance Matching Network

One of the major factors in determining a good RF to DC conversion efficiency is the impedance matching network present between the antenna and the rectifier. Impedance matching, diode rectification, polarization etc. have been one of the primary design factors in this thesis to achieve a good amount of DC power. Good impedance matching from the source antenna and the impedance obtained at the output of the impedance matching network leads to better power conversion, which is very important for wideband, since in real life cases, for some frequencies, we have gain fluctuations at the receiving antenna, yet we need to obtain good amount of DC power at the output. But most of the circuits now include a voltage multiplier or a voltage buck boost converter to solve this problem.

In this circuit, we introduce a two-stage impedance matching network, where we have a high pass type L-section and an inductive L section matching network. The inductive L section is for matching impedance at high frequencies and the high pass L-section network is for the low frequencies. Hence, to achieve good impedance matching throughout the band, we need to calculate the values of the inductors and capacitors such that we get good overall impedance matching. In the inductive L-section, the series inductance L1 is used to adjust the imaginary part Xin of the input impedance Zin and the shunt inductor L2 is used to adjust the real part Rin of the input impedance Zin at the central frequency fc of the desired frequency band [17]. Below are the equations to determine both L1 and L2 as follows.

$$L2 = \frac{1}{w_c} * \sqrt{\frac{ZoRin}{1-Rin/Zo}} \tag{13}$$

$$L1 = -\frac{Xin}{wc} - \frac{L2}{2} \pm \sqrt{\frac{{L_2}^2}{4} - R_{in}^2/w_c^2} \tag{14}$$

Here wc is the center frequency of the desired frequency band. Now, to perform impedance matching for high frequencies, we have the inductive L-section, with the shunt inductance and a series reactance, the values of which can be altered depending upon the desired frequency band.

In this circuit in the figure, which was simulated in ADS, we have different topology for the inductors and capacitors. We have L1 = 10nH, C1 = 500 pF, L3 = 200nH, L2 = 0.01nH, C2 = 200pF, L4 = 0.1nH, C3 = 1uF and RL = 0.7kohms, the model of capacitors and inductors are Murata and coil craft, respectively.

3.3 Results

3.3.1 S PARAMETER PLOT

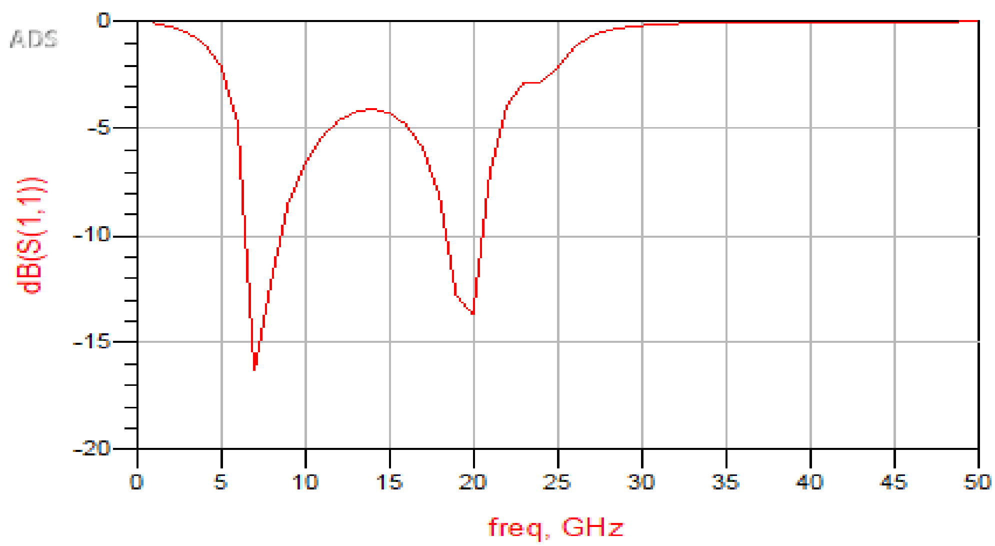

Figure 41 – S parameter plot

Looking at the S parameter plot of the rectifier, we can deduce that this rectifier can perform good RF to DC rectification up until 30GHz, with best performance achieved between 7-22GHz. This can be fruitful in addition to our broadband antennas for this rectenna to yield good DC power at an ultra-wide bandwidth.

3.3.2 RF TO DC CONVERSION EFFIECIENCY

The RF to DC conversion efficiency is calculated in respect to the input power, load resistance and output power, multiplied with one hundred, all obtained from the rectifier circuit.

Efficiency = (Vout*Vout/RL*Pin) *100% (15)

Below is the efficiency plot calculated at different frequencies at different input power levels. The power levels are in dBm, and the efficiency is in percentage. We observe that we get a good efficiency percentage, the highest about 60 percent at 5.5 dBm, especially between 5-20GHz. As we go further above 20GHz, the efficiency drops significantly. We can hence confirm that this behavior can be expected from the above designed rectifier.

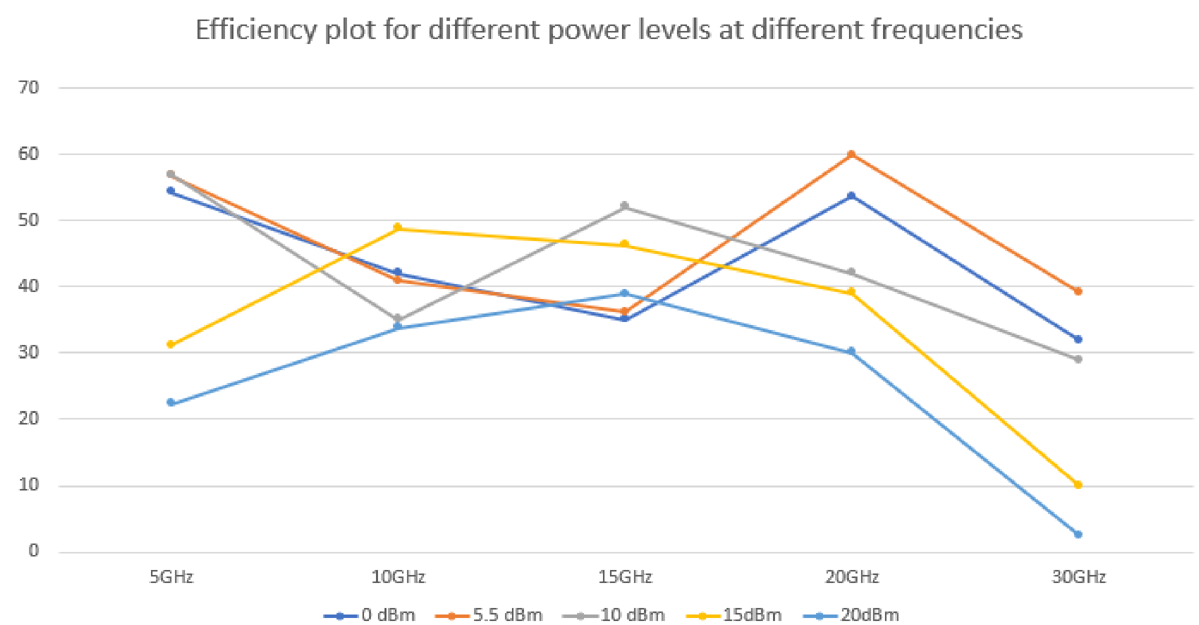

Figure 42 -Efficiency vs Frequency plot at different input power levels

CHAPTER 4

FUTURE WORK AND CONCLUSION

The thesis primarily covers the proposed design ideas for the antennas, and the design of rectifiers including the impedance matching circuit and voltage multiplier. The output of the rectifier has been simulated considering the different power levels we can receive from the antennas in those frequency bands and the results were simulated accordingly. The main future work involving this thesis would involve the designs to be fabricated using INK-JET printing technology. Why INKJET printing? - Inkjet printing has proven to be one of the most flexible technologies that can be used to fabricate RF energy harvesters or rectennas. It uses a technology known as the drop – on – demand (DOD) technology, which can either be of two types, namely the bubble jet or piezoelectric - jet based. The idea behind inkjet printing and fabrication is that a six-color Epson Stylus Photo 1500W low-cost printer with a Micro Piezo print head is used by replacing a genuine cartridge with an empty refill one [18]. We can design and adjust our print sizes and thickness based on a software called the CAD link Filmmaker software. The ink used in the printer possesses good conductivity, hence being suitable to design antennas, rectifiers and rectennas.

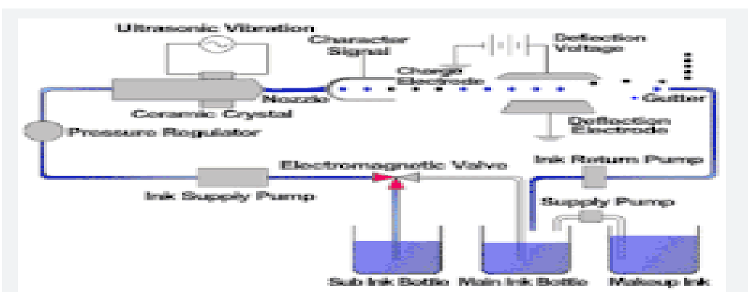

Figure 43 – Inkjet Printing Process

4.1 Conclusion

Broadband RF Energy Harvesting has proven to be one of the solutions to harvest power in a much more efficient manner than a single frequency energy harvester, provided it meets all the requirements in obtaining consistently high or good gain, having good resonance values throughout the frequency bands for the antennas and the rectifiers. This thesis has its main focus on considering various factors in determining a broadband behavior. Starting from experimentation followed by tremendous amount of research, it took effort to get accurate results, and more importantly, good knowledge of each design block, the sub design blocks involved, and understanding each component and its effect on the behaviour of the circuit/antenna. Another focus was made on involving the mmwave frequency band, due to its high yielding data rate, which can help devices designed to operate in these frequencies, and not only the IoT and 5G frequency bands. Hence the results obtained can be applied to various range of applications, such as sensory applications, smart home, WiFi, bluetooth, mobile telecommunications and wireless communications. With ambient energy present around us, and with RF energy harvesters going broadband, we sure have an advantage and also a milestone to achieve – our main milestone being to achieve close to 100 percent power conversion efficiency, which we will, one day.

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