A
Project Report
on

RF Energy Harvester

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Certificate

This is to certify that the project report entitled "**RF Energy Harvester**" is hereby approved as a creditable study carried out and presented by

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Abstract

An emerging technology known as RF energy harvesting has the potential to change the way systems and devices are powered. It makes it possible to turn ambient electromagnetic radiation into electrical energy that can be used to power things like wireless sensor networks, IoT devices, and mobile devices. The ability to operate in remote or difficult-to-reach locations and the absence of the need for batteries are just two of the many benefits offered by this technology. As of late, huge exploration has been directed to work on the proficiency and scope of RF energy gathering frameworks. Maximizing the amount of harvested energy while minimizing losses caused by impedance mismatches and other factors is one of the main obstacles in this field. Impedance matching, antenna design, and rectification circuits are just a few of the methods that researchers have developed to address this issue. Because it ensures that the maximum amount of power is transferred from the source to the load, impedance matching is an essential component of RF energy harvesting systems. Maximum power transfer is achieved by matching the antenna's impedance to that of the rectifier circuit in this method.

The antenna's AC signal is converted into DC power that can be used to power electronic devices by rectification circuits. A variety of topologies, such as voltage doubler, half-wave, and full-wave rectifiers, can be utilized in the design of these circuits. The requirements of the application and the frequency of the incoming RF signal determine which rectifier circuit to use. RF energy reaping has various possible applications, including fueling remote sensor organizations, brilliant homes, clinical gadgets, and wearable hardware, among others. It enables the deployment of devices and systems in remote or difficult-to-reach locations and provides an alternative to traditional battery-powered systems that is both sustainable and cost-effective. In conclusion, RF energy harvesting is a fascinating technology that is rapidly developing and has the potential to change the way systems and devices are powered. Even though a lot of progress has been made in this area, more research is needed to improve the efficiency of energy harvesting, broaden the range of applications, and solve the remaining technical issues.

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Abbreviations

AC	Alternating Current
CP	Circular Polarization
CPW	Conventional Coplanar Waveguide
EM	Electro-Magnetic
GPS	Global Positioning System
GSM	Global System of Mobile Communication
HGA	High Gain Antenna
ITO	Indium Tin Oxide
LTE	Long-Term Evolution
MEMS	Micro electro-mechanical System
MIC	Medical Implant Communication System
MPA	Micro-Strip Patch Antenna
MSA	Micro-strip Antenna
PAIFA	Planar Inverted-F Antenna
PCB	Printed Circuit Board
PIFA	Planner Inverted F Antenna
RF	Radio Frequency
RFE	Radio Frequency Equipment
RFEH	Radio Frequency Energy Harvester
SWR	Standing Wave Ratio

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Chapter 1

INTRODUCTION

The process of converting energy from the electromagnetic (EM) field into the electrical domain—that is, into voltages and currents—is known as radio frequency energy harvesting (RFEH). Because it makes it possible to wirelessly power low-power sensors and systems in a variety of application scenarios, RFEH is especially appealing for use in body area networks. Designers and researchers face a difficult task when trying to extract energy from RF sources because they are at the junction of electromagnetic fields and electronic circuitry. Therefore, in order to create a high-performance RF energy harvester, knowledge from both areas is required.

Here we will be introducing the different techniques of Radio Frequency Energy. State of an art techniques for Harvesting. Their advantages and limitations are described. Application and history are explained as well. Whereas the working of the RF harvester has been briefed.

1.1 What is Radio Frequency?

Radio-frequency (RF) is a measurement representing the oscillation rate of the electromagnetic radiation spectrum, or electromagnetic radio waves, from frequencies ranging from 300 gigahertz (GHz) to as low as 9 kilohertz (kHz). The frequencies at which energy from an oscillating current can radiate off a conductor into space as radio waves are roughly the same as the upper limit of audio frequencies and the lower limit of infrared frequencies. The frequency range has different upper and lower bounds determined by various sources.

Hertz (Hz) is the unit used to measure radio frequency. These represent the number of cycles per second that occur during the transmission of a radio wave. One cycle per second is equal to one hertz; The cycles per second of radio waves range from thousands (kilohertz) to millions (megahertz) to billions (gigahertz). The wavelength of a radio wave is inversely proportional to its frequency. The human eye cannot see radio frequencies. Electromagnetic energy takes on the forms of microwaves, infrared radiation (IR), visible, ultraviolet, X-rays, and gamma rays as the frequency extends beyond that of the RF spectrum.

In the context of information and communications technology, the term “radio frequency” refers to the frequency band at which wireless telecommunications signals are transmitted and broadcast. Radio-frequency is used in numerous fields. The different parts of the frequency band are assigned to various technology industries. The term for this is the radio spectrum. For instance, the VHF (very high frequency) band, which encompasses frequencies between 30 and 300 MHz, is being utilized for FM radio, television broadcasts, amateur radio, and similar activities. The ultra-high frequency (UHF) band is utilized by numerous electronic communication devices. Mobile phones, Bluetooth, wireless LAN, television, and land radio all use this area.

Radiofrequency is created by oscillating current a predetermined number of times and then radiating it into empty space as electromagnetic radio waves from a conductor known as an antenna. By “empty space,” we mean space occupied by air rather than solid objects and not outer space. Conductors are used to send and receive RF signals thanks to the skin effect, in which RF current latches onto the surface of conductors instead of penetrating and passing through them as it does with other non-conducting solids. The core and foundation of radio technology is this effect.

Table 1

Spectrum Bands For Radio Frequencies

Designation	**Frequencies**	**Free-Space Wavelength**
Very Low Frequency	9 kHz TO 30 kHz	33 KM TO 10 KM
Low Frequency	30 kHz TO 300 kHz	10 KM TO 1 KM
Medium Frequency	300 kHz TO 3 MHz	1 KM TO 100 meters
High Frequency	3 MHz TO 30 MHz	100 meters TO 10 meters
Very High Frequency	30 MHz TO 300 MHz	10 meters TO 1 meter
Ultra-High Frequency	300 MHz TO 3 GHz	1 meter TO 100 mm
Super-High Frequency	3 GHz TO 30 GHz	100 mm TO 10 mm
Extremely-High Frequency	30 GHz TO 300 GHz	10 mm TO 1 mm

1.2 What is Radio Frequency Energy Harvesting?

The process of converting energy from the electromagnetic (EM) field into the electrical domain—that is, into voltages and currents—is known as radio frequency energy harvesting (RFEH). Essentially, RF energy harvesting is the process of converting ambient electromagnetic energy into electrical power that can be used. Any kind of radio wave, including those from TV/FM stations, Wi-Fi routers, phone towers, or radar, could be ambient energy. Because it makes it possible to wirelessly power low-power sensors and systems in a variety of application scenarios, RFEH is especially appealing for use in body area networks.

Extracting energy from RF sources is a challenging task for designers and researchers as they find themselves at the interface between the electromagnetic fields and the electronic circuitry. And so knowledge from both domains is required in order to design a high-performance RF energy harvester. The exciting technology of Radio Frequency Energy Harvesting (RFEH) has piqued a lot of interest in recent years, particularly in the IoT sector. RF energy is particularly suitable for use in wearables, ultra-low-power electronics, Internet of Things edge devices, microcontrollers, and wireless sensor networks, even in comparison to other energy harvesting technologies.

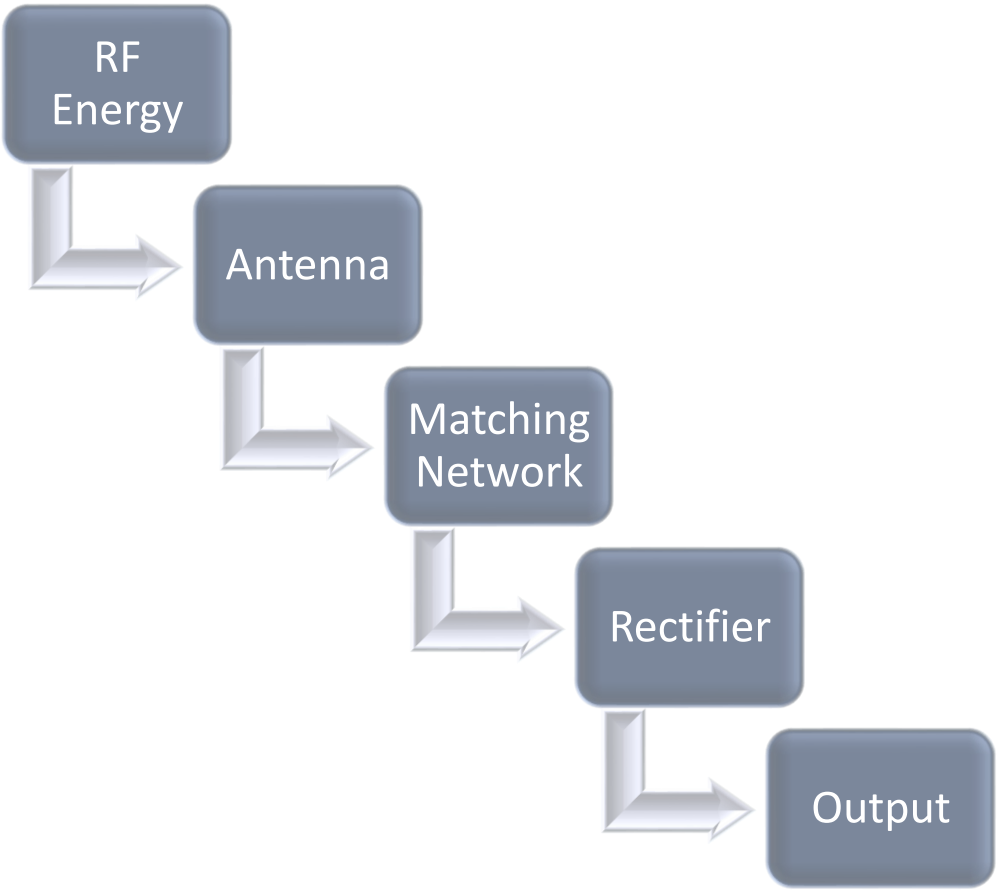
We should have a good idea of why RF energy harvesting is getting so much attention as a green power solution just from this basic understanding of what it is. Radio waves are everywhere today, and there is no way to avoid them. In addition, RF harvesting is well-suited to the particular requirements of IoT devices, which are frequently tiny/macro-sized (even nano-sized) and constructed to operate in extremely harsh, remote environments. Frequently, sensors are embedded in health monitors or other industrial solutions, making them inaccessible for battery replacement or maintenance.

As a result, RF energy harvesting is an almost perfect power source for IoT devices. The fact that RF energy is essentially free energy is another reason why they outperform battery-based power solutions. Regardless of how inexpensive or long-lasting batteries are, their use results in a prohibitively high lifetime cost. It is not economically feasible to maintain, recharge, or replace batteries across an entire IoT operation with hundreds or even thousands of sensors. On the other hand, applications for RF energy harvesting are intended to be cost-effective and self-sustaining. Over many years and frequently throughout the application's lifetime, they typically require little to no upkeep.

Its frequency ranges from 9 kHz to 300 GHz. There are several different bands/ bandwidths inside this mega range of frequency. As low the frequency of the RF the energy generated is low and as the frequency goes on increasing the energy generation also increases.

Chart I

Flow Chart of Energy harvesting process



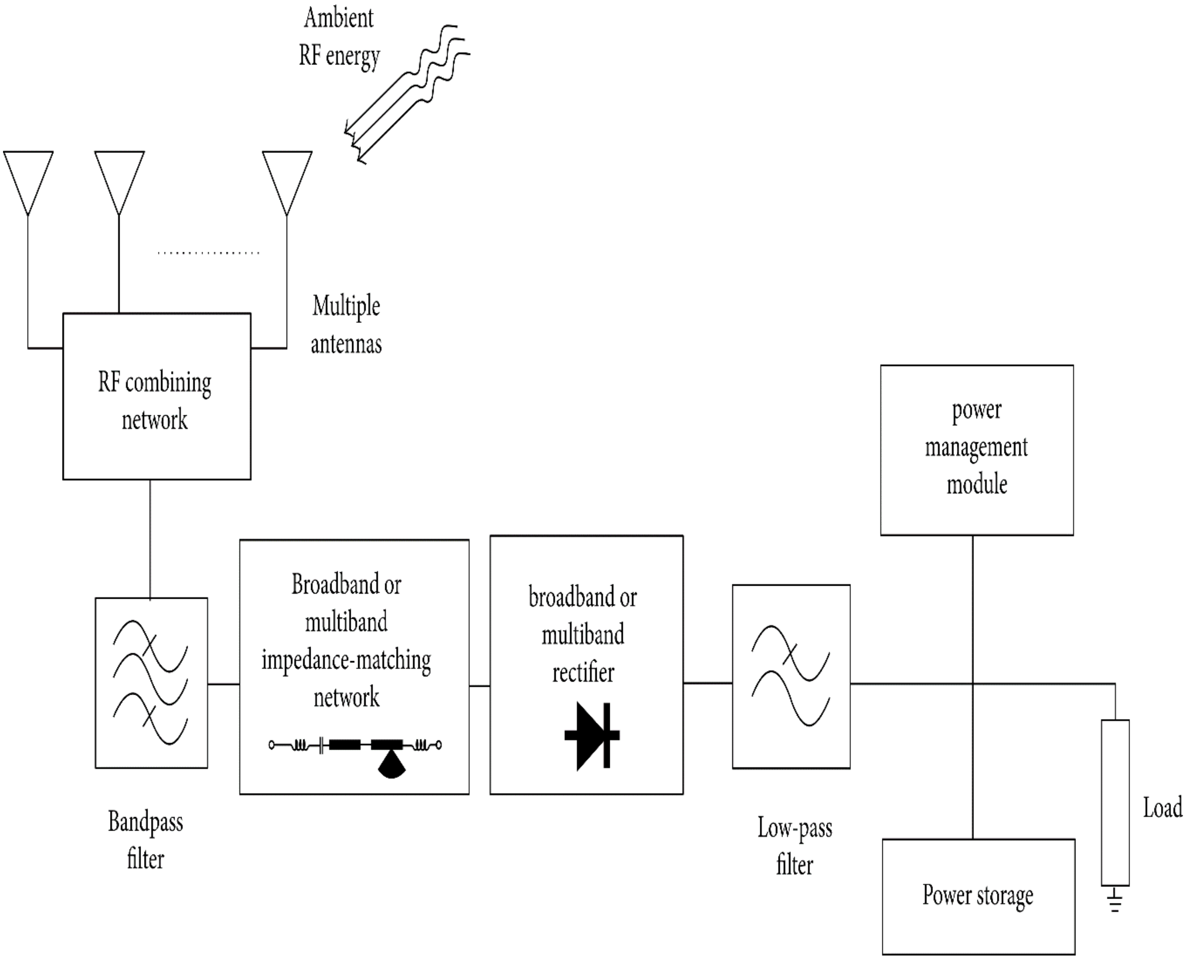


Figure 1. Block Diagram of RF Energy Harvester

1.3 Working of RF Energy Harvester

The process is quite simple. The receiving antenna collects the RF radiation and then it is passed through different stages and the electricity is produced. Now let us take a look at this process in brief:

The RF signals are sent by the source, which can be any electronic device or circuit, and received by the application circuit, which has its own energy conversion circuit, which causes a potential difference along the length of the antenna and causes charge carriers to move through it. The charge carriers now move to the RF to DC conversion circuit, which is the circuit that is temporarily stored in the capacitor and converts the charge into DC current.

The energy is then amplified or converted to the load’s desired potential value through the Power Conditioning circuit. Satellite stations, radio stations, and wireless internet are just a few examples of the many sources that transmit RF signals. The signal would be received by any application that had an attached RF energy harvesting circuit, which would then convert it into electricity.

When the signal is received by the receiving antenna, it causes a potential difference along the length of the antenna, causing further movement in the antenna’s charge carriers. This is the beginning of the conversion process. From the antenna, these charge carriers travel to the wire-connected impedance matching circuit. The impedance matching network (IMN) ensures that the antenna (RF source) and the Rectifier/Voltage Multiplier (Load) both receive the maximum amount of power. For optimal power transfer between the source and the load, the impedance of an RF circuit is just as crucial as the resistance of a DC circuit.

The sinusoidal waveform of the RF signal received by the antenna indicates that it is an AC signal that must be converted into a DC signal. The rectifier or voltage multiplier circuit rectifies and amplifies the signal in accordance with the application’s requirements after passing through IMN. The rectifier circuit is not a half-wave, full-wave, or bridge rectifier; rather, it is a voltage multiplier, or special rectifier, that boosts the rectified signal according to the application’s needs

1.4 Objectives:

- Analyze different Radio Frequency energy harvesters.
- To study the different antennas required for RF Harvesting.
- To design and simulate microstrip patch antenna for different frequencies.
- To design a single band rectifier circuit using a Schottky diode.
- To design impedance matching circuit for the antenna and rectifier.

1.5 Past Studies Related to RF Energy Harvesting

In universities and research and development settings, RF energy harvesting is a prevalent research topic. The majority of circuit designs target a single frequency band due to the extensive range of ambient RF frequencies, which makes antenna design more feasible. The GSM-900 band, where GSM stands for the Global System for Mobile Communications, and 900 stands for the 900 MHz band, is the target of the designed antenna. The 900 MHz band was chosen because of its widespread use, which means that there may be more ambient RF energy that can be captured. This band was the focus of a patch antenna in the shape of an E. The plan in focuses on a recurrence of 915MHz, which lives in the modern, logical, and clinical (ISM) radio groups class. Other designs, including the antenna that will be utilized for receiving ambient RF energy in this research, target two distinct frequency bands while both of these designs target a signal band. The double band plan in targets frequencies of 2.1GHz as well as 2.45GHz. The 2.1 GHz band is known as the UMTS-2100 band, where UMTS stands for Universal Mobile Telecommunications System. Although it is not utilized in North America, the UMTS-2100 band is widely used worldwide for mobile communication. The Wi-Fi band has a frequency of 2.45 GHz. To amplify energy move from the getting radio wire to the handling hardware, the information impedance of the circuit should match the trademark impedance of the radio wire. Impedance matching can be achieved through a stub-matching organization. The lumped elements model is used to create a pi-matching network that matches the antenna impedance of 377 to the impedance at the rectifier's input (63-j117). Impedance coordinating in is achieved with the utilization of a multi-stub network streamlined to accomplish high power transformation at both 2.1GHz and 2.45GHz. As a general rule, the plan of the handling hardware will just rely upon the full recurrence, or frequencies, of the radio wire and won't be subject to the particular recieving wire innovation. The voltage doubler circuit is one very common method for rectification, although there are numerous methods and circuit topologies.

A seven-stage voltage doubler is used in the circuit topology, which not only rectifies the input RF signal but also raises the voltage to a higher DC level. For signal rectification, the RF energy harvesting circuit simply employs a single stage voltage doubler. Research directed in dissects the impacts of expanding the quantity of voltage doubler stages from 1-9, with results showing that rising the quantity of stages builds the proficiency of the circuit, while likewise moving the pinnacle of the effectiveness towards higher information power and expanding power misfortunes for low information abilities. With the IC design of voltage doubler circuits with 20 and 40 stages, as well as circuits with 1-6 stages, the effects of increasing the number of voltage doubler stages are also examined. Results show that rising the quantity of stages builds the addition of the circuit, with p-type diodes performing better compared to n-type diodes.

Chapter 2

RF ENERGY HARVESTER

2.1 History of RFEH

In 1908, when Nikola Tesla demonstrated the wireless transmission of electricity, RF energy harvesting was used for the very first time that was ever documented. Guglielmo Marconi attempted to wirelessly power motors and light bulbs with RF energy at the beginning of the 20th century. Several patents were filed in the 1930s and 1940s for devices that powered electronic devices with RF energy. The paper "On the Possibility of Wireless Transmission of Electrical Energy" by Heinrich Hertz was published in 1941. An RF wave-based system for wirelessly transmitting electrical energy was described in this paper.

"Extra-Terrestrial Relays – Can Rocket Stations Give Worldwide Radio Coverage?" by Arthur C. Clarke, was published in 1954. In this paper, Clarke suggested sending radio signals around the world through satellites. Additionally, he suggested that solar panels or RF energy from Earth could be used to power these satellites.

Peter Glaser made the idea in 1960 to use huge antennas to gather solar radiation and turn it into electrical energy that could be sent to Earth. Power beaming is the name given to this notion. A method for extracting RF energy from ambient sources like radio or television signals was patented by John Perkin in 2001.

The properties of radio waves were only partially understood at the time. Researchers became more convinced of the significance of the behavior of radio waves, i.e. that they are propagating in straight directions like the sun after Hertz published his well-known research in 1888, which provided evidence for the dynamic theory of electromagnetic waves by J. Clerk Maxwell's. Tesla's experiments with the antenna-earth system he designed in 1892 quickly disproved the notion that this property was a major disadvantage due to the expected distance between the transmitter and receiver. He referred to his creation as an open "resonant circuit," with one plate elevated above the ground and the other embedded in the ground. Both the receiving and transmitting sides utilized the same configurations. Then Tesla made the prediction that one-day wireless energy would be easily used by electrically powered devices. Not only does a device that is powered from a distance make it possible to move around more, but it also lets designers make very small devices without using batteries. The publications that Tesla published about wireless power transfer were not well received. His name was mentioned in papers about extremely low frequencies just in the last 20 years.

In 1892, Tesla gave a lecture at the IEE in London in which he discussed his plans for future research in the field of HF currents. London and Paris presented the same lecture once more. During the lectures, he was demonstrating his “single wires,” and he happened to notice that some of the transmitted HF currents easily passed through gases with lower pressure. That inspired him to investigate the possibility of supplying electric power to devices located further away from the energy source. In order to generate ten million volts in an open circuit, he constructed a substantial coil in his brand-new laboratory in the United States in 1899. His goal was to demonstrate the concept of a wireless power supply, and he was successful in powering several electric bulbs from a distance. Due to financial difficulties, he had to cancel his research less than a year later and instead focus on building his new lab, “World Telegraphy,” on Long Island, USA.

The Crystal Radio Set, which was used in the early days of wireless communications (pre-World War I), is another historical example of the early use of low-level RF reception and rectification. Over the course of time, numerous radio types and receiver circuit designs have been discovered and developed. The introduction of additional contemporary radio receiver types had an impact on Crystal Radio’s popularity. Crystal Radio, however, continues to captivate people as the simplest method of radio reception. A well-known method for providing power to devices and processes is to harvest the energy in the surrounding area or ambient energy. Physical motion and solar light comprise the majority of exploitable ambient energy sources, which are already being gathered by means of photovoltaics (calculators), thermoelectric (five), and kinetic energy harvesters, respectively.

2.2 Advantages of RFEH

The following are the advantages of RFEH:

- It captures the electromagnetic waves used for power generation and storage, which are readily available thanks to wireless technologies like cellular towers and WiFi kiosks.
- When power requirements are extremely high, this alternative method can be used to recharge batteries.
- With a good amount of RF to DC conversion efficiency (less than 75 percent), it is the most effective source of energy generation.
- Since this method does not result in waste, it is one of the viable options for producing green energy.
- Because it uses less mains power to charge batteries and other consumer electronics, it saves money on electric bills.
- When traveling, RF to DC power converters can be used as a backup power source.
- RF energy harvesters, in contrast to solar power, can function even in conditions of darkness.

2.3 Disadvantages of RFEH

Following are the disadvantages of RFEH

- The RF-based harvesting method uses wireless sources that are affected by weather, obstacles, and other changes in the atmosphere.
- The RF harvesting chip’s RF to DC converter input receives very little power and also changes over time.
- Diodes, capacitors, batteries, and other electronic components are utilized in an RF harvester. Therefore, its effectiveness is largely dependent on how well these parts work.
- The RF energy harvesting receiver’s design is complicated for a wide frequency range.
- The RF harvester system cannot function without RF sources.

2.4 Merits of RFEH

As far as concerned, RF technology is very convenient for us. Supply of RF in nature is abundant. This ensures that it will be available 24/7. Regardless of this following are the advantages of RF technology:

- Near Universal Supply:

This one is a No-Brainer. Because computing devices and mobile/internet networks are now so commonplace, electromagnetic waves are everywhere. This means that RF energy is free energy that can be used at any time. It is difficult to overstate the significance of this fact; as we mentioned earlier in the post, the apparent lack of an economically and environmentally responsible way to power IoT devices was the single most significant factor that slowed its growth to its predicted full potential. The issue of power availability is essentially resolved by RF energy harvesting.

- Control:

To be fair, this comes after the previous one, but it’s still a big advantage that RF energy has over other modalities. A high degree of control over the energy input is possible due to the abundant and free supply of RF waves. With RF energy harvesting, the reception can be precisely calibrated to meet the requirements of each application.

- Cheaper:

This should go without saying: RF energy harvesting is much more cost-effective over the long term than battery-based solutions. It doesn’t take a rocket scientist to figure out why: first, the higher BOM (bill of materials) and the higher cost of manufacturing batteries. Then there is the unavoidable expense of battery maintenance every few years. RF energy harvesting eliminates all of these costs in a single sweep, even for the longest-lasting batteries, which eventually need to be replaced or recharged. A battery-based solution simply cannot compete with an energy harvesting-based solution over the course of an IoT operation’s lifetime, which may include thousands of sensors placed in a variety of inaccessible and harsh locations.

- Can be Used to Augment Battery Life:

RF-based technology can be incorporated into the solution to support and recharge batteries in situations where power demands are high or of a nature that necessitates the use of batteries. By offering an alternative to labour-intensive methods of battery maintenance and recharging, they have the potential to significantly extend the battery's lifespan. Naturally, this would have significant long-term benefits and would make economic sense for an industrial-scale operation.

- Versatile:

RF energy harvesting outperforms batteries in yet another way. Batteries are not only more expensive and time-consuming to use because they need to be replaced and maintained, but they also limit the number of applications an IoT device can be used in because of their size and weight. The need of the hour for IoT devices is complete versatility, and RF energy harvesting makes it possible for IoT devices to have this flexibility. With wearable technology exploding and many other IoT sectors quickly catching up, because there are no bulky batteries involved and recharging is not required. IoT devices powered by RF energy are simple to incorporate into extremely unique, small devices that are built to operate in extremely inaccessible settings. Consider an implant or healthcare-focused IoT device that is intended to operate in the bloodstream or another part of the body. No matter how long the service interval is, it would not make sense for this device to require battery replacements or even periodic maintenance. RF energy harvesting enables IoT to truly reflect its scope.

- Eco-Friendly:

Batteries play a significant role in the ongoing environmental catastrophe. Since lithium-ion batteries are regarded as hazardous, safely disposing of them is extremely difficult. The worst part is the mining of the minerals like cobalt and lithium can have chilling effects on the local population's health as well as a disastrous impact on the land. A viable alternative that avoids all of these environmental drawbacks associated with batteries is RF energy harvesting.

2.5 Limitations of RFEH

The amount of power that can be transmitted by radio waves limits RF energy harvesting. The distance between the transmitter and receiver also limits the effectiveness of RF energy harvesting. The receiver receives less power the further away you are. Due to its dependence on external sources that are susceptible to atmospheric changes, physical obstacles, and radio wave source uptime, wireless energy harvesting has many limitations. The level of the received power from the sources frequently fluctuates over time and is too low. The performance of the devices' components, such as capacitors, diodes, and backup storage batteries, decreases system efficiency over time. A receiver designed to operate in a single frequency band is limited to that band's spectrum, making it challenging to design receivers across a wide frequency range.

The proponents of remote harvesting for IoT devices assert that this strategy could power a remote sensor in a city. However, as we have seen, a relatively long antenna and a precise orientation toward a television station or another power source are required. Additionally, all of the corresponding IoT devices must be realigned in the event of a power source shift or change. This defeats the whole point of using power harvesting for the Internet of Things, which is to avoid having to physically access the powered device.

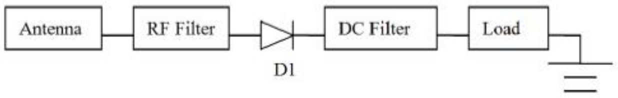
Remote power harvesting for wearable devices is impractical due to the antenna requirements alone. It is difficult to justify deployment when one considers that the incidence of solar energy is so much higher than the amount of RF permitted in areas with a large population in any developed nation. Additionally, there is a limit on the amount of RF power that can be incident in any public space, so the situation is unlikely to change. As RF exposure is being examined with concern due to potential health risks to individuals, the limits are most likely to be reduced.

Chapter 3

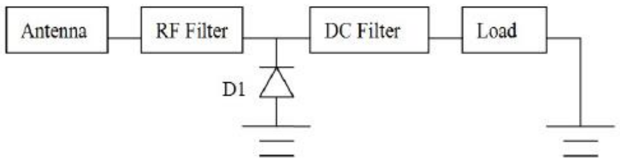
HARVESTING CIRCUITS

3.1 Rectenna's

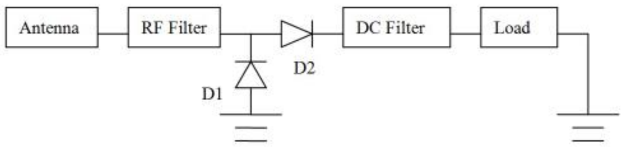
An antenna and a rectifying circuit make up a rectenna. The microwave power is collected by the antenna. The RF energy is transformed into useful DC energy by the rectifying circuit. A Schottky diode or other non-linear element performs the conversion. As a result, rectifying circuits exhibit non-linear properties. Schottky diodes, an input RF filter, an output capacitor, and a resistive load make up a rectifying circuit. Diode-generated harmonics are typically rejected by the band pass filter that serves as the input RF filter. In order to improve efficiency and reduce mismatch loss, matching circuits are required between the antenna and the rectifying circuit.



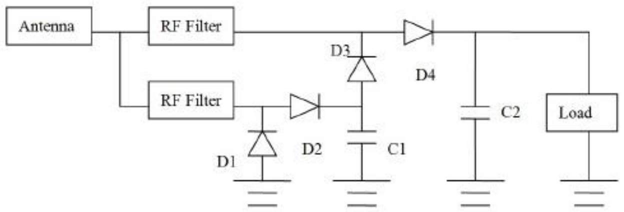
(a) Single serial diode



(b) Single shunt diode



(c) Voltage doubler



(d) Two-step voltage doubler

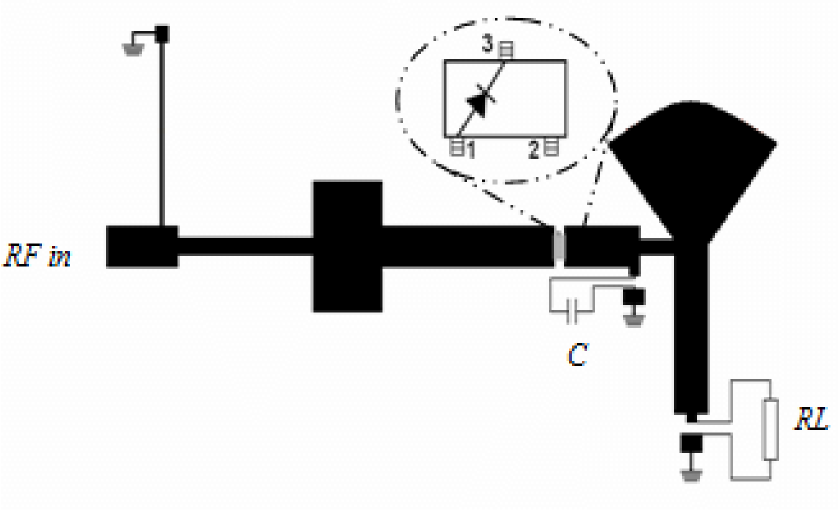
Figure 3.1. Topologies of Rectenna

According to the requirement of output DC voltage and conversion efficiency, single serial diode circuits, single shunt diode circuits, voltage doubler circuits, and multi-step voltage doubler circuits have been considered, as shown in the figure above. All the configurations of rectifying circuits should be accurately optimized to maximize the conversion efficiency.

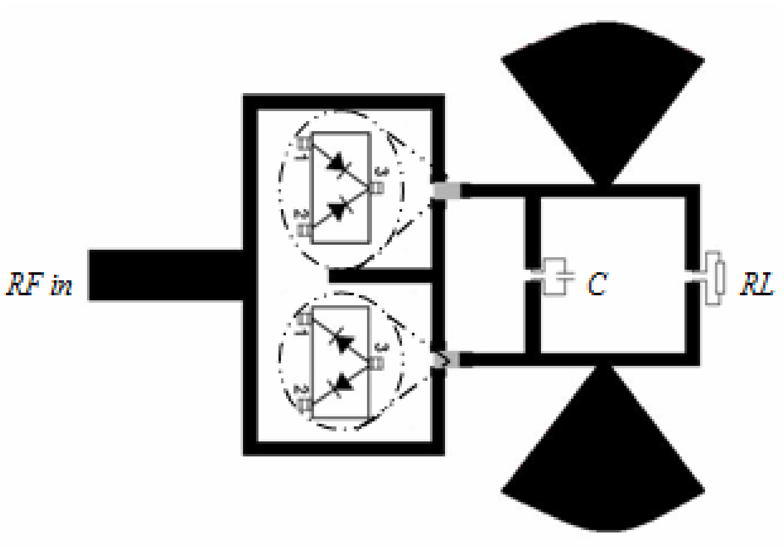
A benefit of structures with single series or shunt diodes is that they reduce the amount of conduction loss caused by diodes. Under the same conditions of input power levels, the structure of a voltage doubler produces a DC voltage at its output that is higher than that produced by a single diode. There are additional parallel diodes participating in the rectification process in the voltage doubler. Despite the increased conduction loss, it is inefficient and produces a higher DC voltage as its output. Finding a balance that works for both the efficiency of RF-DC conversion and the voltage of the DC output is interesting.

3.2 Serial diode rectifier to the bridge rectifier

A quarter-wavelength radial stub stops the RF signal superimposed on the load in a series diode circuit. The input low pass filter is used to match the input and reject harmonics. The Schottky diode HSMS-2860 is used to rectify the problem. It has low parasitic capacitance of 0.18 pF, a low serial resistor of Rs, and an optimal load resistor of 1050 with a 33 pF SMD shunt capacitor. For 12 dBm RF power, the serial diode rectifier achieved the maximum experimental efficiency of 73%, as depicted in Figure below[a].



a



b

Figure 3.2. Serial and Bridge Rectifiers

(a-Serial rectifier   b-bridge rectifier)

A modified bridge rectifier based on the original structure of bridge rectifiers was proposed by H. Takhedmit, as depicted in Figure below (b). Two radial stubs serve as RF short circuits in this circuit, separating the DC and RF components at the output. On the circuit, two Schottky diodes in identical packages—a common anode HSMS-2863 and a common cathode HSMS-2864—are soldered together. The RF-to-DC conversion efficiency is precisely adjusted by a quarter-wavelength open line between the two packages. Adjusting the distance between the diode and the output DC filter reduces the diode's capacitive reactance and increases its efficiency.

3.3 Compact bridge rectifier with no via-hole connection

The Schottky diodes have a low serial resistance of 5 and a low parasitic capacitance of 0.18 pF. There is no need for a via-hole connection because the voltage on the two sides of the load RL is measured differently. Two open stubs with a quarter wavelength each serve as RF short circuits to isolate DC and RF components in the circuit. To cancel the capacitive reactance of the diodes and maximize their conversion efficiency, the length between them and the output DC filter is precisely optimized. For 10 mW of input power, this bridge rectifier converts RF-DC at an efficiency of 61%. Over an optimal resistive load of 1.50, the rectenna exhibits an efficiency of 52% at a power density of 0.15 mW/cm2.

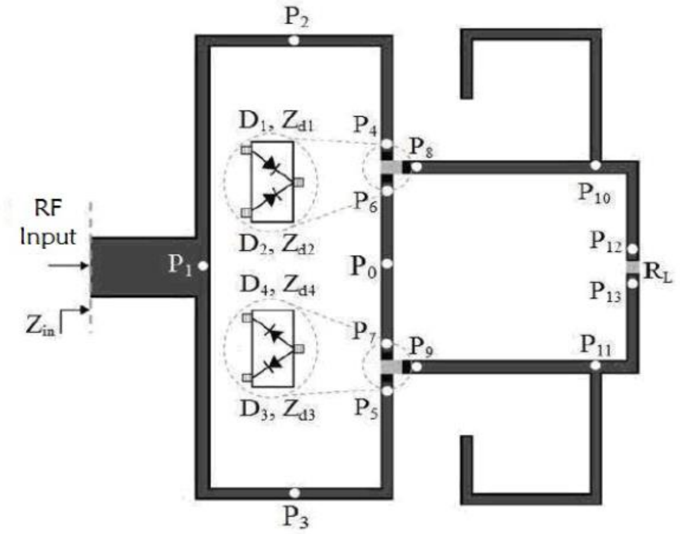


Figure 3.3 Compact bridge rectifier

The electric equivalent model of Schottky diodes takes into account the non-linear component Id. The diode passes through if the voltage applied across it is greater than the threshold voltage. If not, the diode is blocked and the current flowing through it is nearly zero. When the voltage exceeds the threshold voltage, two diodes, D1 and D3, pass through, as depicted in the following diagram. The remaining two diodes, D2 and D4, are both blocked and are not involved in the conversion process. The load RL and the input power PRF determine the diode impedances Zd1 and Zd2.

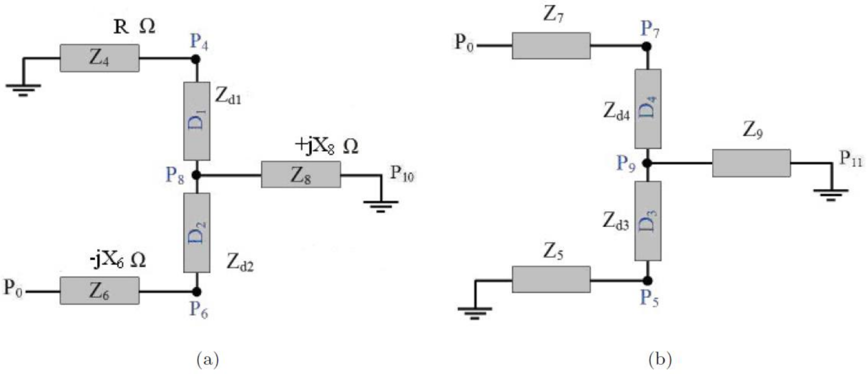


Figure 3.4. Impedance scheme of diode

Transferring the maximum power PRF into D1 and D3 is necessary to maximize RF-DC conversion efficiency. Therefore, the power level at P4 and P5 ought to guide the design of the matching circuit. Symmetrical are the two diodes D1 and D3. At 2.45 GHz, they have the same impedance. The dynamic impedance of the diodes D2 and D4 are also the same. The transmission line ends at a short-circuited point P10, which transforms an imaginary inductive impedance at point P8 for 2.45 GHz. This point is located between the diode D1 and the quarter-wavelength open stub. Additionally, it eliminates D1's capacitance. Currents and voltages at the odd-order frequency components, as deduced from the spectrum analysis of currents and voltages generated by diodes (e.g., 2.45 GHz, 7.35 GHz, etc.) are not cooperating. However, voltages and currents at frequencies of even order (DC, 4.9 GHz, 9.8 GHz, etc.) are advancing. The current components arriving at P0 at 2.45 GHz are out of phase because of the symmetric structure, resulting in an open-circuited point. As a result, the impedance at P6 is fictitious.

For a specific input power, both the current probe and the voltage probe in ADS can determine all impedance. The amplitude and phase of currents and voltages at 2.45 GHz can be used in the frequency domain to calculate impedance. To ensure that the RF input power matches, the length from P1 to P4 or P1 to P5 is chosen. The power generated by D1 and D3 at the second harmonic frequency of 4.9 GHz is also trapped in a loop (P1, P2, P0, P3, and P1).

3.4 Dual-diode rectenna with harmonic-rejecting design

To create a compact structure, the bridge rectifier has been integrated with a patch antenna. A dual Schottky diodes converter employs this compact structure without a via-hole connection, as shown in Figure below. At the frequency of interest, the rectifier has two folded quarter-wavelength open stubs that serve as short circuits and isolate the resistive load RL. In addition, the reactance at the diode input can be adjusted by adjusting the length L7 between the diode and the open stub. Without making any reference to the RF ground plane, the voltage difference between V1 and V2 across the resistor load is measured to determine the DC voltage. As a result, there are no through-holes required.

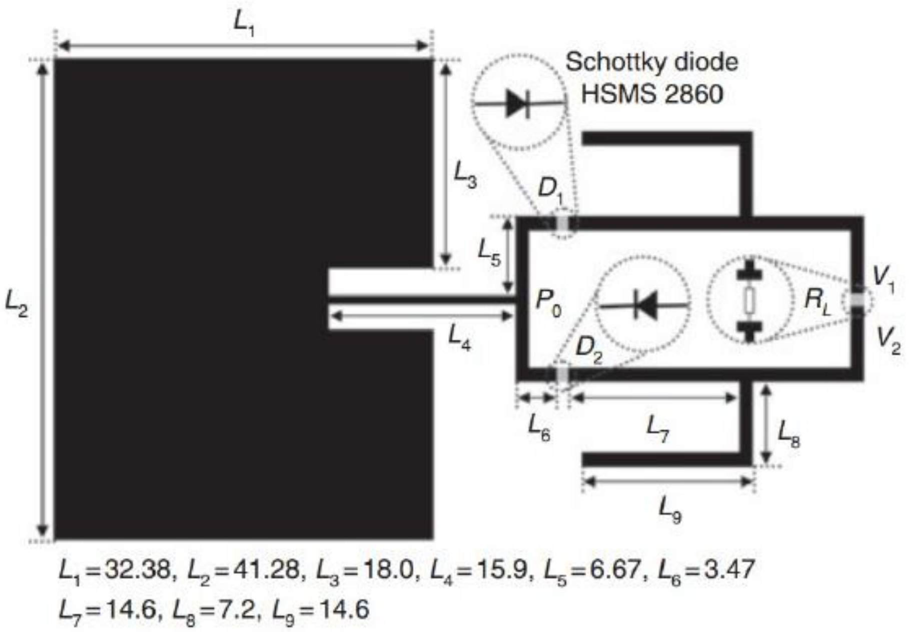


Figure 3.5 The geometry of dual-diode rectenna (in mm)

Because there is no need for a via-hole connection and no input low pass filter, the rectifying circuit is suitable for wireless sensor applications. Harmonics produced by the diodes are rejected by the input LPF, which then matches the rectifier to the antenna. By making use of antennas that reject harmonics, it can be integrated directly into the radiating element. A rectangular patch antenna with linear polarization and a 2.45 GHz frequency is included in the rectenna.

The optimized symmetric lines are chosen to match the patch antenna's 2.45 GHz and 10 dBm input power input to the rectifier. The antenna splits the power into two independent, comparable RF components. On both parallel and symmetrical microstrip lines, the RF signals travel in phase toward the diodes D1 and D2. After that, a portion of them is transformed into DC current with undesirable higher-order harmonics.

3.5 Stacked rectenna with radial stubs

The rectenna's dimensions and conversion efficiency are two of its primary design parameters. The rectifying circuit is installed on the patch antenna's backside. Consequently, the rectifying circuit's ground plane is also the ground plane of the antenna. To stop the antenna from re-radiating the harmonics, radial stubs are placed between it and the rectifier, as shown in Figure. Because the patch antenna's radiating modes are closely matched by the operating frequency's harmonics. Radial stubs are the source of the excited higher harmonics, which are less significant than the first harmonic. Two radial stubs are also positioned in the space between the load and the rectifier. The harmonic signals are prevented from dissipating in the load by these radial stubs.

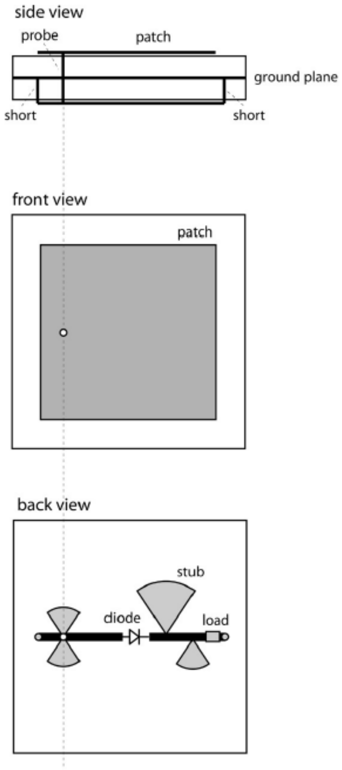


Figure 3.6 The layout of stacked rectenna

The analytical models are used to match the rectifying circuit, including the radial stubs, to the microstrip patch antenna. Selecting a probe position with a favorable Schottky diode conversion efficiency maximizes conversion efficiency. The photo-etched copper-clad FR4 material that makes up the layered rectenna allowed for a quick realization. At 2.45 GHz, the conversion efficiency is 52% for an input power of 0 dBm (53.2 W/cm2).

3.6 Circularly polarized rectenna with unbalanced circular slots

The figure depicts a circular patch, which is distinct from the straightforward structure of a rectangular patch. Unbalanced circular slots change this patch antenna's polarization from linear to circular. Size reduction and 2nd harmonic rejection are two of the reasons this structure is used. The slotted CP antenna has the advantages of being small, circularly polarized, and able to reject second harmonics. The antenna has a 137 MHz return loss bandwidth of -10 dB and a 30 MHz CP bandwidth for a 3 dB axial ratio and is constructed on a low-cost FR4 substrate.

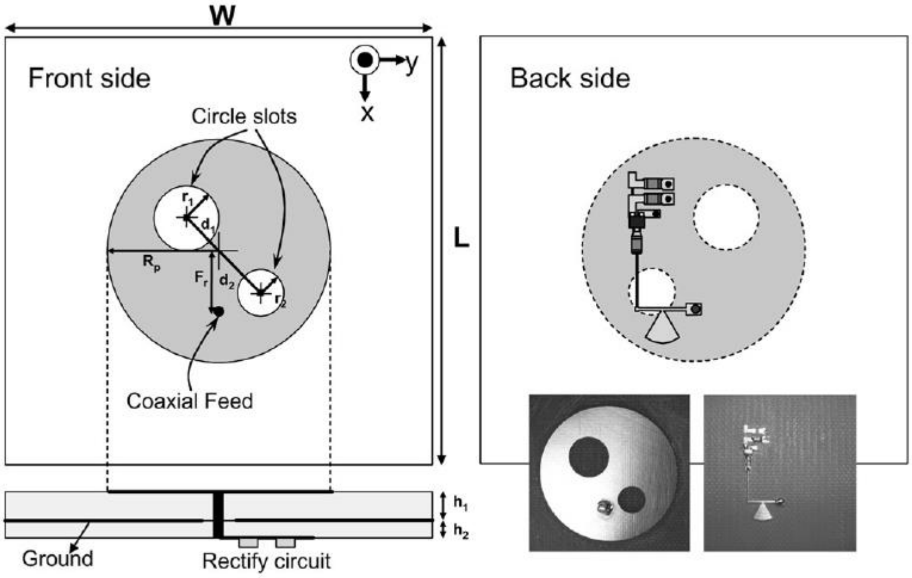


Figure 3.7 Antenna and rectifying circuit

The transmission line may result in a complicated layout schematic for antenna array applications when integrating circuits with the antenna. In addition, the characteristics of the antenna may be affected by coupling effects introduced by the nearby circuit. The doubler rectifier circuit with Schottky detector diode pair HSMS-282c and 3rd order harmonic rejection radial stub serves as a rectenna for the RF-to-DC power conversion. Under the ANSI/IEEE uncontrolled and controlled RF human exposure limits, respectively, the RF-to-DC conversion efficiency reaches 53% and 75% with a 1 k resistor load thanks to harmonic rejection up to the third order.

The voltage doubler includes half of the single diode rectifier's input impedance and produces at least twice the DC output, as depicted in Figure. The non-linear diode harmonics can be largely suppressed with the help of the second harmonic rejection CP antenna and the third harmonic rejection stub for improved efficiency and elimination of interference. The DC pass filter also blocks unwanted RF signals that leak to load.

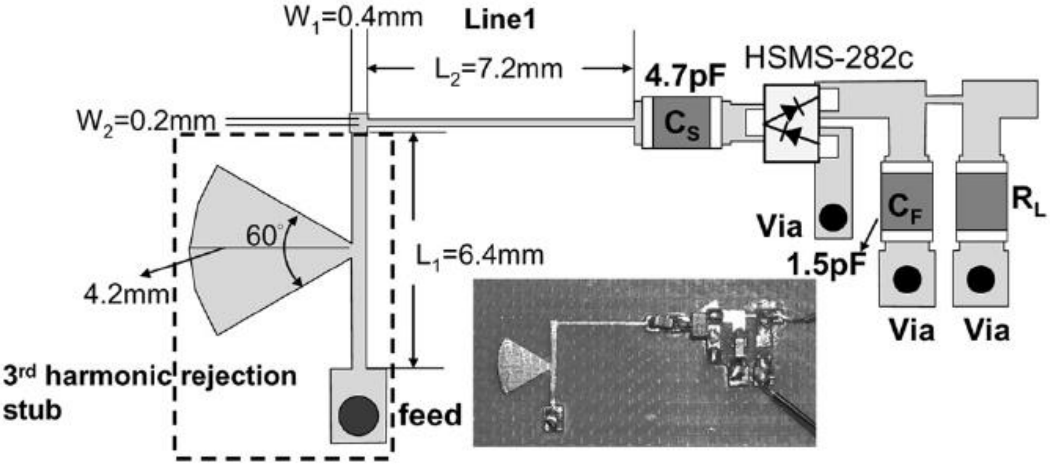


Figure 3.8 Schematic and photograph of double rectifier with 3rd harmonic rejection radial stub

A compact circular polarized rectenna, as proposed, with two unbalanced circular slots and the ability to reject harmonics. The two unbalanced circular slots are the source of the second harmonic rejection property, which makes rectifying circuit design simpler. At 16.5 mW/cm2 incident power density, the doubler rectifier achieves an optimal DC voltage of 15.8 V and RF-DC conversion efficiency of 78 percent.

3.7 Harmonic-rejecting circular-sector rectenna

A standard patch antenna typically exhibits resonant frequencies at multiple harmonics. A non-linear diode emits harmonic radiation, which must be stopped by using filters. A rectenna with a microstrip harmonic-rejecting circular sector of 240 was proposed. For impedance matching, he used an insert feeding strategy with a quarter-wavelength transformer operating at 2.4 GHz and 30 degrees from the circular sector's edge, as shown in Figure. The gain of the circular sector antenna is 4.677 dBi higher than that of a standard square-patch microstrip antenna. It has high coefficients of reflection at the second and third harmonics.

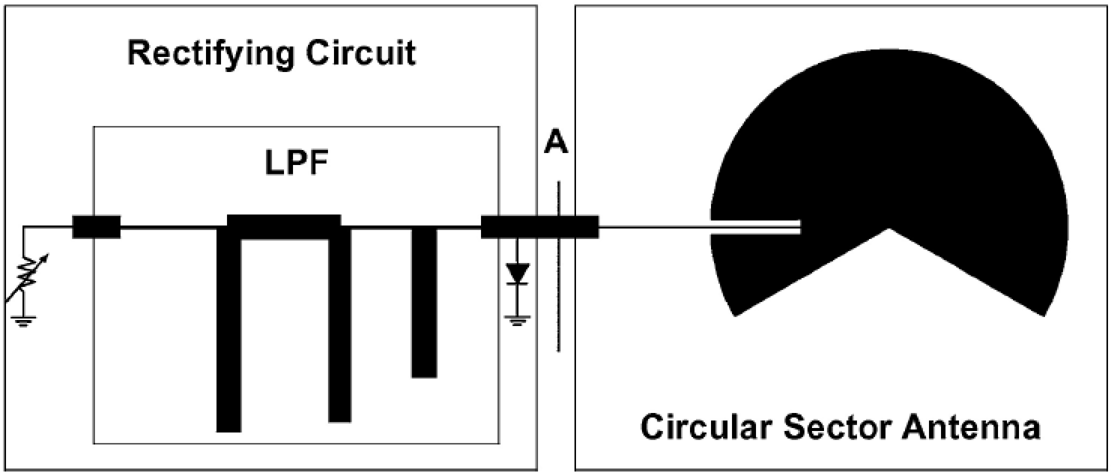


Figure 3.9 Rectenna with microstrip circular-sector antenna

A band pass filter between the antenna and the diode is eliminated by the rectenna with integrated circular sector antenna, resulting in high output power. Additionally, at the Schottky diode HSMS-2820's output, a microstrip low pass filter completely eliminates not only the fundamental frequency but also the second and third harmonics. As the input power increases, so does the efficiency. When the input power is 10 dBm (0.27 mW/cm2), the load resistor of 150 achieves a maximum efficiency of 77.8%.

3.8 Rectifier with high Q resonators

The majority of approaches to rectenna circuits for far field radiation either rely on RF power inputs (greater than -25 dBm) or have low efficiency (less than 10%) at input power levels of -30 dBm. It is necessary to rectify low ambient radiation energy in order to supply autonomous measurement systems because the transmitting power for the health standard is restricted by law. A voltage double rectifier with a quartz resonator of high Q and a proposed resonant frequency of 24 MHz is depicted below.

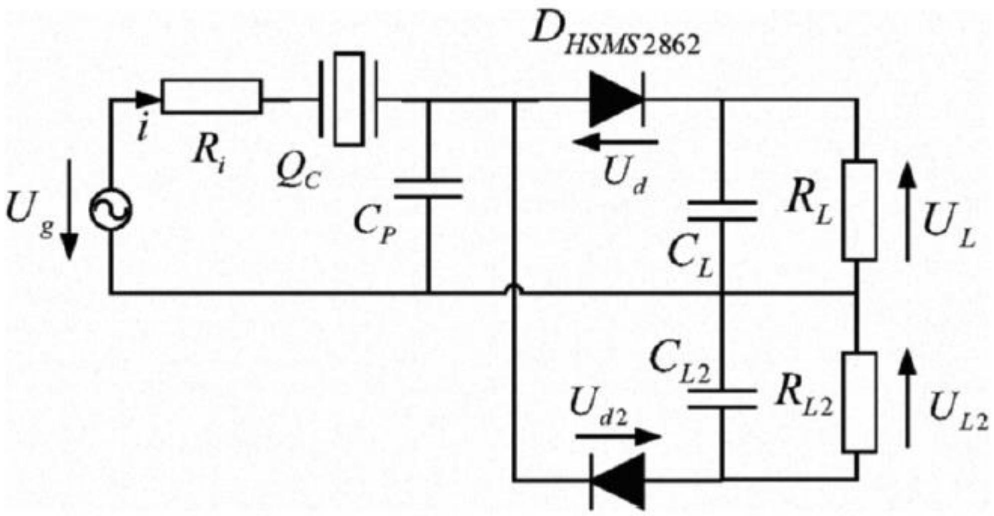


Figure 3.10 Equivalent circuit with resonator and diodes

The diode's voltage sensitivity, quality factor, and system efficiency all have an impact on the output voltage for a given RF power and frequency. Quartz resonators have a significantly higher Q factor and frequency stability than integrated passives. By increasing the input voltage to the rectifier, the resonance circuit makes it possible for passive voltage boosting in a proportional way to its loaded Q. For a DC output voltage of 1 V, this rectifier has a sensitivity of -30 dBm and an efficiency of over 22%.

3.9 Spiral rectenna for surrounding energy harvesting

In broadband (1GHz to 3.5GHz), the surrounding RF power density is about -12 dBm/m2 (6.3 nW/cm2). The frequency range of 1.8 GHz to 1.9 GHz has the highest RF power density, which is approximately -14.5 dBm/m2 (3.55 nW/cm2). Under this circumstance, spiral rectennas at 1.85 GHz and 2.45 GHz, as proposed, were measured close to an urban base station. When the RF power is approximately -38 dBm and the frequency range is 1.8 GHz to 1.9 GHz, the efficiency of rectifying circuits is estimated to be 0.7% for a DC power reaching 1.2 nW over an optimum load of 18 k. With a DC power of 1.3 W and an input RF power of -20 dBm at 2.45 GHz, the efficiency is 13% over a load of 7.4 k. The rectenna was at a distance of 1.3 meters from the ground and the base station was at a height of 29 meters in the outdoor measurements.

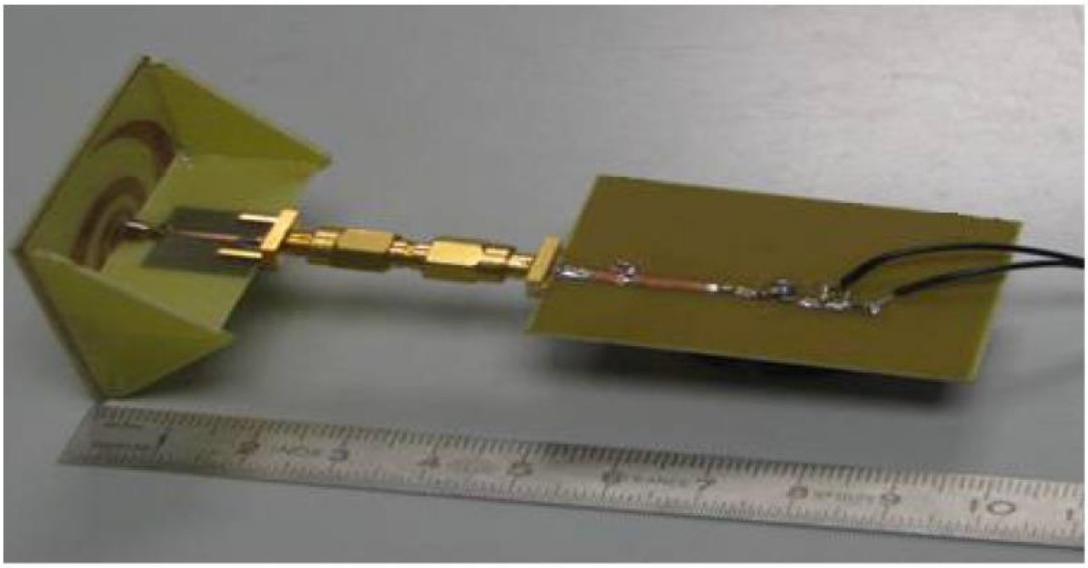


Figure 3.11 Rectenna prototype with spiral antenna

The measurement in urban RF power density conditions produces very low DC energy, so the energy harvested is insufficient to continuously supply an electronic application. However, the maximum DC voltage reaches 42 mV, which is equivalent to a dissipated DC power of 0.1 W. The average DC voltage reaches 8 mV for an equivalent power of 3.55 nW. However, you can store this energy for later use. An antenna array or a specific emitting source can be used to increase the DC power scavenging and to charge the micro batteries for wireless sensors. The DC power recovered by a rectenna at 1.85 GHz was approximately 0.5 pW to 100 nW, with an average value of approximately 3.5 nW.

3.10 Dual-frequency for energy harvesting at low power levels

Rectennas are made up of antennas and RF-to-DC conversion circuits with the intention of continuously supplying electronic devices with RF power. To make the most of the RF power that is captured, the dual-frequency rectenna is used. A rectenna with double circular slot antennas and a hybrid ring antenna were proposed. The receiving wire is advanced with two roundabout spaces on the ground plane for the double recurrence property. To produce circular polarization, a short circuit is present in each slot. As depicted below.

On an Arlon 25N substrate with a thickness of 1.524 millimeters, a Schottky diode SMS7630, and a r value of 3.4 and a tan value of 0.0025, three converting circuits are printed. With a 180° phase shift, the incident RF power travels from Port 2 to Ports 1 and 4. Additionally, Port 3 contains all signals passing through Ports 1 through 4.RA and RC operate at 1.8 GHz, while RB operates at 2.45 GHz. In order to maximize the output DC voltage and power, these circuits in the rectifying system, which are based on a hybrid ring, are serial and parallel. At 1.8 and 2.45 GHz, the rectifying system performs similarly to one another. The measurement was carried out at 1.8 and 2.35 GHz because of the distortion that occurs at resonant frequencies. When the received power is -20 dBm at 1.8 and 1.35 GHz, this rectenna is efficient at 21%, and when the RF power is -6 dBm, it is efficient at 50%.

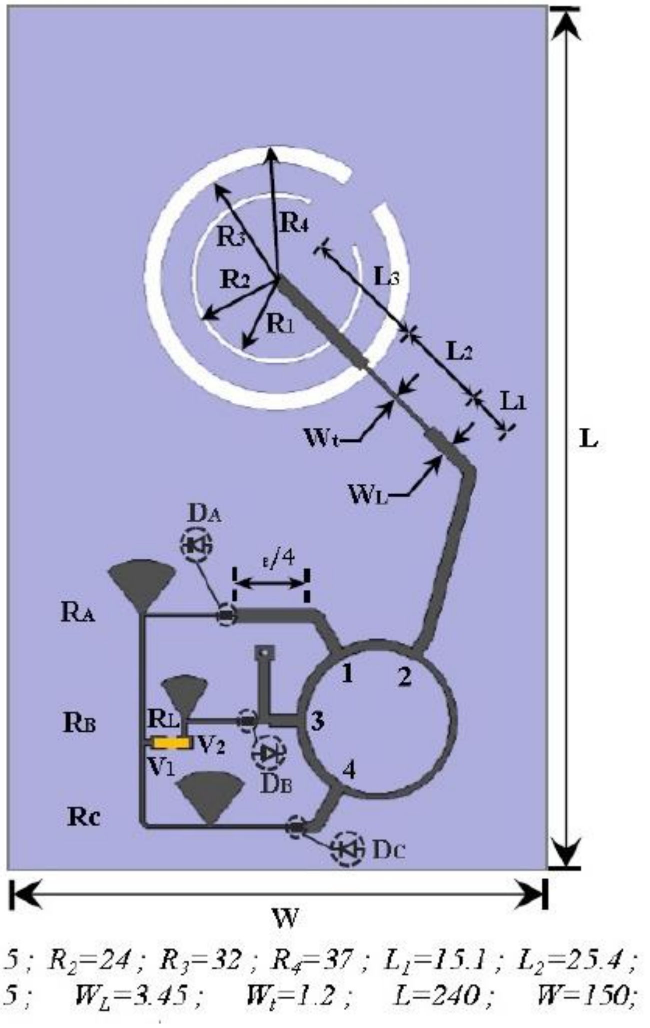
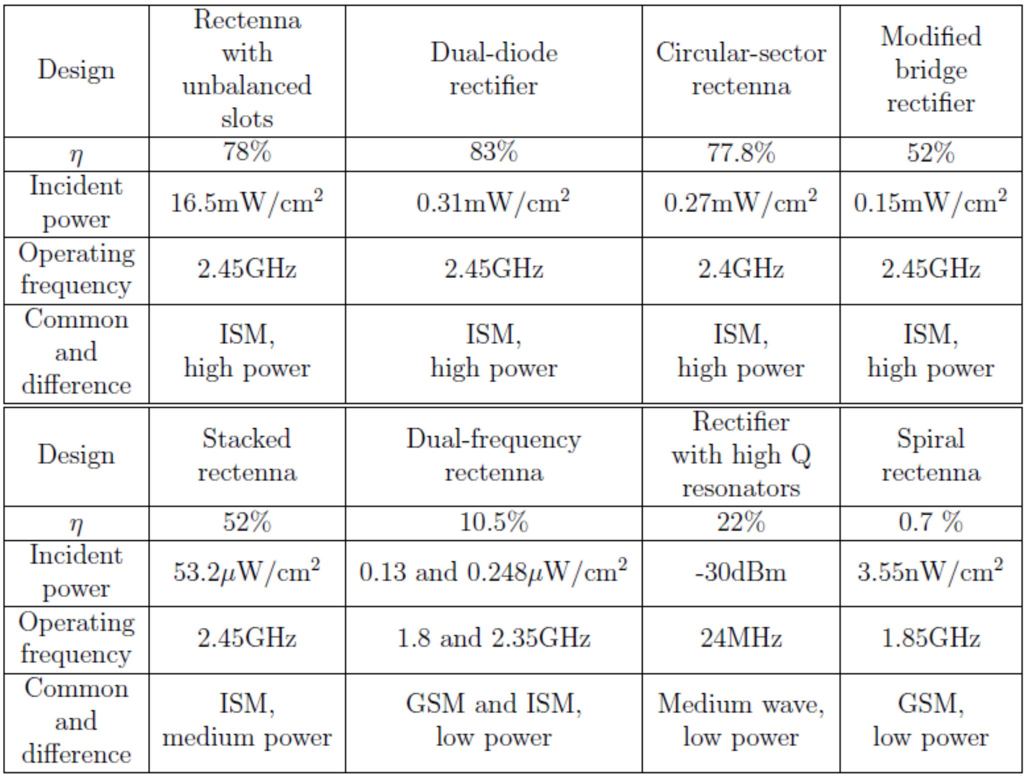


Figure 3.12 Dual frequency rectenna (dimensions in mm)

Table 2

Comparison of Rectenna Design (a)

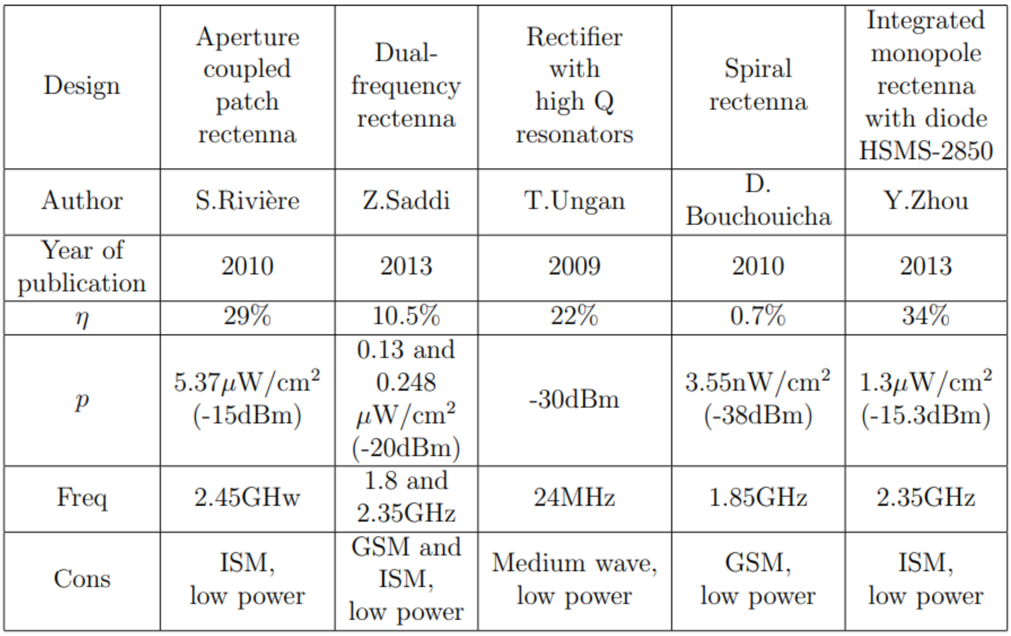


Design	Rectenna with unbalanced slots	Dual-diode rectifier	Circular-sector rectenna	Modified bridge rectifier
η	78%	83%	77.8%	52%
Incident power	16.5mW/cm^2	0.31mW/cm^2	0.27mW/cm^2	0.15mW/cm^2
Operating frequency	2.45GHz	2.45GHz	2.4GHz	2.45GHz
Common and difference	ISM, high power	ISM, high power	ISM, high power	ISM, high power

Design	Stacked rectenna	Dual-frequency rectenna	Rectifier with high Q resonators	Spiral rectenna
η	52%	10.5%	22%	0.7 %
Incident power	53.2μW/cm^2	0.13 and 0.248μW/cm^2	-30dBm	3.55nW/cm^2
Operating frequency	2.45GHz	1.8 and 2.35GHz	24MHz	1.85GHz
Common and difference	ISM, medium power	GSM and ISM, low power	Medium wave, low power	GSM, low power

Table 3

Comparison of rectenna design(b)



Design	Aperture coupled patch rectenna	Dual-frequency rectenna	Rectifier with high Q resonators	Spiral rectenna	Integrated monopole rectenna with diode HSMS-2850
Author	S.Rivière	Z.Saddi	T.Ungan	D. Bouchouicha	Y.Zhou
Year of publication	2010	2013	2009	2010	2013
η	29%	10.5%	22%	0.7%	34%
p	5.37μW/cm^2 (-15dBm)	0.13 and 0.248 μW/cm^2 (-20dBm)	-30dBm	3.55nW/cm^2 (-38dBm)	1.3μW/cm^2 (-15.3dBm)
Freq	2.45GHw	1.8 and 2.35GHz	24MHz	1.85GHz	2.35GHz
Cons	ISM, low power	GSM and ISM, low power	Medium wave, low power	GSM, low power	ISM, low power

Chapter 4

ANTENNAS FOR RF ENERGY HARVESTER

Advanced communication systems require antennas with more bandwidth and smaller dimensions compared to conventional antennas. The specifications for these antennas such as low profile, lightweight, compact size, polarization multiband and planar structure characteristics are also discussed. In addition, the recent related work of our group should be taken into consideration. An antenna is a fundamental device used in electronic transmission systems that enables wireless communication. The main function of an antenna is to take an electrical signal and transmit it in a radio frequency, which propagates through the air.

The antenna act like transitional structure which converts one from of energy into others, by acting like a medium between guiding device and free space. It is a device which converts electrical signal energy given to it into Electromagnetic waves which can travel through free space without the help of any medium and vice-versa. With reference from IEEE, "Antenna can be viewed as a device used to radiate or receive electromagnetic waves within a transmitting or receiving system". These are 3-D structures and can be measured in terms of beam area, square degree, Ste radians, and solid angles. It has three polarizations: linear, circular and elliptical. The figure shows the working of antenna where transition from a guided wave to a free-space wave is taking place at receiver end and thus, Antenna acts like a transducer or a wireless link or a between the transmitting and receiving antennas.

Alternating current (AC) is fed into the dipole at a defined resonant frequency, which sends energy into the dipole for transmission. Because the transmission line is open ended all the energy is reflected, and as it reflects back a standing wave of energy is created. This causes the dipole to radiate its energy orthogonal to the direction of the current. Dipoles and monopoles are used today for radio transmission and cell tower broadcasting. Printed circuit board antennas, known as patch antennas or planar inverted-F antennas (PIFA) are another type of antenna commonly used in portable devices due to their small form factor.

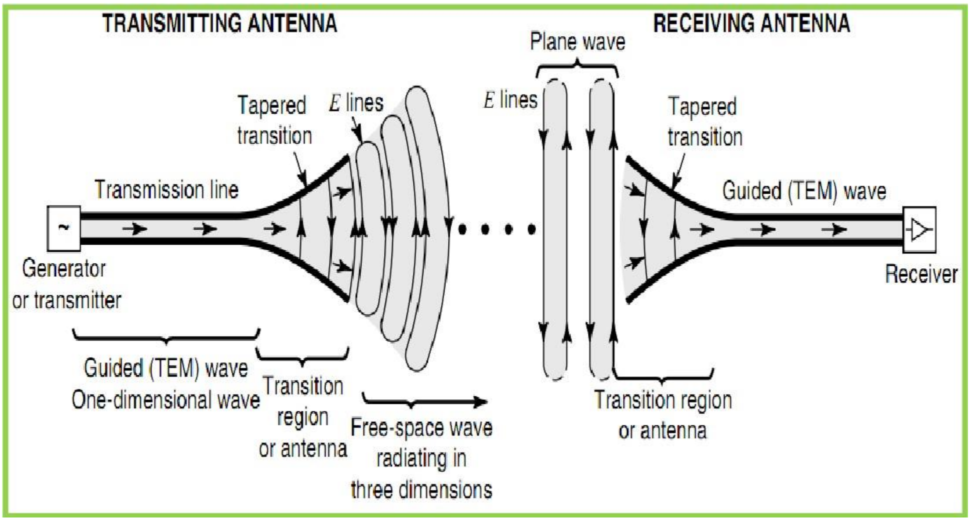


Fig. 4 Wireless connection showing Transmitting and Receiving Antenna

In RF energy harvesting, an antenna plays a crucial role in capturing and converting radio frequency (RF) energy into usable electrical energy. The antenna serves as the interface between the electromagnetic waves in the RF spectrum and the energy harvesting system.

1) The key parameters and considerations regarding the relationship between the antenna and RF energy harvesting:Frequency compatibility: The antenna should be designed to resonate at the frequency or frequency range of the RF signals to be harvested. Matching the antenna's resonant frequency with the operating frequency maximizes its efficiency in capturing energy.
2) Antenna efficiency: The efficiency of the antenna determines how effectively it can convert the incident RF power into electrical energy. High antenna efficiency ensures that a greater portion of the available RF energy is harvested.
3) Antenna size and form factor: The size and form factor of the antenna depend on various factors, including the desired frequency range, application requirements, and space constraints. Smaller antennas are typically suitable for higher frequencies, while larger antennas are needed for lower frequencies.
4) Directivity: Antennas can be designed to have specific radiation patterns, such as omnidirectional or directional. The choice of directivity depends on the application requirements. For example, an omnidirectional antenna is

suitable when the RF energy source is not fixed, while a directional antenna can be advantageous when there is a known direction for the RF signals.

5) Matching network: An antenna is typically connected to a matching network, which ensures efficient power transfer between the antenna and the energy harvesting circuit. The matching network matches the impedance of the antenna to the impedance of the energy harvesting system, maximizing power transfer.
6) RF signal strength: The antenna should be sensitive enough to capture and convert the available RF power. In some cases, amplification or signal conditioning may be required to improve the signal strength or to adapt the antenna's impedance to the energy harvesting system.

4.1 Working of Antenna

An antenna consists of a metal conductor that conveys radio frequency (RF) waves between two points in space. This device can either transmit a signal or receive one. When a voltage is applied to a transmitting antenna, it generates radio signals which travel to a receiving antenna where the signal is converted back into electrical energy in the form of information. The antenna at the transmitter generates the radio wave. A voltage at the desired frequency is applied to the antenna. The voltage across the antenna elements and the current through them create the electric and magnetic waves, respectively. At the receiver, the electromagnetic wave passing over the antenna induces a small voltage. Thus, the antenna becomes the signal source for the receiver input. Any antenna will work for either transmit or receive. In many wireless applications, the antenna is switched between the transmitter and receiver, this is called Antenna Reciprocity. The dipole consists of two linear conductors end-to-end with a length of one-half wavelength ($\lambda/2$) *(Fig. a)*. Here, one wavelength (λ) is 300/fMHz in meters. One half wavelength in feet is 468/ fMHz or 5616/fMHz in inches. The term f is the frequency of operation in megahertz.

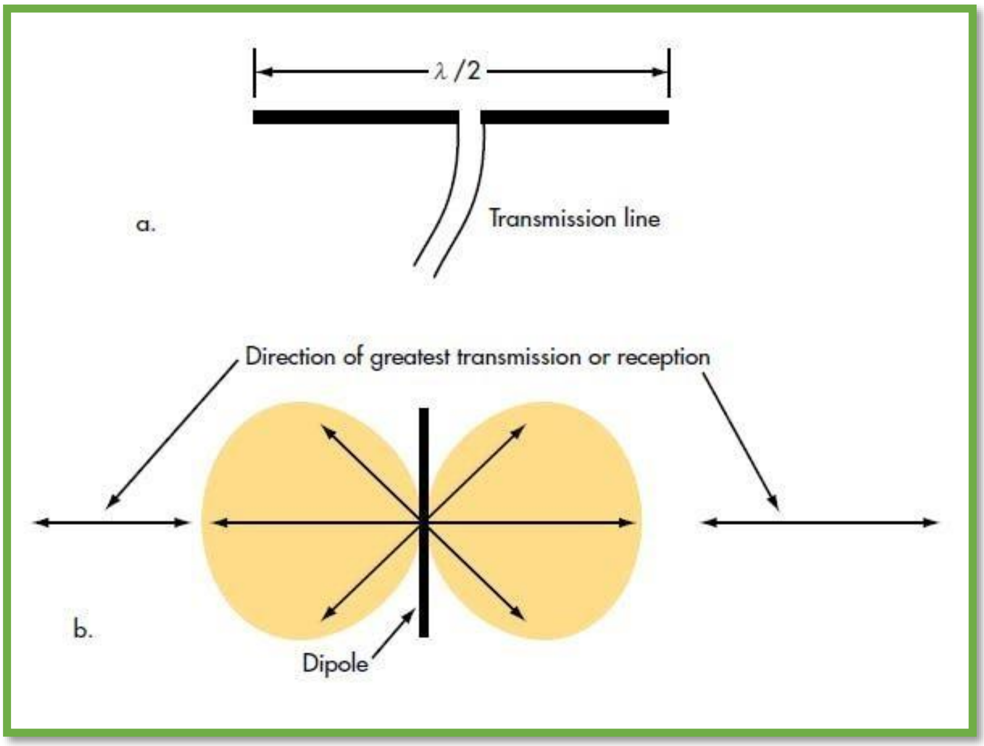


Fig 4.1 Dipole Structure

4.2 Types of Antennas

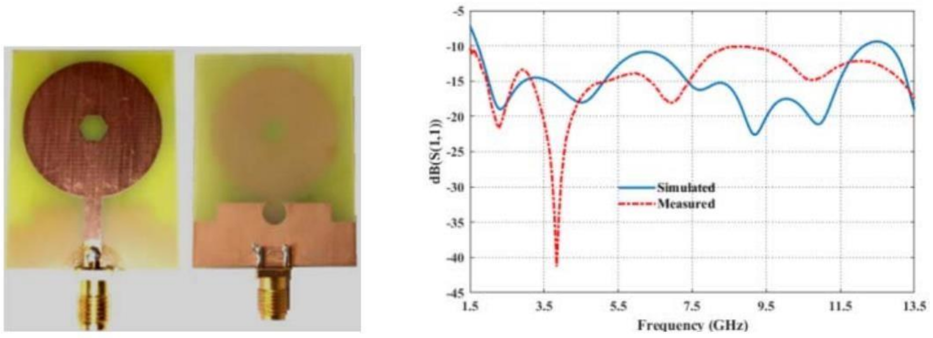
Antennas have to be classified to understand their physical structure and functionality more clearly. There are many types of antennas depending upon the applications.

The most popular Antennas are:

1. **High Gain Antenna**
2. **Dual Band Antenna**
3. **Compact and Multiband Antenna**
4. **Transparent Antenna**
5. **Omnidirectional Antenna**

4.2.1 High Gain Antenna

A high-gain antenna (HGA) is an antenna with a narrow radio beam that is used to increase signal strength. High-gain antennas provide a more precise way of targeting radio signals and are therefore very essential to long-range wireless networks. They even amplify weak signals. A high-gain antenna may also be known as a directional antenna. High-gain antennas are focused antennas with narrow radio beams, allowing for precise targeting of radio signals. This antenna is used in space missions as well as in flat, open areas where the geography won't disrupt radio waves. High-gain antennas transmit more power to the receiver, increasing the strength of the signal it receives. As a result of their reciprocity, high-gain antennas can also make transmitted signals 100 times stronger by capturing more energy when used in receiving antenna. As a result of their directivity, directional antennas send fewer signals from a direction other than the main beam. This property reduces interference.



(a) (b)

Fig 4.2.1 High gain antenna and frequency graph

4.2.2 Dual Band Antenna

A dual-band design of a finite ground coplanar waveguide (CPW) fed antenna is presented for simultaneously wireless local area network (WLAN) and worldwide interoperability for Microwave Access (WiMAX) applications. The proposed antenna, comprising a rectangular planar patch element embedded with two L shaped slots. This type of antenna possesses two different resonating frequencies. Use of the Dual band antennas in the RF energy harvesting leads to collect the possible frequency. As the RFEH required more input at the first end so the maximum output can be accessing the concept of dual band antenna can help to receive two different frequencies using a single antenna.

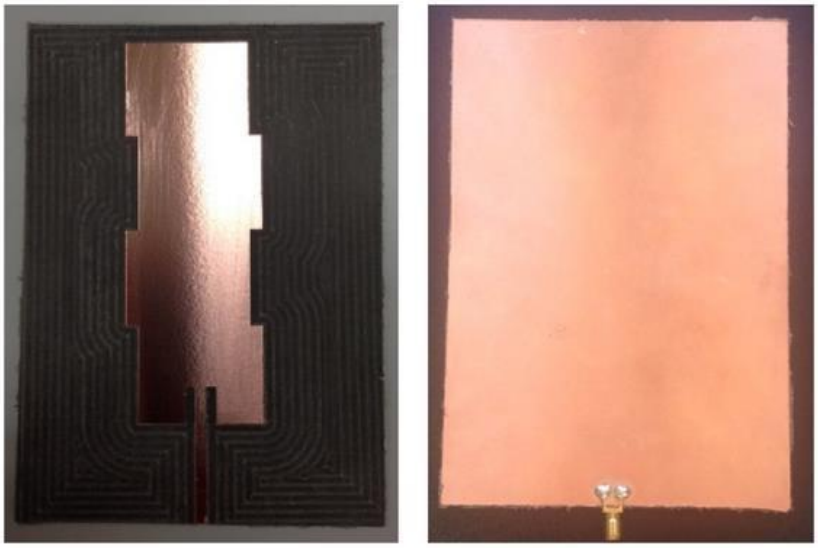
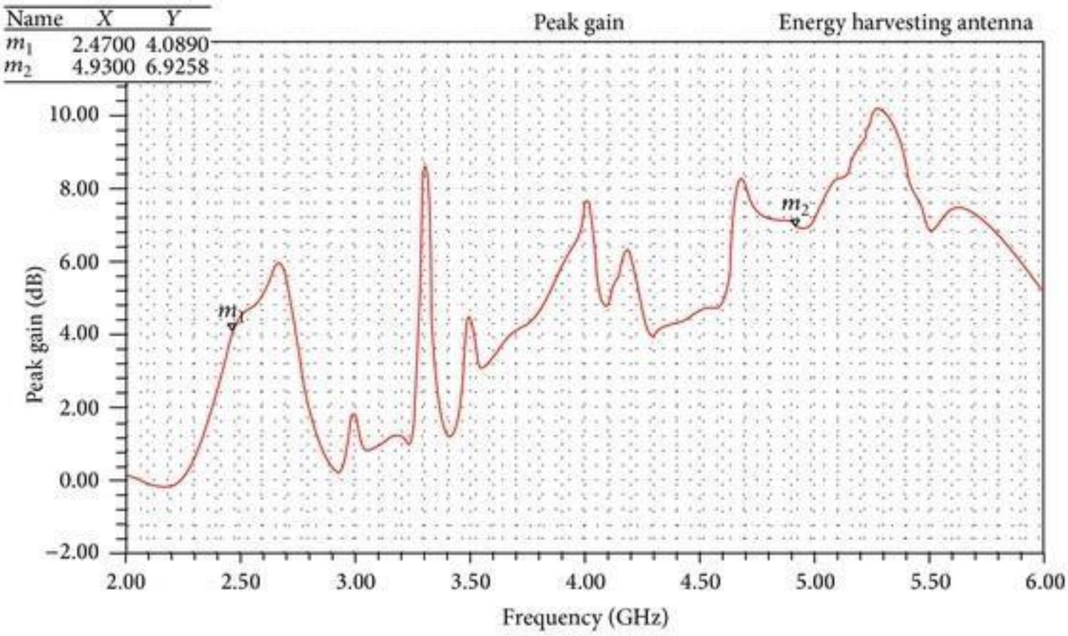


Fig 4.2.2 Dual-band Antenna



Name	X	Y
m_1	2.4700	4.0890
m_2	4.9300	6.9258

Fig 4.2.3 Peak gain of dual band antenna

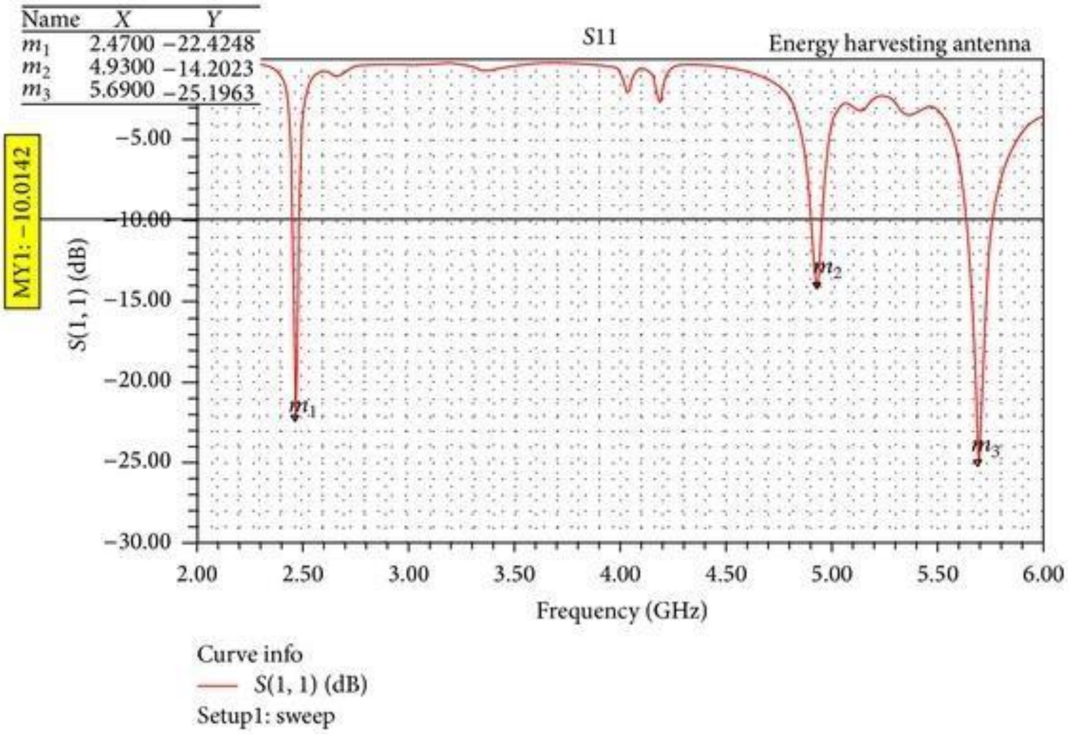


Fig 4.2.4 Return loss vs frequency

4.2.3 Compact and Multiband Antenna

The main goal is to design antennas for wireless communication applications where the space value of the antenna is quite limited while it reserves the characteristics of multiband, lightweight, low cost, robustness, diversity, packaging capabilities and ability for RF PIN switches/MEMS integration for smart antenna systems. Famous techniques for antenna size reduction include dielectric loading to reduce the electrical size, top hat loading, and use of shorting PINs or plates. Reduction in the size of the antenna can help to build the miniaturized RF energy harvester. The interesting choices are slot-coupled multiresonators, printed spiral antennas, planar inverted “F” antennas (PIFA), and a fractal implementation, such as the Koch. Multiband antenna can receive a greater number of frequencies at the same instance. As per the MIMO the gain and efficiency of the antenna and RFEH increases gradually.

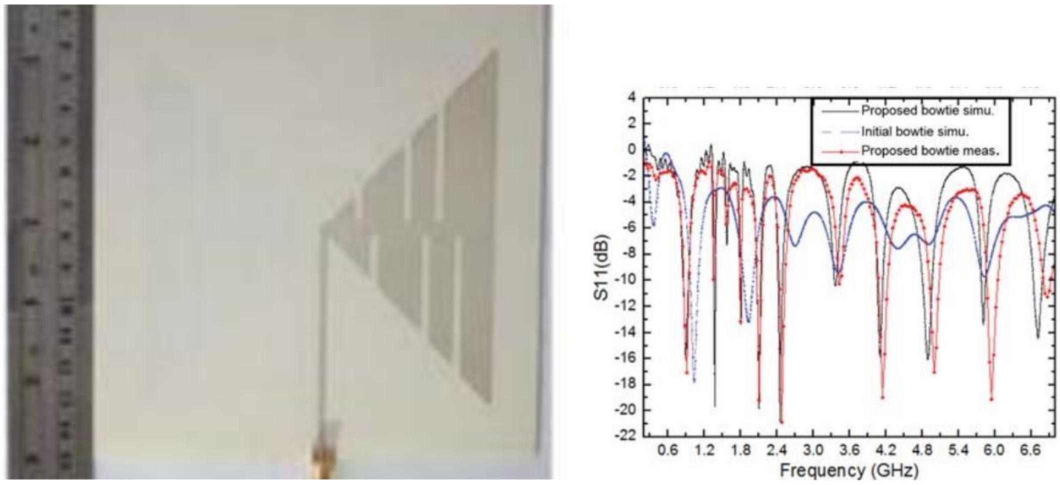


Fig 4.2.5 Multiband bow-tie antenna and S11 coef.

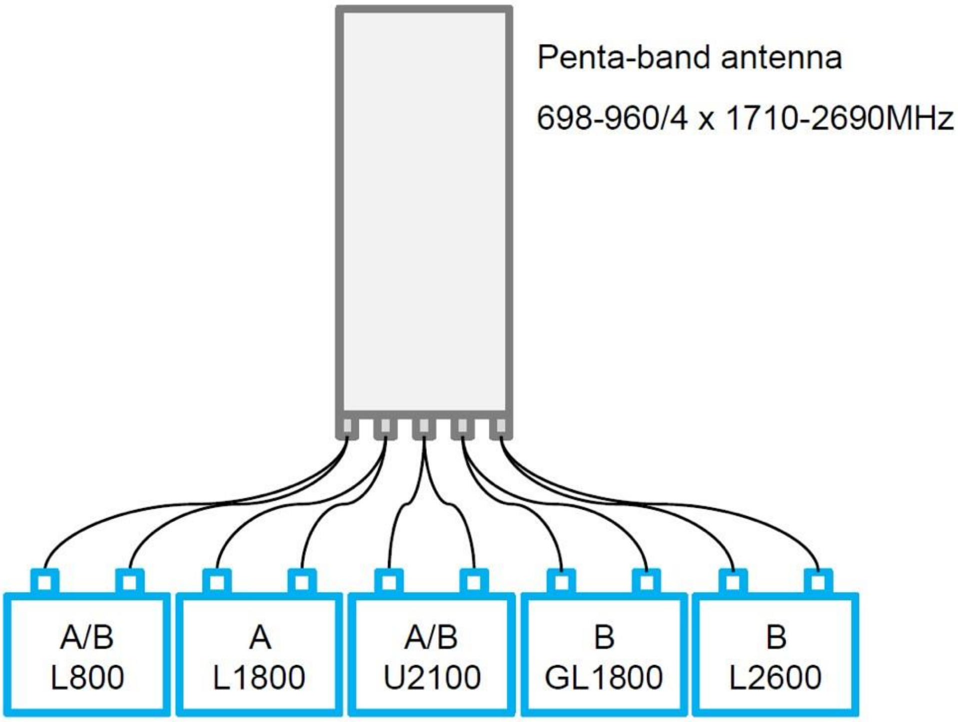


Fig 4.2.6 Multiband Antenna (Penta-Band)

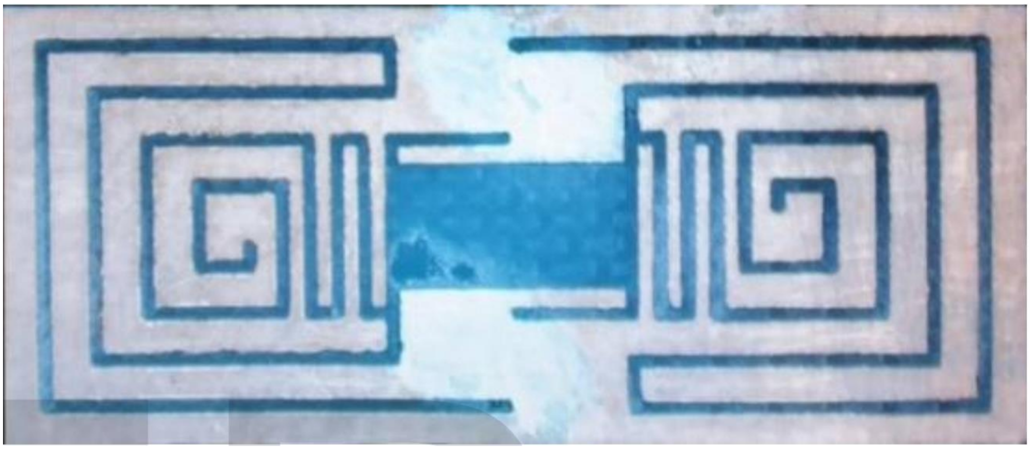


Fig. 4.2.7 Compact antenna

4.2.4 Transparent Antenna

The transparent antenna was first presented by the National Aeronautics and Space Agency (NASA) when researchers Simmons and Lee demonstrated the use of AgHT-8 to produce single patch antennas to operate at 2.3 and 9.5 GHz. To design and produce workable antennas, different materials are used such as indium tin oxide (ITO) and aluminium-doped zinc oxide. Except for those produced using ITO or AgHT, most of the so-called transparent antennas are simply antennas constructed by coating transparent polymer substrates with nontransparent conductive traces of silver or other conductive ink. Some selected shapes of the transparent antennas as shown in Figures 8 and 9 cannot be really categorized as fully transparent antennas since the traces are visible to the eye. The transparent antennas in this section are those that are fully transparent, in other words, even the conductive traces are transparent and discreet to the eye.

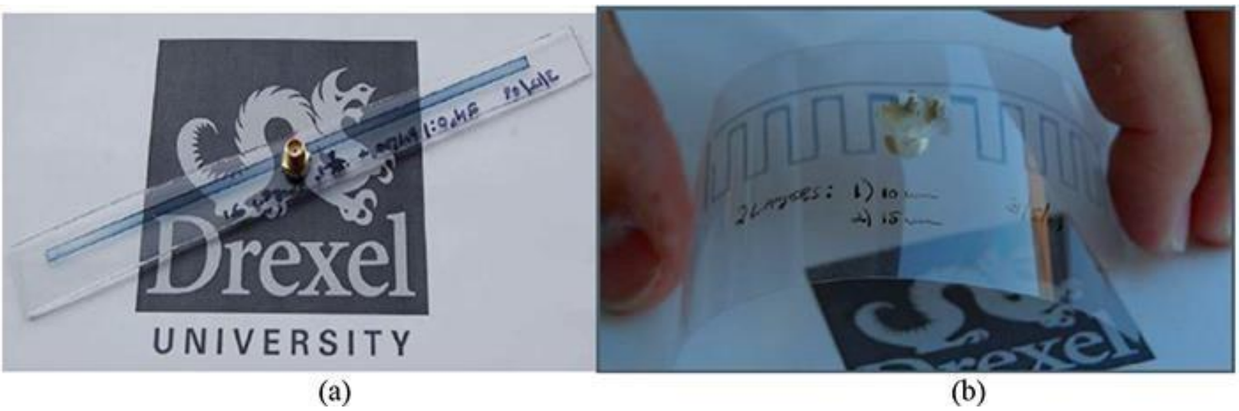


Fig 4.2.8 Transparent Antenna

4.2.5 Omnidirectional Antennas

Omnidirectional antennas are commonly referred to as “Omnis.” In addition, an omni often refers to an omnidirectional antenna but specifically not a dipole. Often, an omni refers to an omnidirectional antenna that has more gain than a dipole. However, a dipole is an omnidirectional antenna as we will see in the next section. The dipole is just a special case.

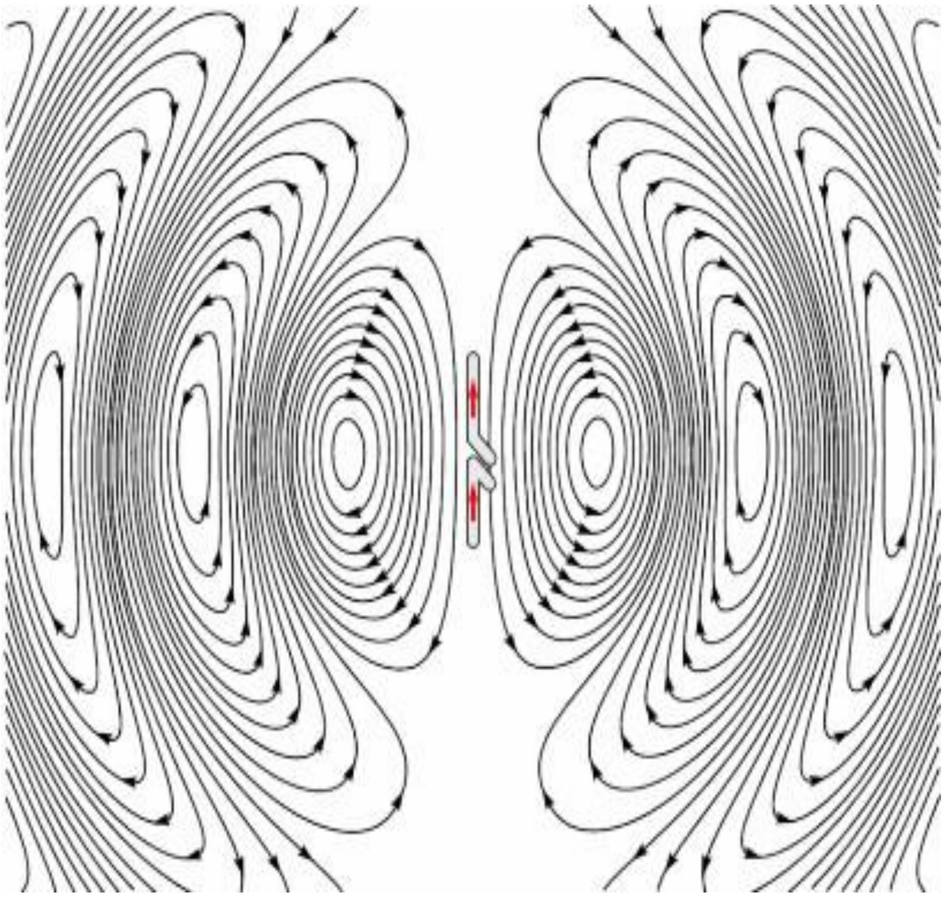
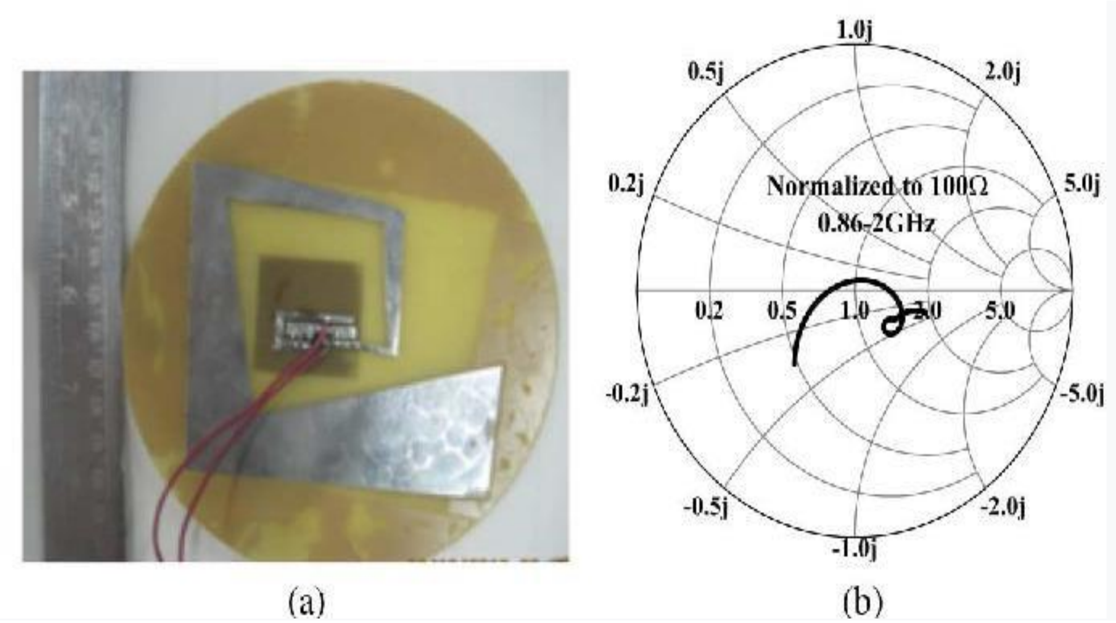


Fig 4.2.9 Animation of an omnidirectional half-wave dipole antenna transmitting radio waves



(a) (b)

Fig. 4.2.10 Omnidirectional antenna

An omnidirectional antenna is a class of antenna that radiates equal radio power in all directions perpendicular to an axis (azimuthal directions), with power varying with angle to the axis (elevation angle), declining to zero on the axis. When graphed in three dimensions (see graph) this radiation pattern is often described as doughnut-shaped. Note that this is different from an isotropic antenna, which radiates equal power in all directions, having a spherical radiation pattern. Omnidirectional antennas oriented vertically are widely used for nondirectional antennas on the surface of the Earth because they radiate equally in all horizontal directions, while the power radiated drops off with elevation angle so little radio energy is aimed into the sky or down toward the Earth and waste.

4.3 Microstrip Patch Antenna

4.3.1 Definition:

Microstrip antennas are low-profile antennas. A metal patch mounted at a ground level with a dielectric material in-between constitutes a Microstrip or Patch Antenna. These are very low-size antennas having low radiation. The patch antennas are popular for low-profile applications at frequencies above 100MHz.

4.3.2 Theory:

In high-performance aircraft, spacecraft, satellite, and missile applications, where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints, low-profile antennas may be required. Presently there are many other government and commercial applications, such as mobile radio and wireless communications, that have similar specifications. To meet these requirements, microstrip antennas can be used. Deschamps first proposed the concept of the MSA in 1953. However, practical antennas were developed by Munson and Howell in the 1970s. Major operational disadvantages of microstrip antennas are their low efficiency, low power, high Q (sometimes in excess of 100), poor polarization purity, poor scan performance, spurious feed radiation and very narrow frequency bandwidth, which is typically only a fraction of a percent or at most a few percent.

The telemetry and communications antennas on missiles need to be thin and conformal and are often MSAs. Radar altimeters use small arrays of microstrip radiators. Other aircraft-related applications include antennas for telephone and satellite communications. Microstrip arrays have been used for satellite imaging systems. Patch antennas have been used on communication links between ships or buoys and satellites. Microstrip patch antennas are used in mobile handsets due to simple look, lower cost, small size and lighter in weight. This antenna does not take any much extra size and can be etched on the same mobile PCB itself.

4.3.3 Why Microstrip Patch Antenna for RFEH?

- Energy Capture: The antenna serves as the primary component for capturing RF energy from the surrounding environment. It acts as a transducer that converts the electromagnetic waves in the RF spectrum into electrical energy. The efficiency and performance of the antenna directly impact the amount of energy that can be harvested.

- Maximizing Harvested Power: A well-designed antenna can optimize the power transfer from the RF source to the energy harvesting circuit. By matching the impedance of the antenna to the impedance of the energy harvesting system.
- Compatibility with Energy Harvesting Circuit: The antenna needs to be properly matched to the energy harvesting circuitry to ensure maximum power transfer and efficiency. This may involve the use of matching networks or impedance matching techniques to match the antenna's impedance to the input impedance of the energy harvesting circuit. A well-matched antenna enables efficient power extraction and improves the overall performance of the energy harvesting system.
- Frequency Selectivity: RF energy exists across a wide range of frequencies, and different sources may operate at specific frequencies or frequency bands. The antenna's design can be tailored to resonate at specific frequencies or cover a broader frequency range, allowing it to capture energy from different RF sources. By selecting the appropriate antenna design, the energy harvesting system can target specific RF signals or operate in multiple frequency bands.
- Size and Form Factor: Antennas used in RF energy harvesting systems can be designed to be compact and lightweight. This flexibility allows for integration into various devices and environments, making them suitable for applications such as wireless sensors, IoT devices, or wearable electronics. The size and form factor of the antenna can be optimized to meet the specific requirements of the application while maintaining good performance.

In summary, the antenna is a critical component in RF energy harvesting systems as it directly influences the efficiency, power capture, frequency selectivity, and overall performance of the system. A well-designed antenna enhances the energy harvesting capability and enables the successful conversion of RF energy into usable electrical power.

4.3.4 Basic characteristics

- An MSA in its simplest form consists of a radiating patch on one side of a dielectric substrate and a ground plane on the other side.
- Normally, it consists of a very thin (h << λ0, where λ0 is the free-space wavelength) metallic strip (patch) placed a small fraction of a wavelength (h << λ0, usually 0.003λ0 ≤ h ≤ 0.05λ0) above a ground plane. The microstrip patch is designed so its pattern maximum is normal to the patch (broadside radiator).
- Radiation from the MSA can occur from the fringing fields between the periphery of the patch and the ground plane. The length L of the rectangular patch for the fundamental TM10 mode excitation is slightly smaller than λ/2, where λ is the wavelength in the dielectric medium.
- The value of Ɛr is slightly less than the dielectric constant Ɛr of the substrate because the fringing fields from the patch to the ground plane are not confined in the dielectric only, but are also spread in the air.
- For a rectangular patch, the length L of the element is usually λ/3 < L < λ/2. The strip (patch) and the ground plane are separated by a dielectric sheet (referred to as the substrate), as shown in *Figure 3.3.3.1*
- There are numerous substrates that can be used for the design of microstrip antennas, and they're the ones that are most desirable for good antenna performance are thick substrates whose dielectric constant is in the lower end of the range because they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space, but at the expense of larger element size. Dielectric constants are usually in the range of 2.2 ≤ Ɛr ≤ 12.
- Thin substrates with higher dielectric constants are desirable for microwave circuitry because they require tightly bound fields to minimize undesired radiation and coupling, and lead to smaller element sizes; however, because of their greater losses, they are less efficient and have relatively smaller bandwidths.
- Often microstrip antennas are also referred to as patch antennas. The radiating elements and the feed lines are usually photoetched on the dielectric substrate.

- The radiating patch may be square, rectangular, thin strip (dipole), circular, elliptical, triangular, or any other configuration.

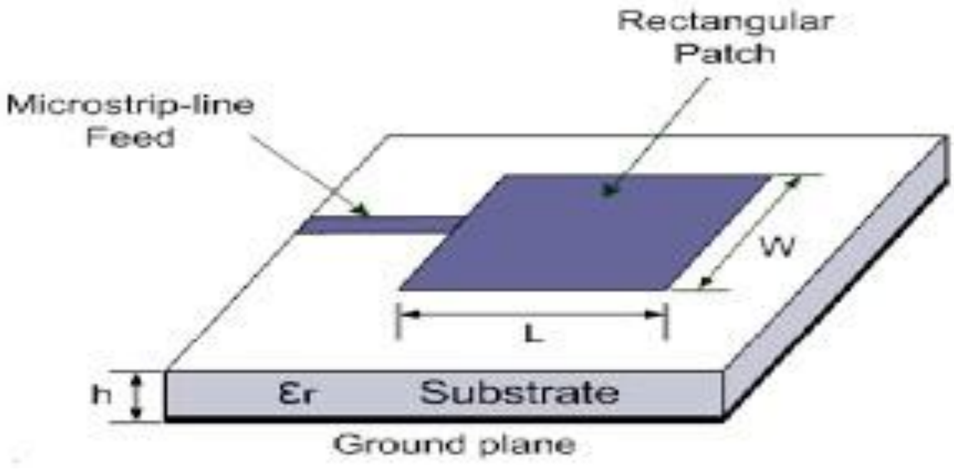


Fig 4.3 Microstrip Antenna

4.3.5 Application of Microstrip Patch Antenna

- The telemetry and communications antennas on missiles need to be thin and conformal and are often MSAs.
- Radar altimeters use small arrays of microstrip radiators.
- Other aircraft-related applications include antennas for telephone and satellite communications.
- Microstrip arrays have been used for satellite imaging systems.
- Patch antennas have been used on communication links between ships or buoys and satellites.
- Smart weapon systems use MSAs because of their thin profile.
- Pagers, the global system for mobile communication (GSM), and the global positioning system (GPS) are major users of MSAs.

4.3.6 ADVANTAGES OF MICROSTRIP PATCH ANTENNA

- Operate at microwave frequencies
- They can be made conformal to the host surface.
- Will provide small size end devices.
- Easily etched on any PCB
- They are easier to integrate with other MICs on the same substrate.
- Provide easy access for troubleshooting during design and development.
- Various shapes e.g., rectangular, square, triangular etc. are easily etched.
- Lower fabrication cost and hence they can be mass manufactured.
- They are capable of supporting multiple frequency bands (dual, triple).
- They support dual polarization types viz. linear and circular both.
- They are light in weight.
- They are robust when mounted on rigid surfaces of the devices.
- As the patch antennas are fed along centreline to symmetry, it minimizes excitation of other undesired modes.
- Works at the four most important frequencies for energy harvesting.

4.3.7 Disadvantages of Microstrip Patch Antenna

- Offers lower gain.
- It offers low efficiency due to dielectric losses and conductor losses.
- Complexity involved in the design and manufacturing process.
- Higher level of cross polarization radiation.
- It has inherently lower impedance bandwidth.
- The microstrip antenna structure radiates from feeds and other junction points.
- It has lower power handling capability.

4.4 Antenna Parameters

There are different types of parameters in antennas such as VSWR, Return Loss, Antenna Gain, Directivity, Antenna Efficiency, and Bandwidth analyzed.

(a) Gain: - Gain is defined as in the terms of the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The gain is given by the formulas G=4π. U (θ, Φ)/Pin, where U (θ, Φ) is a intensity in a given direction and Pin is input power.

(b) Radiation pattern: - The radiation pattern is a function of mathematical and graphical representation of the radiation properties of the antenna as a function of space coordinates.

(c) Antenna efficiency: - It is defined as the ratio of total power radiated by an antenna to the input power of an antenna.

(d) VSWR: - it is defined as the ratio of VSWR=Vmax/V min. In the ideal case it should be 1 and for better antenna performance the vswr value should be VSWR ≤ 2. VSWR = ଵ||□| ଵି|□| The VSWR is always a real and positive number for antennas. As smaller the VSWR value, the better the antenna is matched to the transmission line and the more power is delivered to the antenna.

(e) Return loss: - Return Loss is the power loss in the signal form which returned or reflected by a discontinuity in a transmission line or optical fiber. This discontinuity can be a mismatch with the terminating load or with a device inserted in the line. It is expressed as a ratio in decibels (Db). Return Loss (Db) = 10log10 (Pi/Pr) Where RL (Db) is the return loss, Pi is the incident power and Pr is the reflected power. Return loss is related to both standing wave ratio (SWR) and reflection coefficient (Γ). Increasing the return loss, lower the SWR. Return loss is a measure of how well devices or lines are matched. If the return loss is high mean match is good. A high return loss means lower insertion loss. RL = -20log |Γ| (Db).

Chapter 5
RECTIFIERS FOR RF ENERGY HARVESTER

The radio frequency signal captured by the antenna is an alternating current (AC) signal. In order to get a DC signal out of AC signal and improve the efficiency of the RF–DC power conversion system, a rectifier circuit is used. The rectification subsystem or peak detector, which has been already used on crystal radio, consists only of diodes and capacitors. When the distance from the RF source is far and the received power is not high enough, the rectifier input needs to be amplified in order to power the circuit (sensor networks or RFID tags require at least 3.3 V). The most popular rectifier used is a modified Dickson multiplier, which has the function of rectifying the radio frequency signal and increasing the DC voltage. Moreover, many works have used complementary metal–oxide–semiconductor (CMOS) technology to replace the diodes. Other different ways to rectify AC signals have been introduced, including the Greinacher circuit or voltage doubler, Cockcorft–Walton circuit, multiplier resonant, Villard multiplier, and boost converter.

The choice of rectification circuits depends on the radio frequency signal and power received since different values of DC voltage could be obtained with the same circuit and different radio frequency sources. The multiplier is usually formed using different stages; each stage includes two diodes and two capacitors. The voltage output is more important with a large number of stages. However, because diode loss increases with the stage number, the system efficiency is affected. The impact of the rectifier stage number on the power received is presented in Figure below. For the low received power (Pin < 0 dBm), the output voltage (V_{out}) is practically independent of the stage number, while efficiency is good for fewer stages. The high voltage range is achieved when the power received is around 0 dBm and the number of stages is large, whereas efficiency decreases when V_{out} reached its maximum. Therefore, it seems difficult to achieve a good design due to the received signal influence on the RFEH system.

Multiplier efficiency (η_{rect}) depends on the input and output powers (P_{in_rect} and P_{out_rect}, respectively), as expressed in Eq. below. However, the efficiency of RFEH system (η_{RFEH}) depends on the power generated (P_{out_dc}) and the power received (P_{in_rf}). The η_{RFEH} can be calculated using below equation:

$$\eta_{rect} = P_{out\_rect} / P_{in\_rect}$$

$$\eta_{RFEH} = P_{out\_dc} / P_{in\_rf}$$

Diodes commonly used as rectification components are Schottky diodes, while Germanium diodes are also used for radio circuits of the peak detector. Performance analysis of some Schottky diodes is outlined in Table 4.1.1.

Device	IS (A)	RS (Ω)	CJO (Pf)	VJ (V)	BV (V)	IBV (A)
SMS7630	5E-6	20	0.13	0.33	2	1E-03
HSMS-282X	2.2E-8	6	0.7	0.65	15	1E-03
HSCH-9161	12E-6	50	0.03	0.26	10	10E-12

Table 4: Power requirement of various components

5.1Background

5.1.1 Topologies:

The microwave rectifier can take several topologies depending on the configuration of the diodes used for rectification. The serial and shunt topologies are the most used in the literature. Furthermore, in order to improve the output DC voltage, the voltage doubler or voltage multiplier topology can also be used. These conventional rectifier circuit topologies are illustrated in fig 4.1.1.

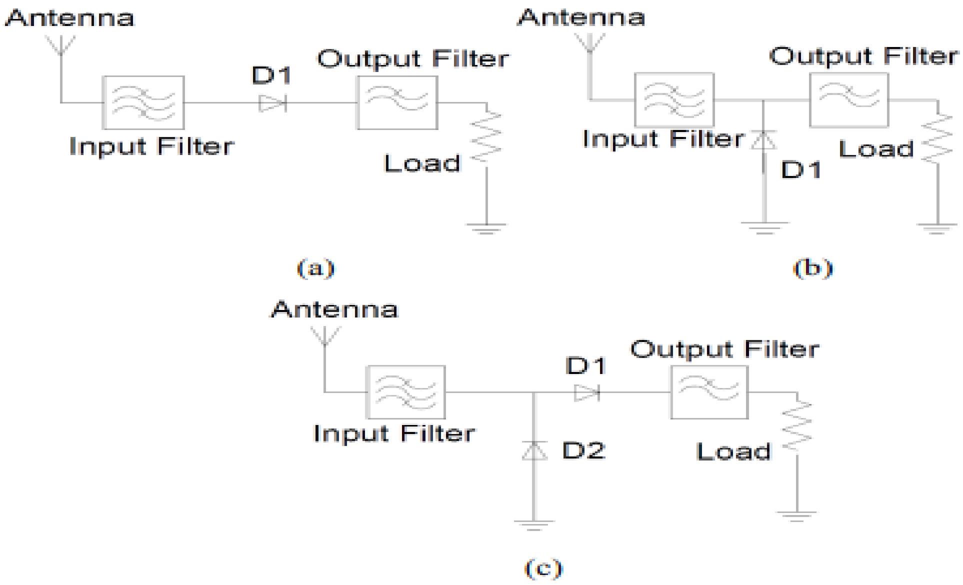


Figure 5.1.1. The conventional rectenna topologies: (a) series; (b) shunt; (c) single stage voltage doubler

In the serial topology, the single diode is placed between the RF filter and the DC filter. In the shunt topology, the diode is connected in parallel between the filters. The diode is self-biased by the DC voltage that it generates. The single stage voltage multiplier circuit or voltage doubler topology can be seen as the combination of the two preceding topologies. It consists of two diodes, one mounted in serial and the other in parallel, to produce a larger output voltage.

In effect, the mono diode topologies are mainly preferable because of their ease of implementation, their high efficiency, their small size and their low cost. They offer the theoretical advantage of minimizing the losses in the diodes. However, the output voltage levels for both topologies are low. The voltage doubler topology provides a high output voltage, but a low RF-DC conversion efficiency compared to the mono diode topology. The simulations performed prove that the voltage doubler circuit is more suitable for high input power levels applications (>20 dBm). The serial topology presents a good RF-DC conversion efficiency for low input power level applications (around -10 dBm and 20 dBm). Each of these topologies has its advantages and limitations. The choice of the suitable rectifier circuit topology is generally depends on the voltage required at the output, the available input power and the size constraint.

5.1.2 Diode:

In designing a rectifier circuit with high RF-to-DC conversion efficiency, the choice of a proper diode is one of the most important factors since the diode is the main source of loss and its performance and characteristic determine the overall performance of the circuit. Zero bias Schottky diodes are usually used for high frequency rectifiers because of their high switching capacity, low barrier (high saturation current), low junction capacitance and low voltage threshold than the common PN diodes. In fact, the low threshold allows for more efficient operation at low powers, and the low junction capacitance increases the maximum frequency at which the diode can operate. Below Fig. shows the equivalent electrical circuit of a Schottky diode.

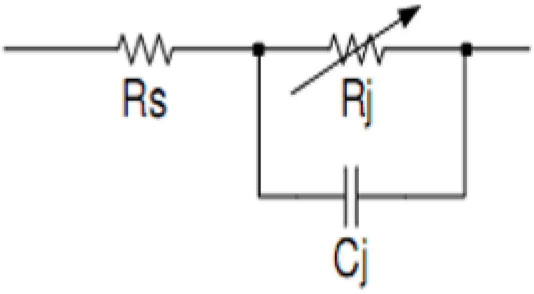


Figure 5.1.2 The equivalent electrical circuit of a Schottky diode.

With the junction capacitance in Farad, the series resistance in Ω (This resistance is due to the inability of charges to easily move through the crystal lattice structure), it models the losses by joule effect of the diode, and the junction resistance in Ω. The variable junction resistor models the fact that the diode is either conducting or blocked. The Schottky diodes have two main classes. The first class is the n-type silicon with a high- barrier and low values of. The second class is the p-type silicon characterized by low barrier and high. For low input power levels applications, the p-type Schottky diode is recommended since it provides a higher output voltage compared to the n-type.

5.1.3 Energy conversion efficiency:

The main characteristics that should be optimized when designing rectifier circuit are the DC output voltage and the RF-DC conversion efficiency. This last one refers to the ratio of the PDC power recovered at the output of the rectifier and the PRF power injected at the input of the rectifier using a microwave source. It is determined using the formula

$$\eta\ (\%) = 100.\ \frac{Pdc}{Prf}$$

The PDC power is calculated as follows:

$$PDC = \frac{VDC^2}{RL}$$

With RL is the load resistance, and VDC is the maximum DC voltage across the diode, limited by the reverse breakdown voltage Vbr by:

$$VDC = \frac{Vbr}{2}$$

The PRF power is calculated using the FRIIS transmission equation:

$$Prf = Pe.Ge.Gr.\frac{\lambda}{3\pi r}^{2}$$

It gives the received RF power as a function of the transmitted power Pe, the maximum gains of the transmitting Ge and receiving antennas Gr and the losses in the free space which depend on the frequency and the distance r between the two antennas.

In fact, a variety of loss mechanisms make it difficult to achieve high RF-DC conversion efficiency, especially in nonlinear devices such as the diodes. The maximum energy conversion efficiency of the rectifier circuit is limited by impedance matching, device parasitics, and harmonic generation. It generally depends on the microwave input power, the optimum connected load, the own junction voltage and breakdown voltage of the diode. The efficiency becomes quite low when the power is small or the load is not matched. When the input voltage to the diode is lower than the junction voltage or is higher than the breakdown voltage the diode does not show a rectifying characteristic. Fig 4.1.3 illustrates the general relationship between the efficiency and losses in microwave energy conversion circuits as a function of input power.

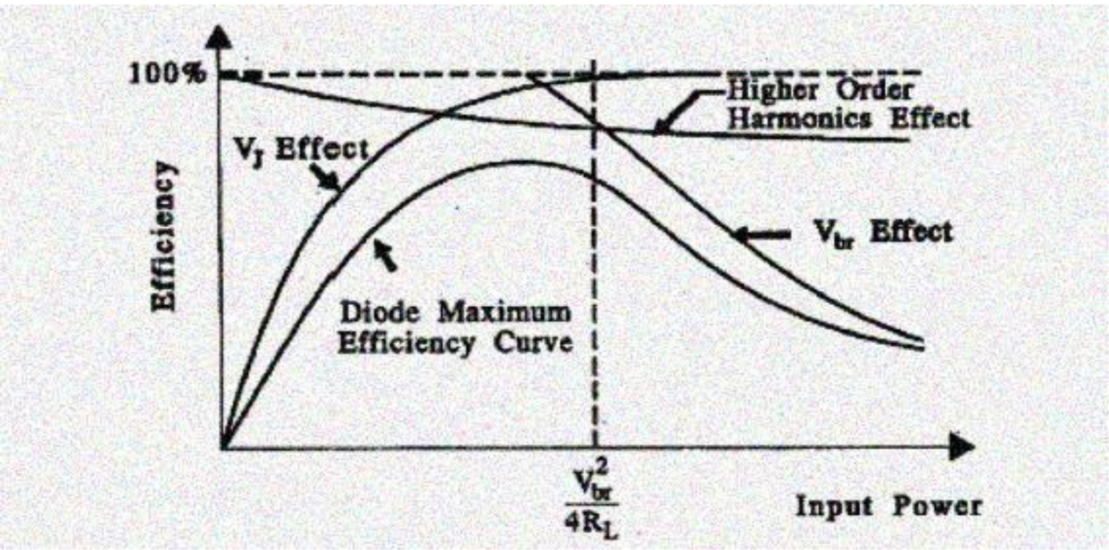


Figure 5.1.3 General Relationship between the efficiency and losses in microwave energy conversion circuits as a function of input power.

At low input power region, the efficiency is small because the voltage swing at the diode is below or comparable with the diode turn-on threshold voltage (VT Effect). As the power continues to increase, the efficiency increases and levels off with the generation of higher order harmonics. At high input power region, the efficiency sharply decreases because the voltage swing at the diode exceeds the breakdown voltage (Vbr Effect) of the diode. The critical input power where the breakdown effect becomes dominant is expressed as $\frac{Vbr^2}{3Rl}$.

In addition, the RF-DC conversion efficiency strongly depends on the characteristics and internal parameters (Vbr, VT, Rs, Cj, Vj) of the used diode, as well as the value RL of the load. The simulations performed prove that:

- As the turn-on threshold voltage VT is decreased, the energy conversion efficiency at a given power increases. So a low turn-on threshold is required for efficient and low input power applications.
- When the series resistance Rs increases, the energy conversion efficiency decreases. So a low value of Rs means that it is low losses in the diode and therefore a high efficiency.
- As the junction tension Vj is decreased, the RF-DC conversion efficiency increases.
- As the junction capacitance Cj, is decreased, the RF-DC conversion efficiency increases. Cj limits the maximum frequency for which a diode can operate.
- When the resistance of the load RL is low, the efficiency is high. Hence, an optimization must be done to determine the optimum RL.

5.1.5 DC filter:

The DC filter is a low-pass filter that is the most often composed of capacitors placed in parallel with the load resistance. The filtering capacitor is the part of the rectifier that will block the fundamental signal and the harmonics downstream of the diode. The cutoff frequency must be lower than that of the fundamental signal. The value of the filtering capacitor is determined from the following equation:

$$\mathbf{C} = \frac{\mathbf{1}}{\mathbf{2}.\boldsymbol{\pi}.\boldsymbol{fc}}$$

In general, the design of microstrip low pass filters involves two main steps. The first one is to select an appropriate low pass prototype (lumped-element filter design). The choice of the type of response, including passband ripple and the number of reactive elements (filter order), will depend on the required specifications. Chebyshev and Butterworth are the most popular low pass prototypes in microstrip filters design. Chebychev filter tolerates a slight ripple in the bandwidth, but has a better rejection than the Butterworth filter. The next step is to find an appropriate microstrip realization that approximates the lumped element filter. The low pass filter is widely implemented with stubs (shunt, radial) or stepped impedance lines.

5.2 Rectifier Circuit:

5.2.1 Definition:

The process of converting an AC (sinusoidal) signal into a DC signal is called Rectification. The electronic circuit which performs the rectification is known as the Rectifier circuit. In short, we can call it a rectifier. So, by using this circuit, we can convert the electrical signal, which is of sinusoidal (AC) form, into DC form.

5.2.2 Half Wave Rectifier:

The most fundamental rectifier topology is the half-wave rectifier. As shown in Fig. 4.2.1, the half-wave rectifier consists of a series diode followed by a shunt capacitor. The load of the rectifier is placed in parallel with the capacitor. The operation of the circuit is centered on the nonlinear properties of the diode. When applying an AC voltage on the anode of the diode, the diode will conduct during the positive portion of the cycle. If an ideal diode is assumed with an infinite breakdown voltage and constant threshold voltage Vd, the capacitor will charge to a peak voltage $V\text{p} – V\text{d}$ where $V\text{p}$ is the peak voltage of the input AC signal. When the voltage drop across the diode is less than Vd the diode will be reversed biased and will consequently prevent the discharging of the capacitor when the input signal becomes negative. The result is that the capacitor will retain its charge with an open-circuit load, and the output voltage will be a constant DC signal.

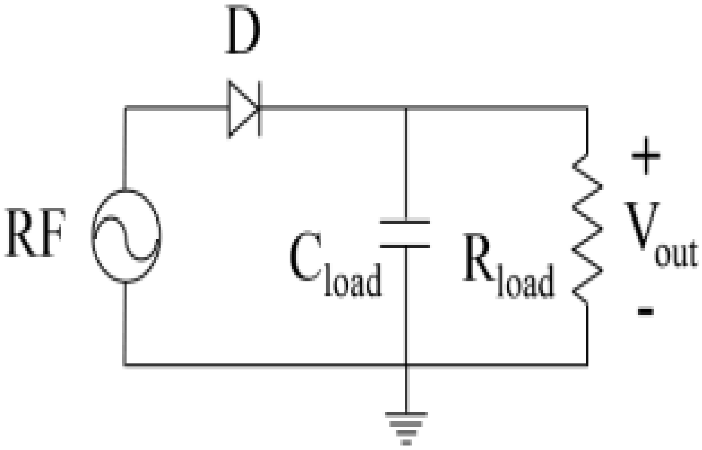


Fig. 5.2. Half-wave rectifier

When a finite load is used, the capacitor will discharge during the negative portion of the input signal, which results in a voltage ripple on the output. If the voltage on the capacitor does not go to zero in steady state operation, then the resulting output voltage will be an offset equal to the average voltage across the capacitor with a peak-to-peak voltage ripple Vr approximated by

$$\boldsymbol{V}\mathbf{r} = \boldsymbol{V}\mathbf{p}\left(\mathbf{1} - \boldsymbol{e}^{\frac{\mathbf{1}}{\mathbf{2}\boldsymbol{fRC}}}\right)$$

Using Kirchoff's voltage law, above equation can be derived by solving the associated differential equations for both the charging and discharging states of the circuit. The output ripple can be reduced by using a larger capacitance $C,$ larger load R, and by using a higher input frequency f. In most power supplies, the output voltage ripple is a critical specification so that sensitive electronics that require precise voltages can be safely powered. It is for this reason that large capacitors are typical in rectifiers used for powering every day devices from a wall outlet. However, in wireless energy harvesting systems, it is not always practical to reduce voltage ripple by using a larger capacitance. The reason is that the small available input power combined with large capacitances can result in inconvenient charge and discharge times. As reports a wait time of 2 days for their first stage capacitor to fully charge. Therefore, the half-wave rectifier illustrates an important design consideration common to most rectifiers in which there exists a tradeoff between signal quality and the settling time of the circuit for a particular load. In this case, the rectifier is combined with an antenna to form a rectenna. Using a Schottky diode, it was shown in that a rectifying efficiency of at least 55% can be obtained for a rectenna system utilizing a half-wave rectifier. A similar circuit to the half-wave rectifier is shown in Fig. 4.3. In the case when the low pass filter block is implemented with a shunt capacitor, the circuit is essentially a diode clamp that shifts the DC operating point of the voltage at the cathode of the diode. The DC pass filter following the diode removes the superimposed voltage ripple to produce the rectified signal. Using this topology, efficiencies of 85% at 2.35 GHz and 82% at 5.8 GHz have been reported. While being trivial circuits, both of these single diode rectifiers serve as a building block for more complicated rectifier topologies.

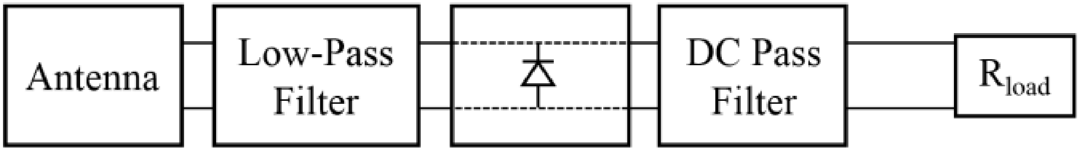


Fig. 5.3 Typical rectenna with single diode topology.

Half Wave Rectifier Circuit:

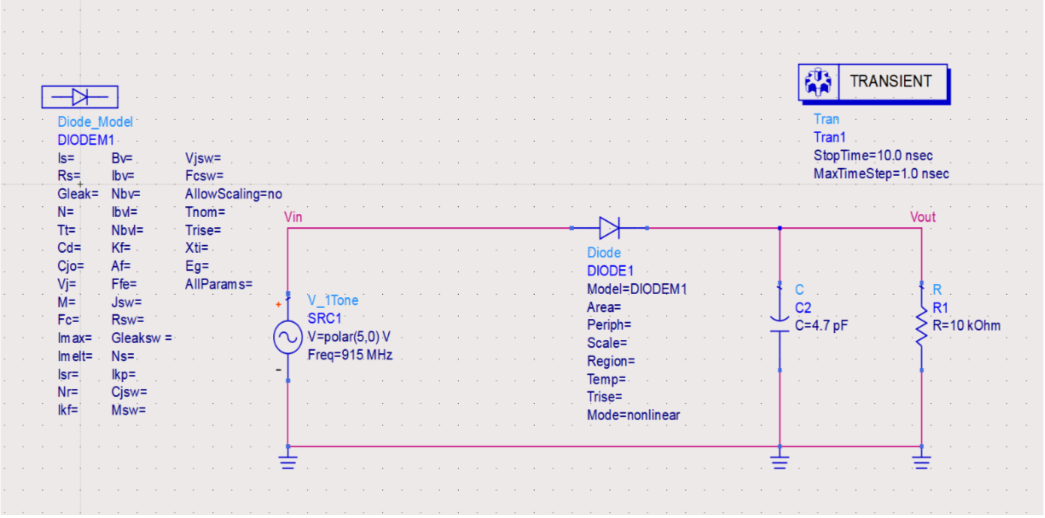


Figure 5.4 Schematic of Half Wave Rectifier using single diode

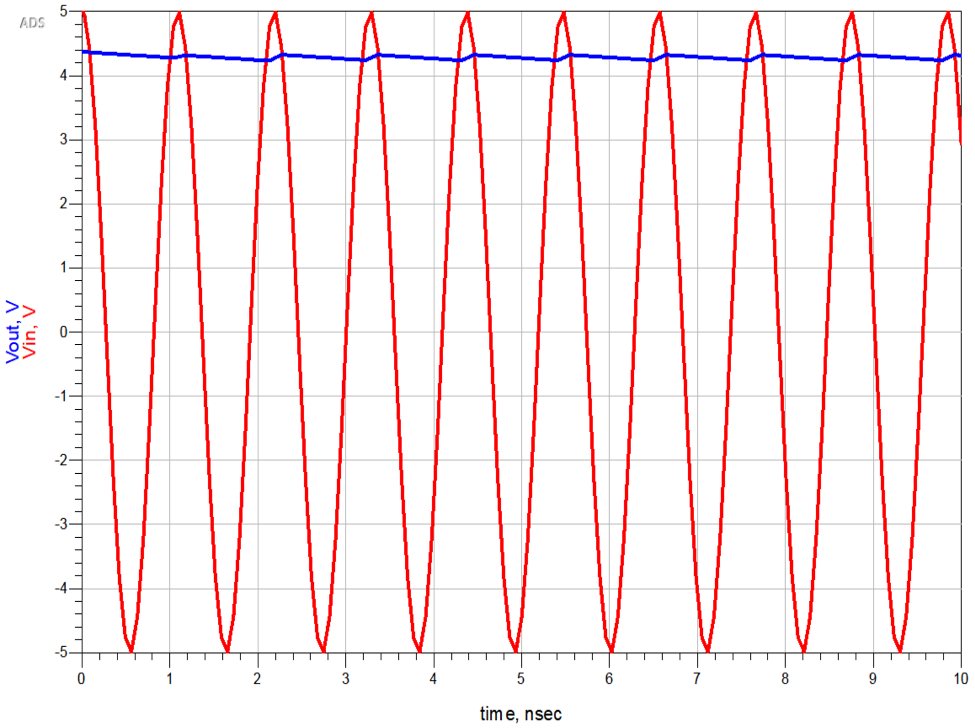


Figure 5.5 Simulation of Half Wave Rectifier using single diode

5.2.3 Greinacher Voltage Doubler Rectifier:

A natural extension of the half-wave rectifier is the Greinacher voltage doubler. The circuit can be thought of as a diode clamp followed by a half-wave rectifier. Thus, when a signal with a peak voltage of $V\mathrm{p}$ is applied at the input, the diode clamp will shift the DC operating point of the signal to $V\mathrm{p} - V\mathrm{d}$. This occurs when the clamp capacitor charges through the diode during the negative portions of the input cycle. During the positive portion, the voltage across the clamp capacitor adds in series with the input voltage. The result is that the half-wave capacitor charges to a peak value of $2V\mathrm{p} - 2V\mathrm{d}$. Note that as before, ideal diodes are assumed. The importance of the voltage doubler circuit is that it demonstrates that both rectification and voltage multiplication can be achieved simultaneously. It is for this reason that voltage multipliers are popular topologies used widely in energy harvesting systems.

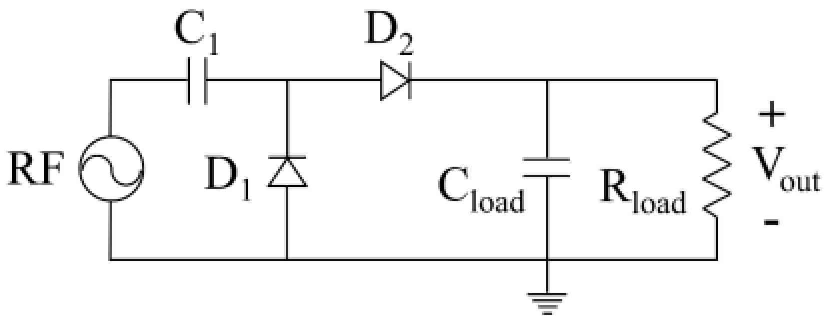
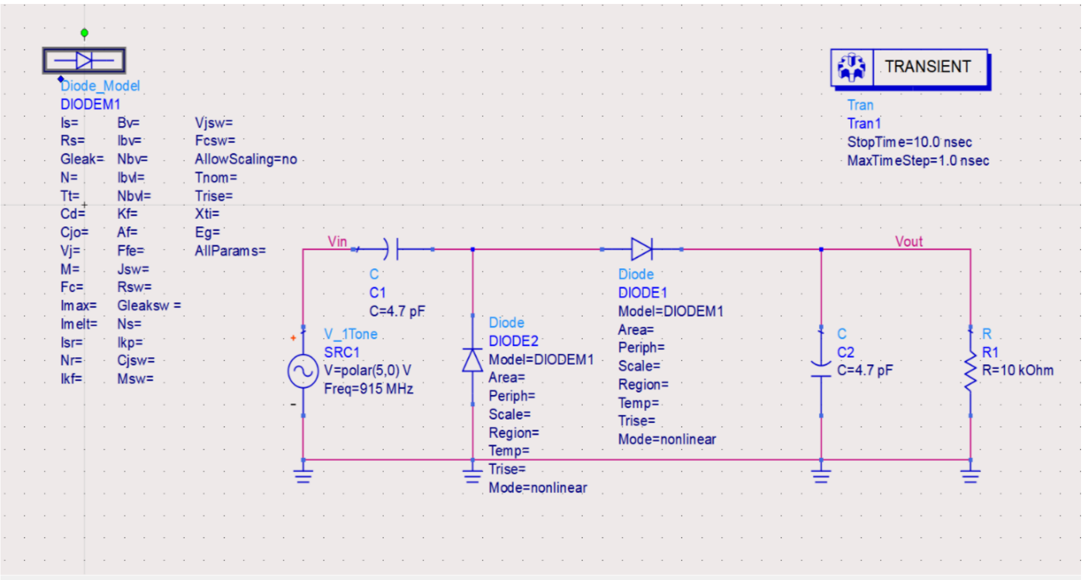


Fig. 5.6 Greinacher voltage doubler.

Greinacher Voltage Doubler Circuit:



Diode_Model
DIODEM1
Is=
Rs=
Gleak=
N=
Tt=
Cd=
Cjo=
Vj=
M=
Fc=
Imax=
Imelt=
Isr=
Nr=
Ikf=
Bv=
Ibv=
Nbv=
Ibvl=
Nbvl=
Kf=
Af=
Ffe=
Jsw=
Rsw=
Gleaksw =
Ns=
Ikp=
Cjsw=
Msw=
Vjsw=
Fcsw=
AllowScaling=no
Tnom=
Trise=
Xti=
Eg=
AllParams=

TRANSIENT
Tran
Tran1
StopTime=10.0 nsec
MaxTimeStep=1.0 nsec

Vin

C
C1
C=4.7 pF

V_1Tone
SRC1
V=polar(5,0) V
Freq=915 MHz

Diode
DIODE2
Model=DIODEM1
Area=
Periph=
Scale=
Region=
Temp=
Trise=
Mode=nonlinear

Diode
DIODE1
Model=DIODEM1
Area=
Periph=
Scale=
Region=
Temp=
Trise=
Mode=nonlinear

Vout

C
C2
C=4.7 pF

R
R1
R=10 kOhm

Figure 5.7 Schematic of Greinacher Voltage Doubler Circuit

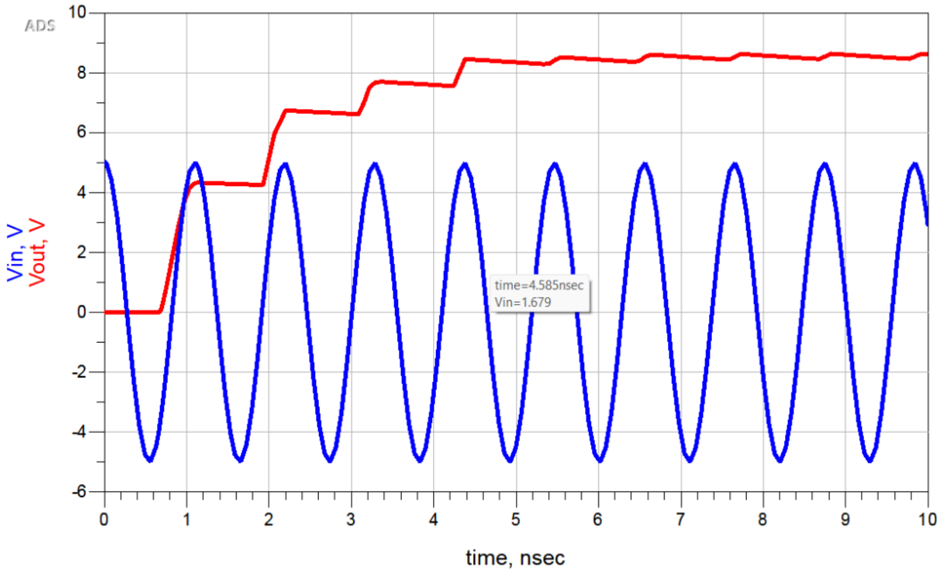


Figure 5.8 Simulation of Greinacher Voltage Doubler Circuit

5.2.4 Villard Voltage Doubler Rectifier:

Through cascading multiple stages of the Greinacher voltage doubler, a Villard (Cockcroft-Walton) multiplier is generated. A typical two stage Villard multiplier is shown below. Since the Villard multiplier is constructed out of multiple doubler stages, the operation of the circuit is very similar. Each doubler stage shifts the DC operating point of the output voltage from the previous stage. The voltage gained from each stage is approximately equal to $2V\text{p}$ so that the overall voltage is given by

$$V_{out} = 2NV\text{p}$$

Where N is the number of stages.

The use and theory of the Villard multiplier can be found in many papers. In certain case, a full wave Greinacher multiplier is described and analysed using steady state analysis techniques.

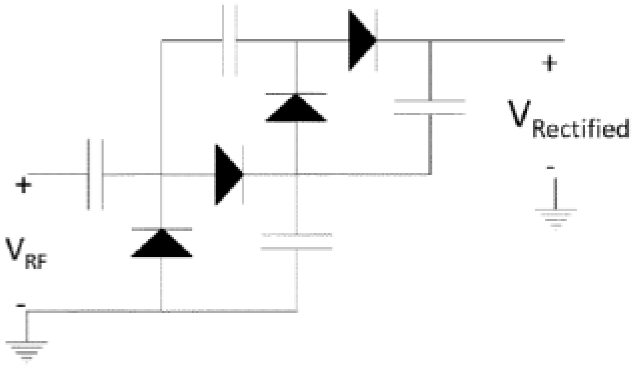


Fig. 5.9 Two-stage Villard multiplier.

Villard Voltage Doubler Circuit:

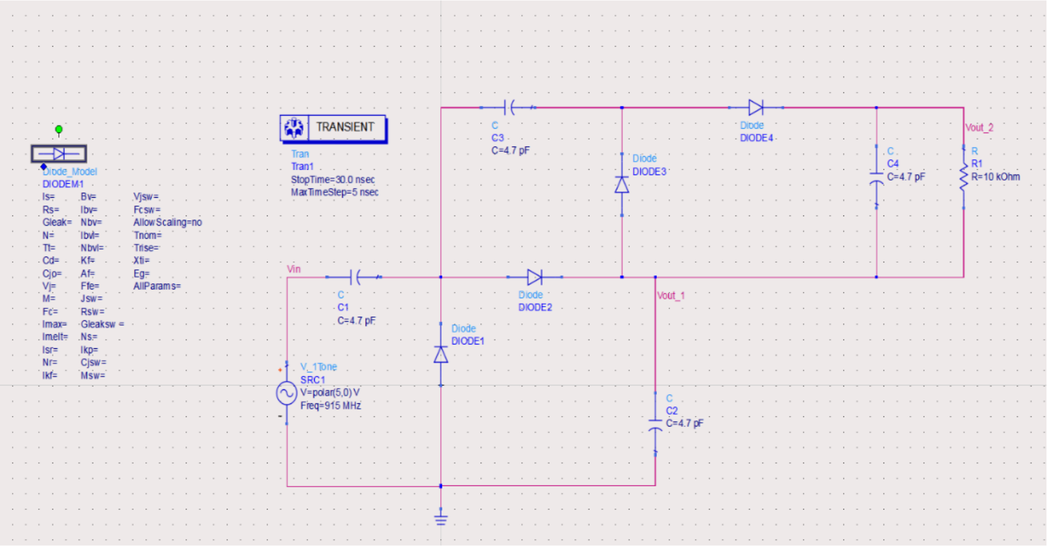


Figure 5.10 Schematic of Villard Voltage Doubler Circuit

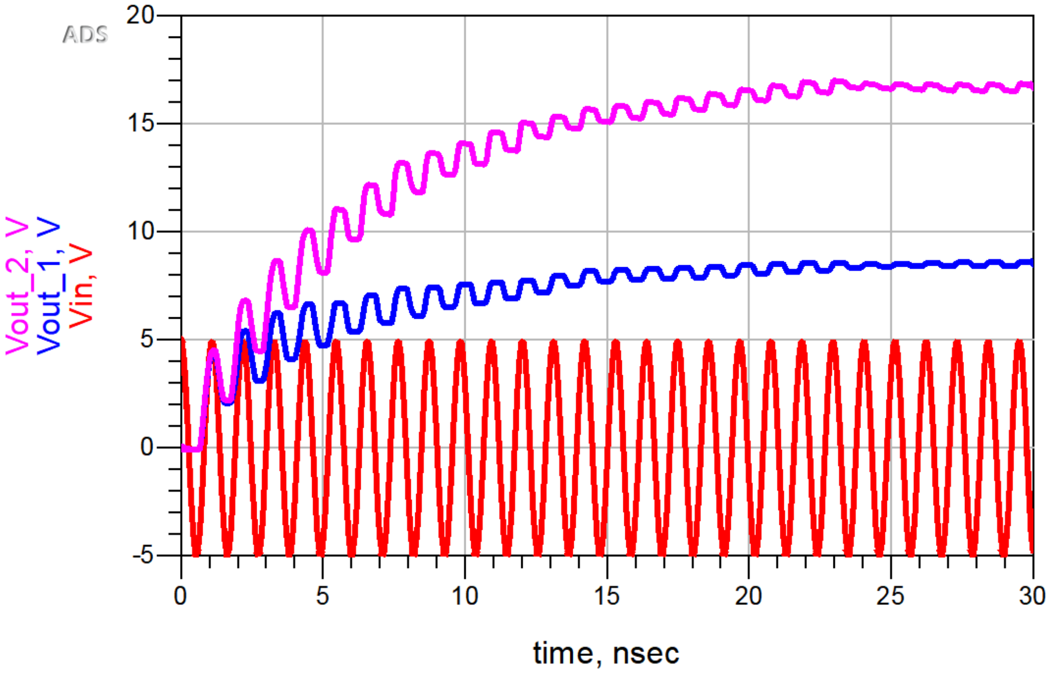


Figure 5.11 Simulation of Villard Voltage Doubler Circuit.

5.3 Rectifier Efficiency

Rectifier efficiency is used as a parameter to determine the efficiency of the rectifier to convert AC into DC. It is the ratio of DC output power to the AC input power. The efficiency of the rectifier (η) can be calculated by

$$\eta = Pout \,/\, Pin$$

Where, Pout = (V^2 "out")/"Rload "

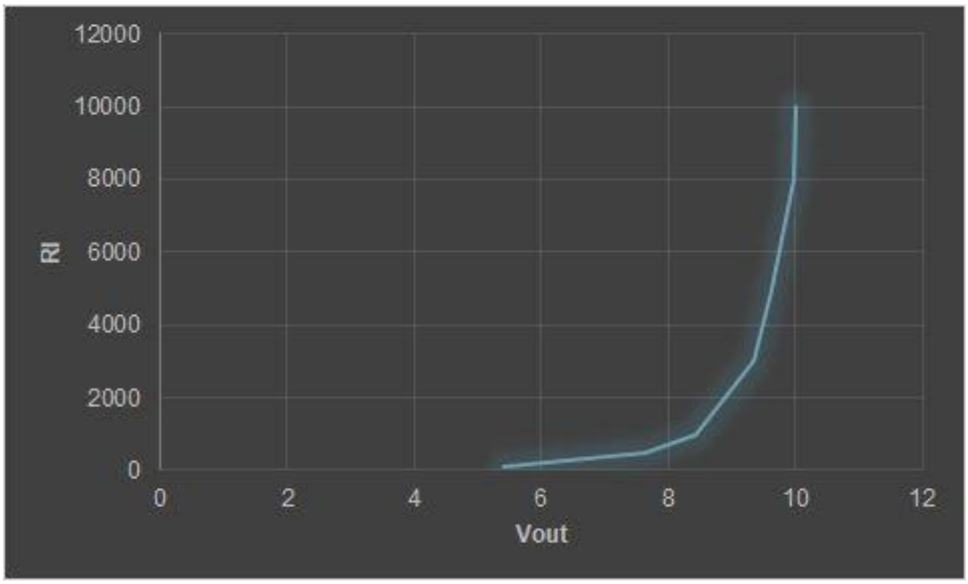
Vout = Output DC Voltage

Rload = Resistive load present at the output

Table 5 Calculated Efficiency of the Rectifier

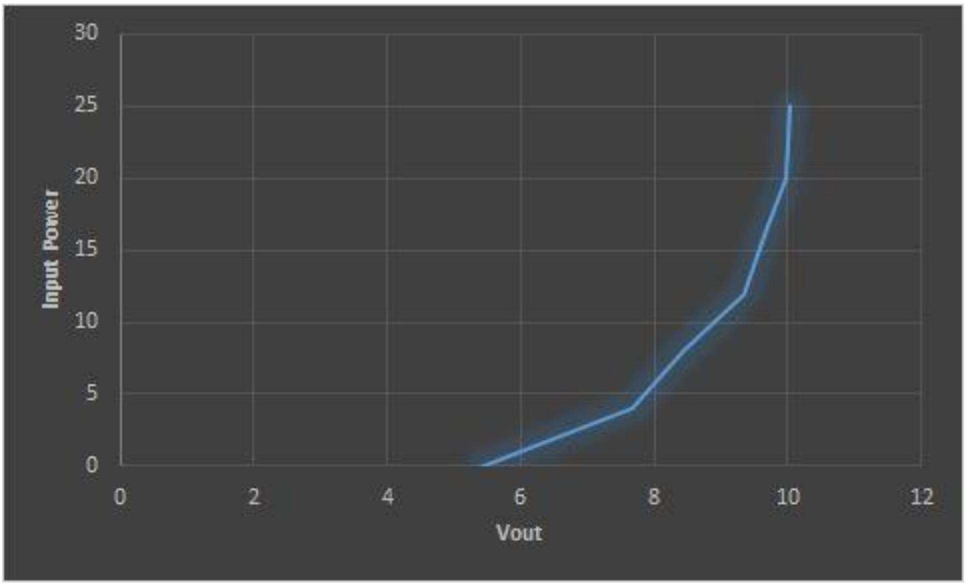
Input Power (dBm)	Input Power (mWatt)	RI (Ohm)	Vout (volt)	Rectifier Efficiency (%)
0	1	100	0.005	0.025
4	2.5	500	0.13	6.76
8	6.3	1000	0.41	26.68
12	15.8	3000	0.88	49.01
13	39.8	5000	1.64	67.57
20	100	8000	2.86	81.79
25	316.22	10000	5.42	92.89

The following graph shows the output voltage versus input load resistance variation wherein input power is constant.



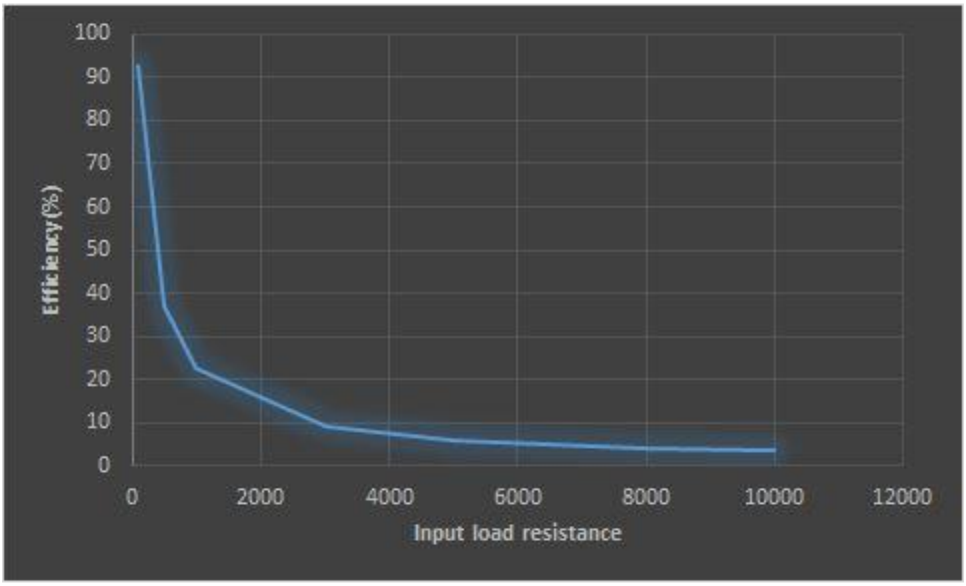
Graph 1 Output voltage vs load resistance

The following graph shows the output voltage versus input power variation wherein input load resistance is constant.



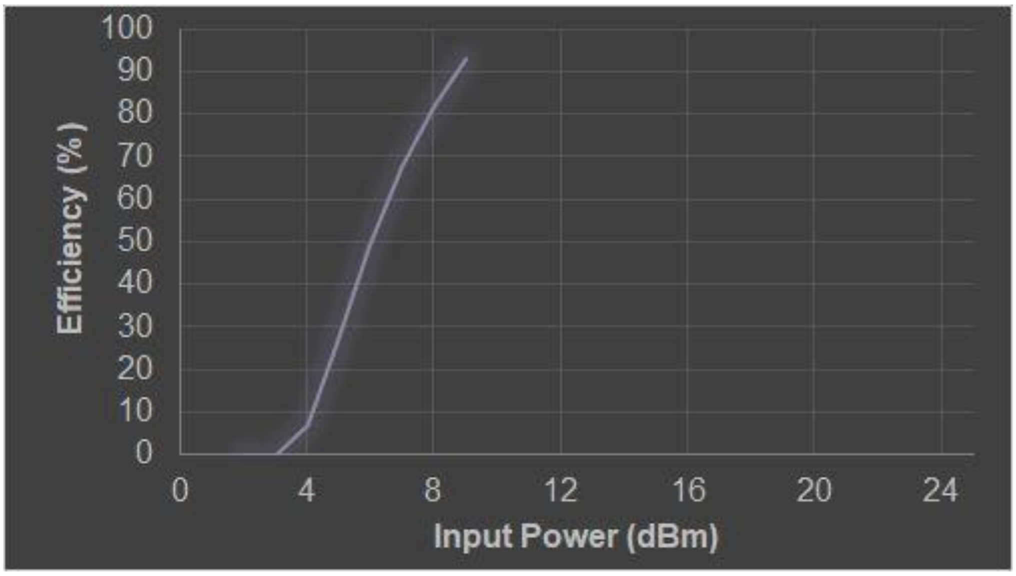
Graph 2 Output voltage vs input power

The following graph shows the input load resistance versus efficiency variation wherein input power is kept constant.



Graph 3 Input load resistance vs efficiency

The rectifier is highly efficient with maximum efficiency of 92.89 % for the 25dBm input power. The proposed rectifier system is able to produce sufficient DC voltage form low incident RF power. This simple rectifier system is very efficient for design of a RF energy harvesting system. The input power versus efficiency variation (keeping the load constant) is shown in Figure.



Graph 4 Input power vs efficiency

Chapter 6

CALCULATIONS, DESIGN AND RESULT

6.1 Geometry of single band MPA for 2.4 GHz:

a) Height = 0.508mm

b) Metal Thickness = 1.4 mil (1oz Copper i.e.35 um)

c) Er = 3.2

d) TanD = 0.0001

e) Conductivity = 5.8E7 S/m Resonant frequency = 2.4 GHz 1) Rectangle with lower left X&Y = 0.

W=10.35mm H=8.20mm

Calculating patch Antenna feed line (λ/4) Using Line Calc.

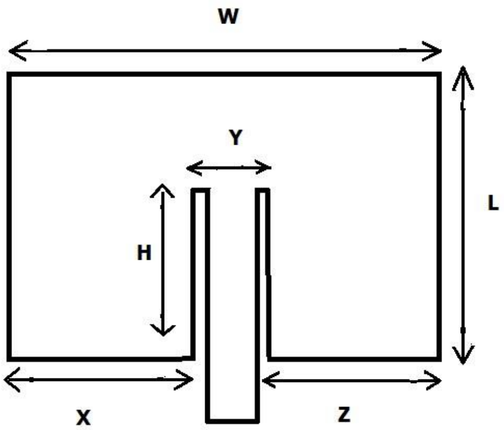
W=0.3031mm L=4.9472mm

Rectangle with lower left X= 14.6243 mm ((29.55/2) -(0.3014/2)

Y= -14.1780 mm

Rectangle with Lower left, W = 1.181 mm L = H = 5mm

X = 4.582((10.35/2) -(1.181/2)) & Y = -9.9472 mm



W=L=29.2 mm
H=12 mm
Y=5.8 mm
X=Z=11.7 mm

Fig 6.1 Design of Dual Band Microstrip Patch Antenna

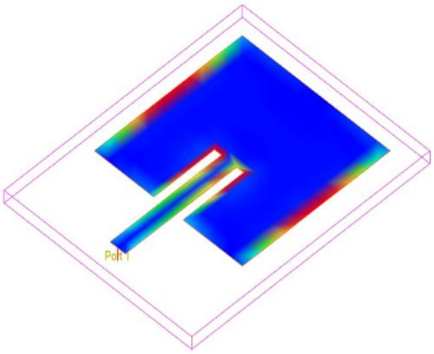


Fig. 6.2 3D View of Patch

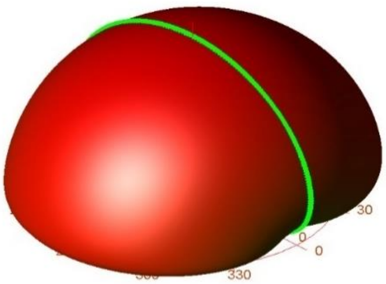


Fig. 6.3 3D View of Microstrip Patch Antenna

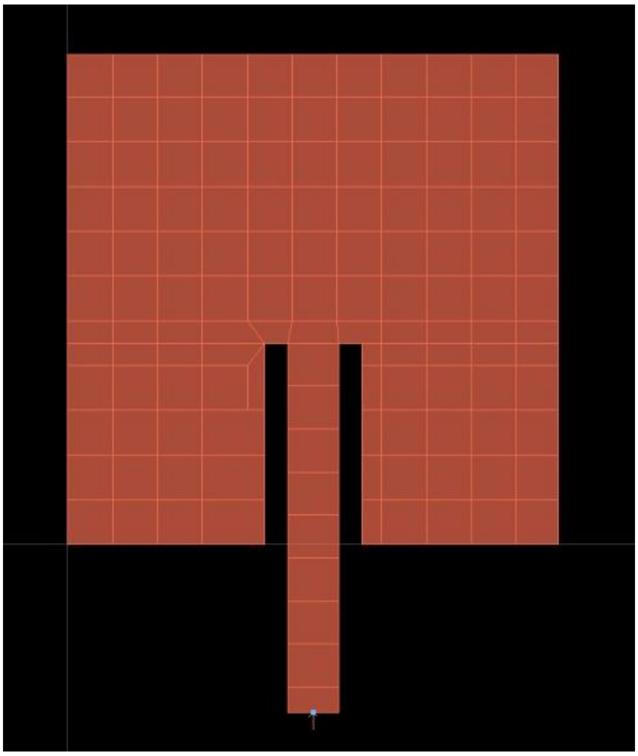


Figure 6.4: Microstrip Patch Antenna

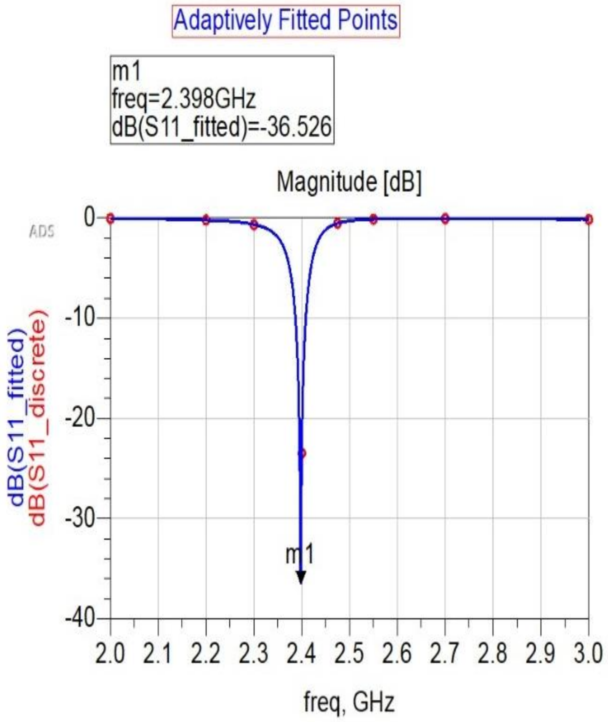
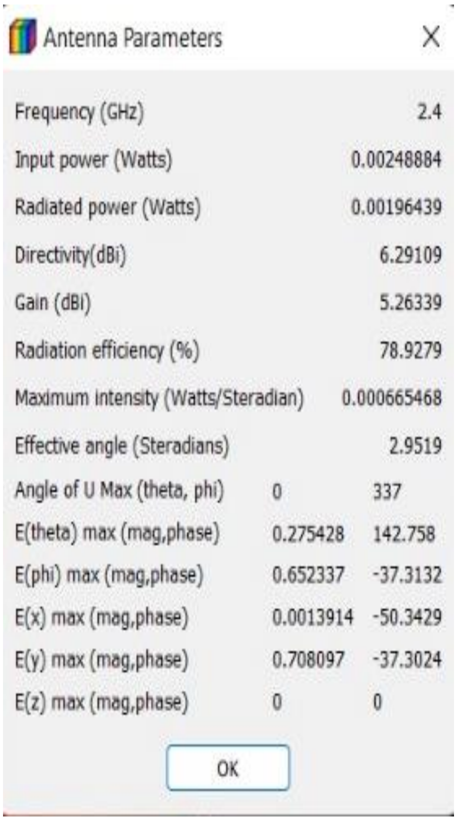


Fig 6.5 Frequency Graph



Frequency (GHz)		2.4
Input power (Watts)		0.00248884
Radiated power (Watts)		0.00196439
Directivity(dBi)		6.29109
Gain (dBi)		5.26339
Radiation efficiency (%)		78.9279
Maximum intensity (Watts/Steradian)		0.000665468
Effective angle (Steradians)		2.9519
Angle of U Max (theta, phi)	0	337
E(theta) max (mag,phase)	0.275428	142.758
E(phi) max (mag,phase)	0.652337	-37.3132
E(x) max (mag,phase)	0.0013914	-50.3429
E(y) max (mag,phase)	0.708097	-37.3024
E(z) max (mag,phase)	0	0

Fig. 6.6 Antenna Parameters

Antenna Parameters in Data Display:

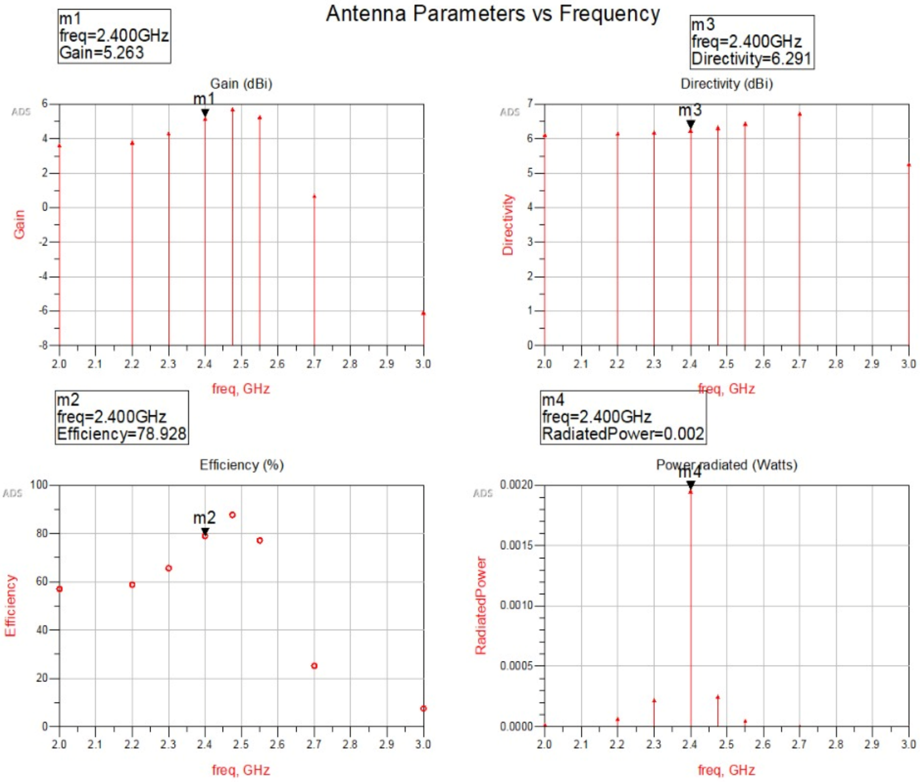
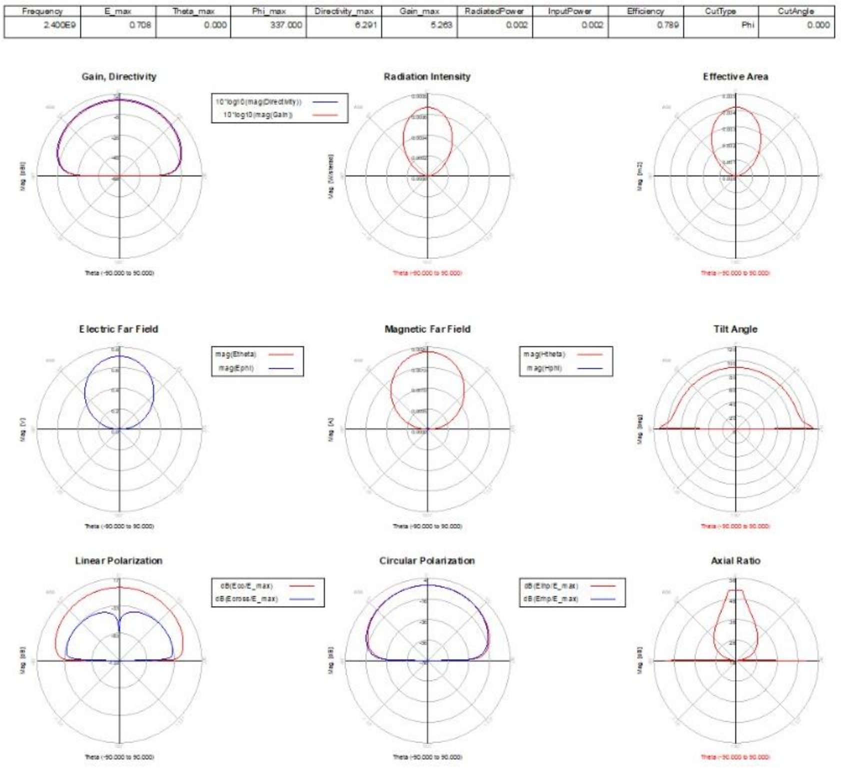


Fig. 6.7 Antenna Parameters vs Frequency Graph

Radiation Pattern in Data Display:



Frequency	E_max	Theta_max	Phi_max	Directivity_max	Gain_max	RadiatedPower	InputPower	Efficiency	CutType	CutAngle
2.400E9	0.708	0.000	337.000	6.291	5.263	0.002	0.002	0.789	Phi	0.000

Fig. 6.8. Radiation Pattern Graph Phi

6.2 Calculation and Geometry of Dual Band MPA

Subset Details:

a) Height 1.6 mm
b) Metal Thickness = 1.4 mil (1oz Copper i.e.35 um)
c) Er = 3.2
d) TanD = 0.001
e) Conductivity = 5.8E7 S/m

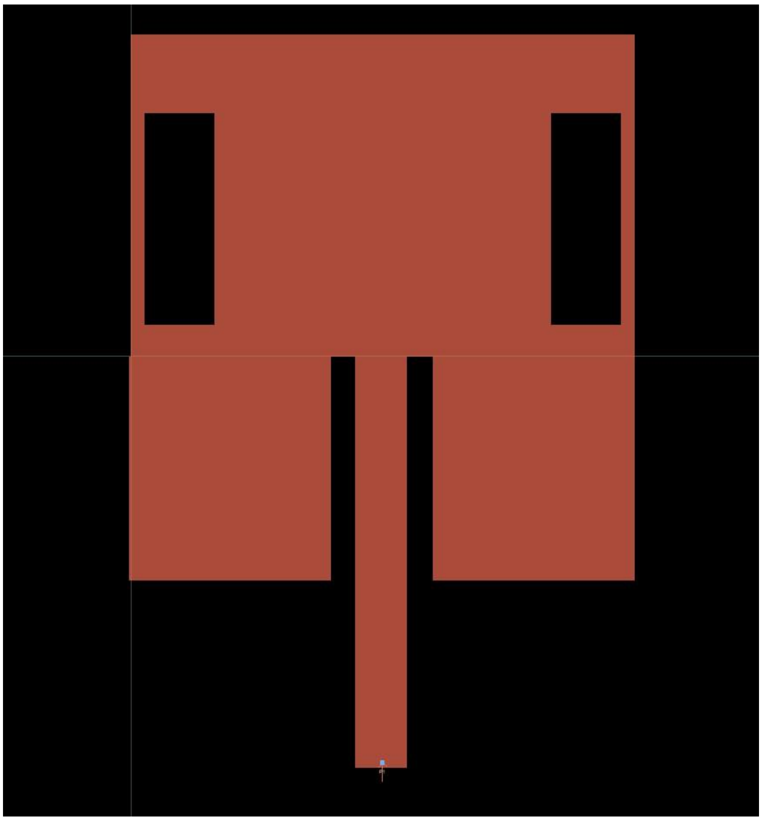


Fig. 6.9 Antenna Layout of Dual Band Microstrip Patch Antenna

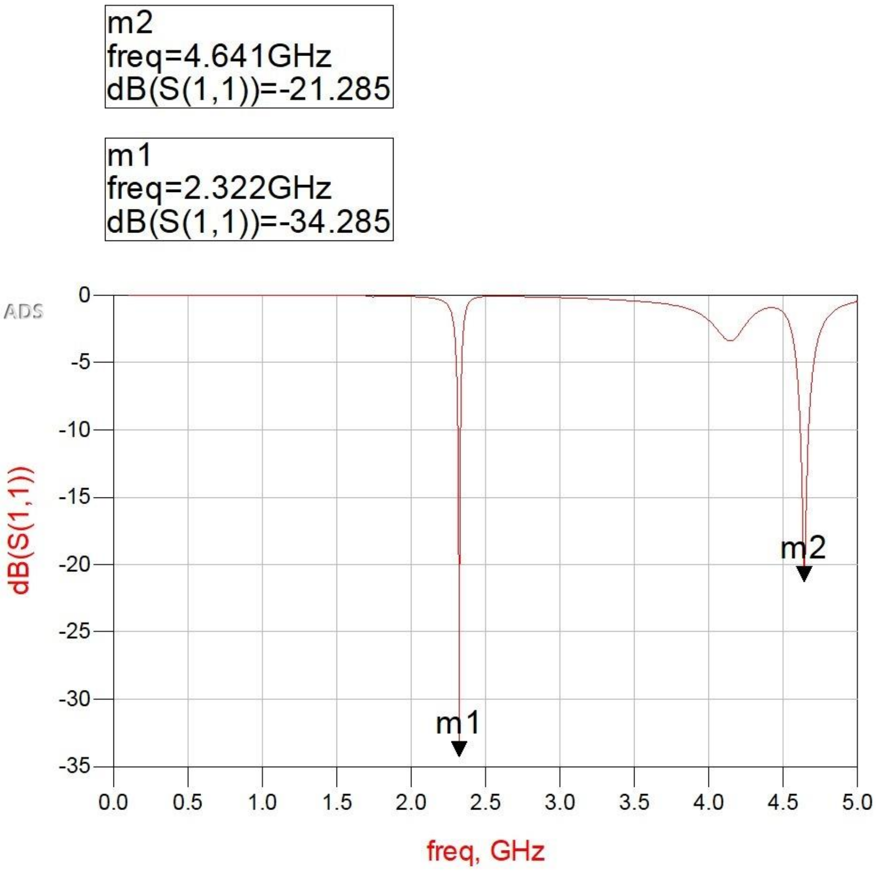
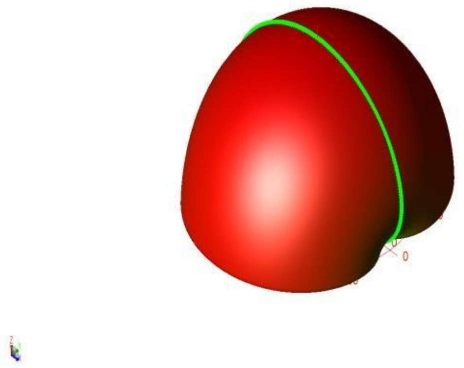


Fig. 6.10 Frequency Graph



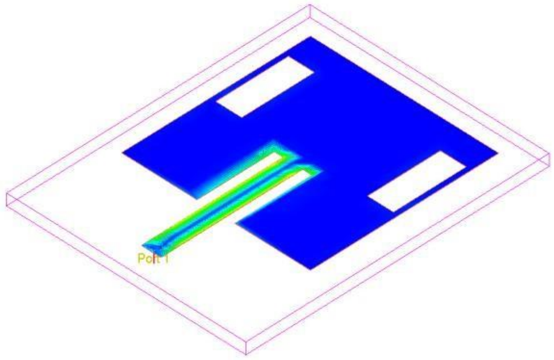


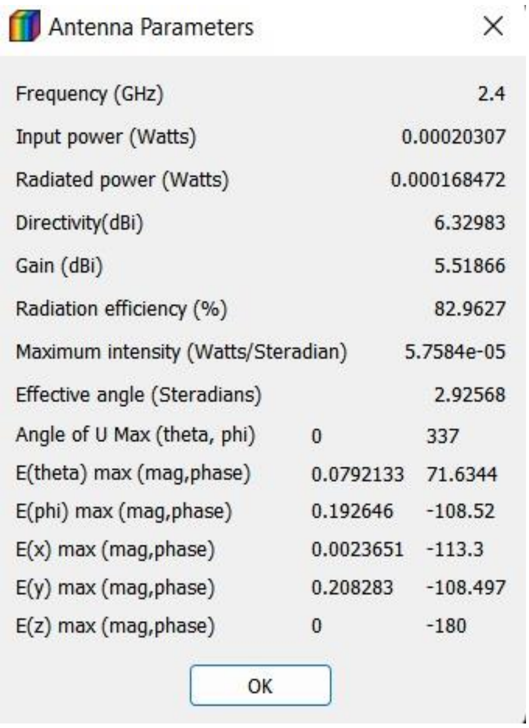
Fig. 6.11 3D View of Dual Band

Microstrip Patch Antenna Radiation.

Antenna Antenna Parameters

Fig. 6.12 3D View of Dual

Band Patch



Frequency (GHz)		2.4
Input power (Watts)		0.00020307
Radiated power (Watts)		0.000168472
Directivity(dBi)		6.32983
Gain (dBi)		5.51866
Radiation efficiency (%)		82.9627
Maximum intensity (Watts/Steradian)		5.7584e-05
Effective angle (Steradians)		2.92568
Angle of U Max (theta, phi)	0	337
E(theta) max (mag,phase)	0.0792133	71.6344
E(phi) max (mag,phase)	0.192646	-108.52
E(x) max (mag,phase)	0.0023651	-113.3
E(y) max (mag,phase)	0.208283	-108.497
E(z) max (mag,phase)	0	-180

Fig. 6.13 Antenna Parameter

_Antenna Parameters in Data Display:

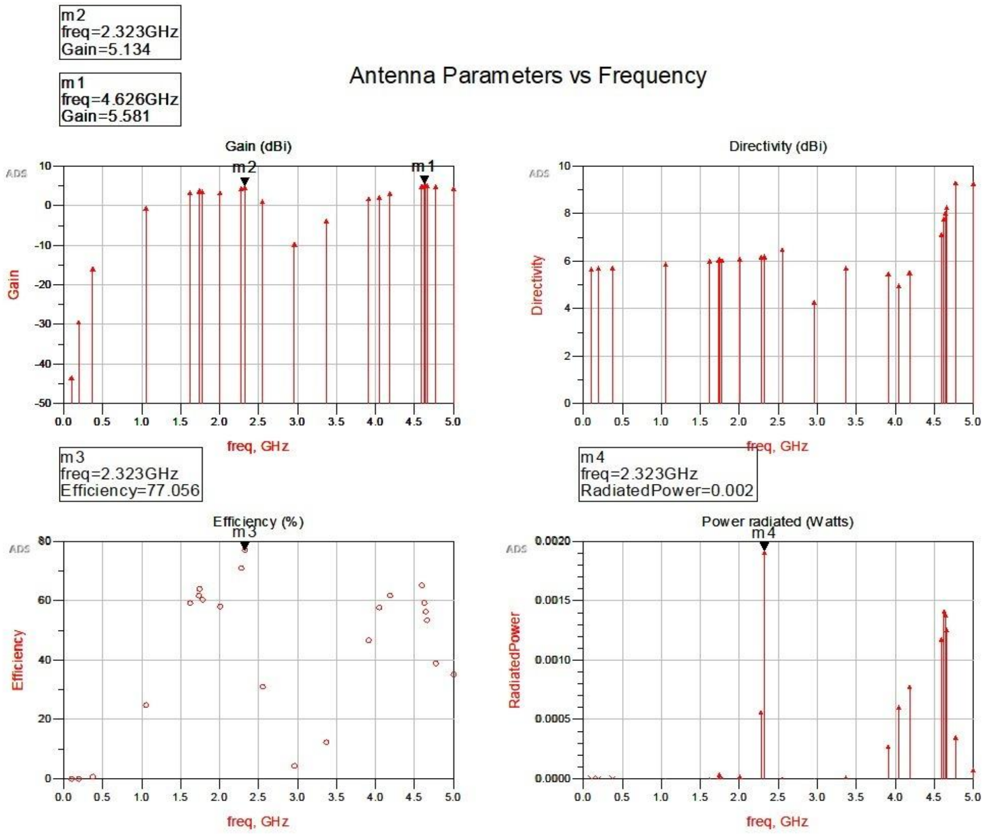
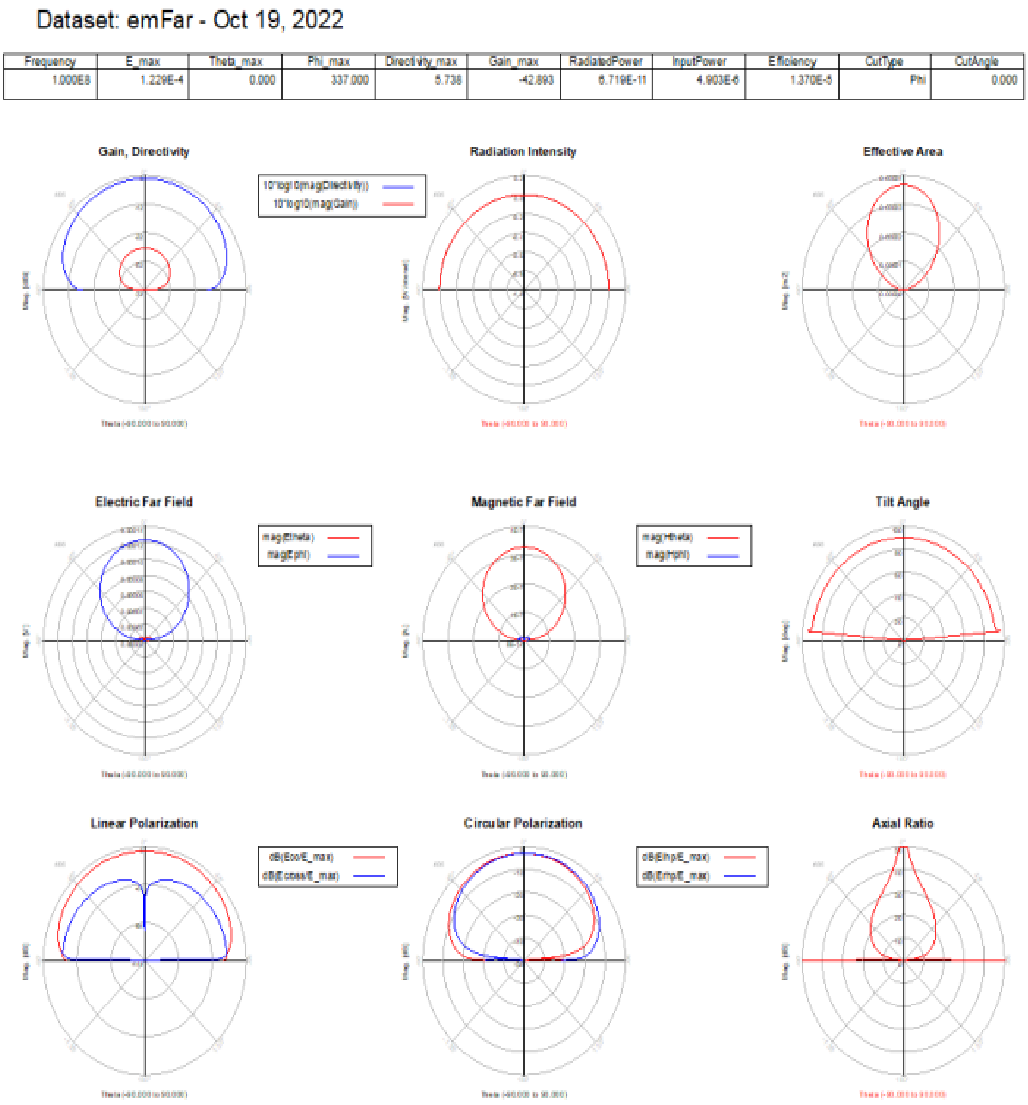


Fig. 6.14 Antenna Parameters vs Frequency Graph

Radiation Pattern in Data Display:



Dataset: emFar - Oct 19, 2022

Frequency	E_max	Theta_max	Phi_max	Directivity_max	Gain_max	RadiatedPower	InputPower	Efficiency	CutType	CutAngle
1.000E8	1.229E-4	0.000	337.000	5.738	-42.893	6.719E-11	4.903E-6	1.370E-5	Phi	0.000

Fig 6.15: Radiation Pattern Graph Phi

6.3 Design and Simulation of Microstrip patch Antenna at 915 MHz

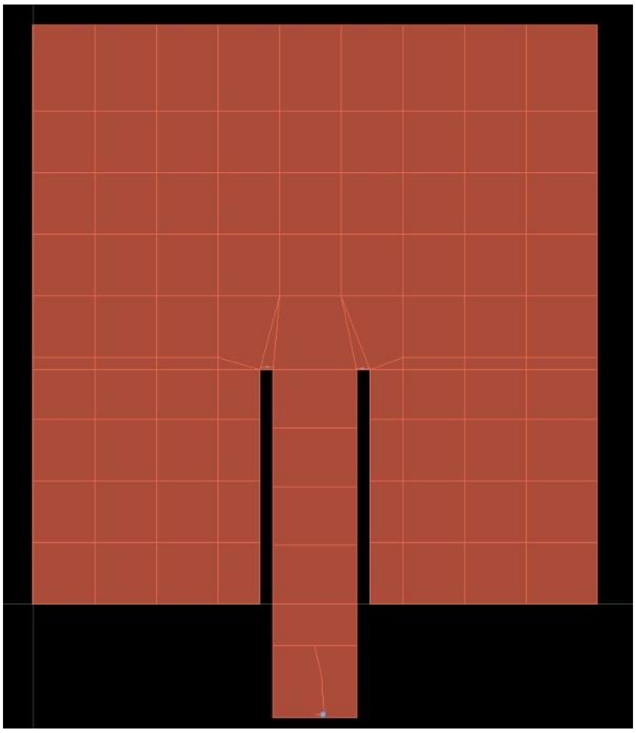
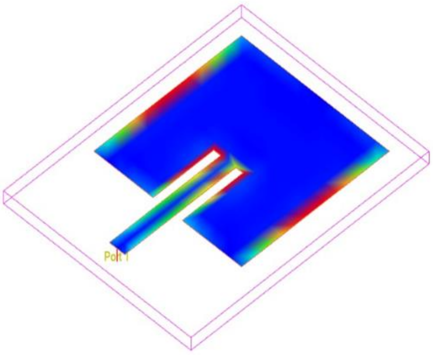


Figure 6.16 Microstrip Patch Antenna for 915MHz



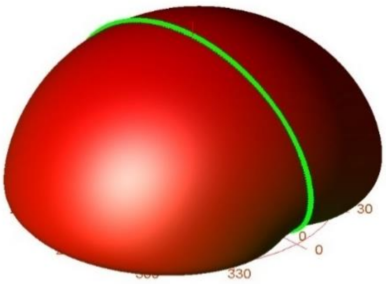


Fig 6.17 3D View of Patch

Fig. 6.18 3D View of Microstrip Patch Antenna

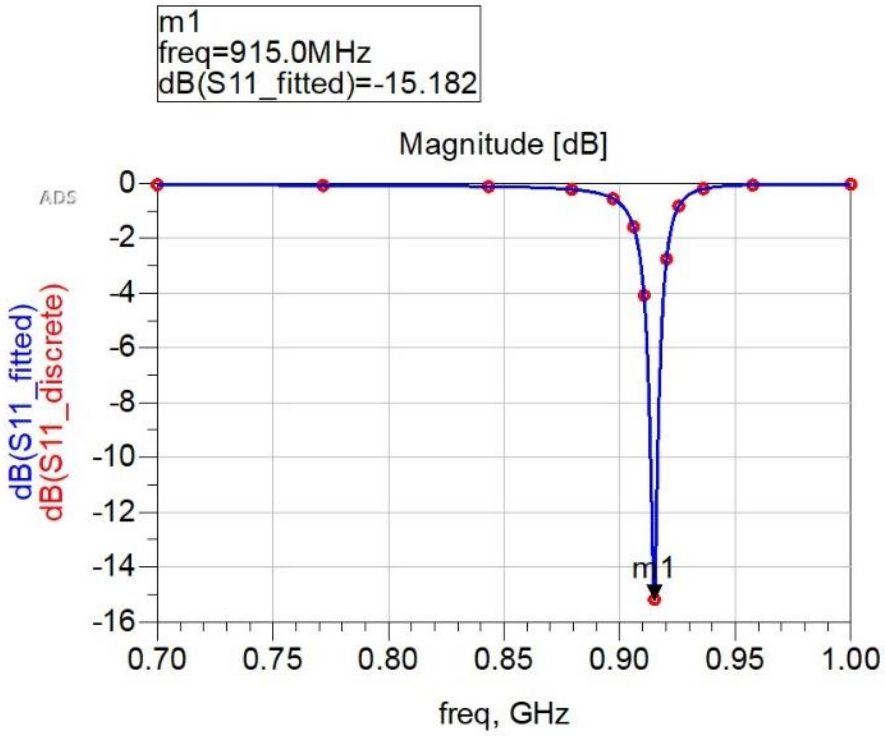
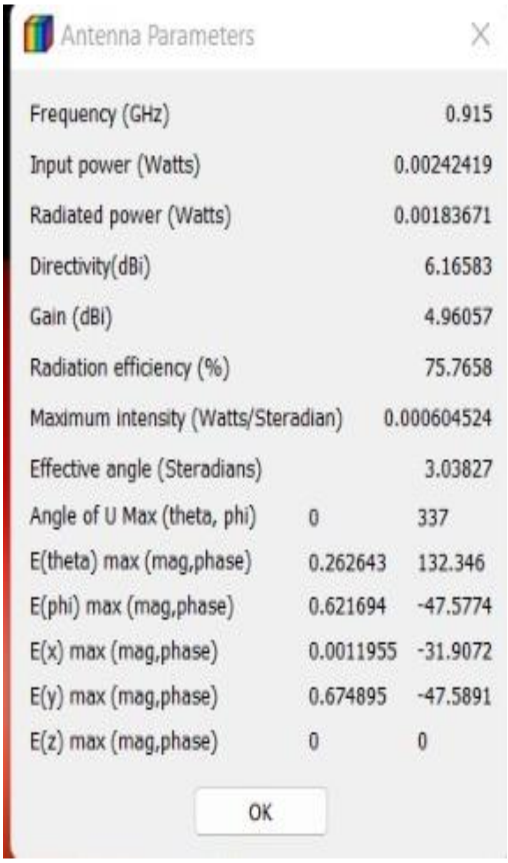


Figure 6.19 Frequency Graph



Frequency (GHz)		0.915
Input power (Watts)		0.00242419
Radiated power (Watts)		0.00183671
Directivity(dBi)		6.16583
Gain (dBi)		4.96057
Radiation efficiency (%)		75.7658
Maximum intensity (Watts/Steradian)		0.000604524
Effective angle (Steradians)		3.03827
Angle of U Max (theta, phi)	0	337
E(theta) max (mag,phase)	0.262643	132.346
E(phi) max (mag,phase)	0.621694	-47.5774
E(x) max (mag,phase)	0.0011955	-31.9072
E(y) max (mag,phase)	0.674895	-47.5891
E(z) max (mag,phase)	0	0

Figure 6.20 Antenna Parameters for 915MHz

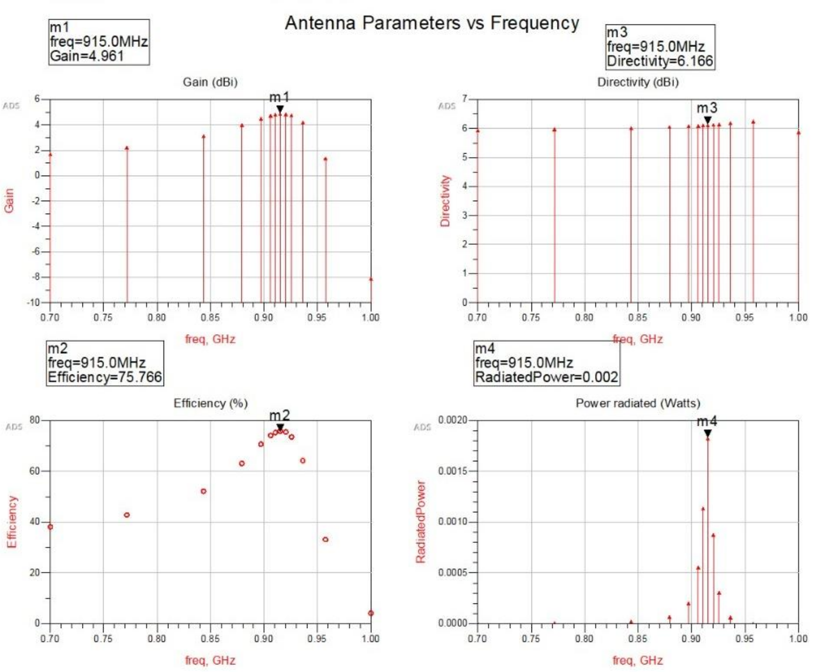
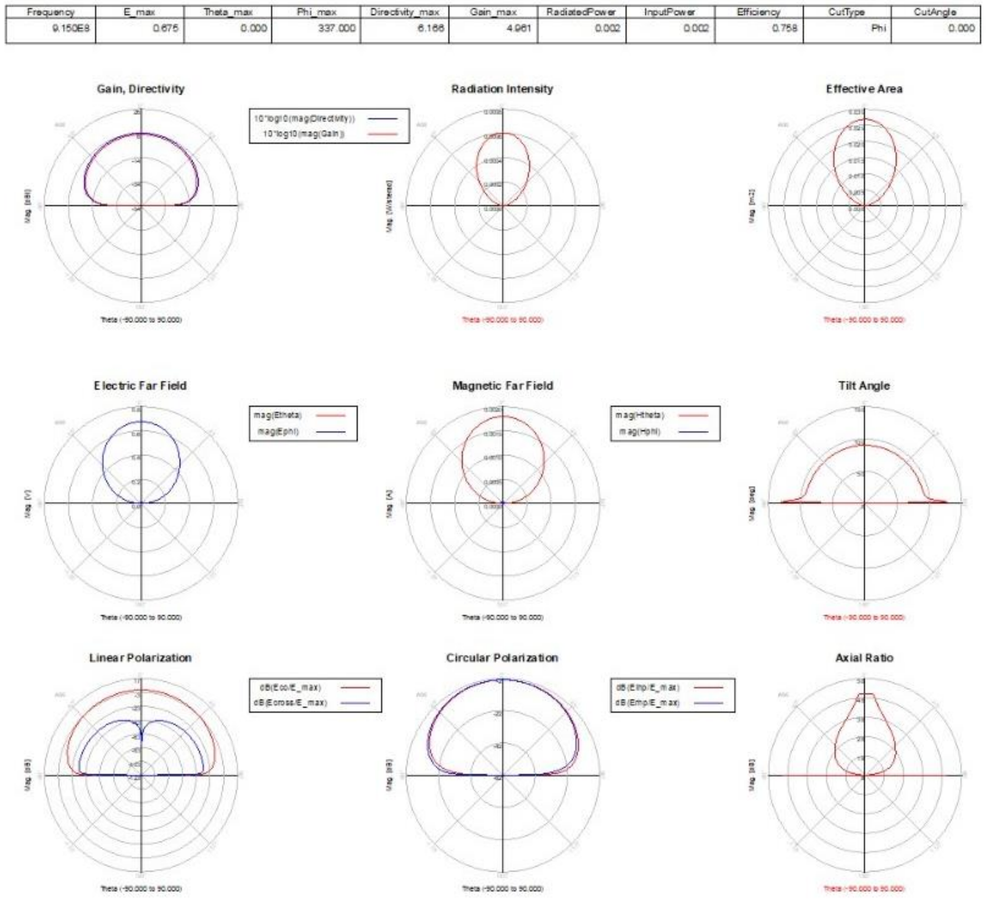


Figure 6.21 Antenna Parameters vs Frequency Graph



Frequency	E_max	Theta_max	Phi_max	Directivity_max	Gain_max	RadiatedPower	InputPower	Efficiency	CutType	CutAngle
9.150E8	0.675	0.000	337.000	6.166	4.961	0.002	0.002	0.758	Phi	0.000

Figure 6.22 Radiation Pattern Graph Phi

6.4 A matched single band rectifier circuit:

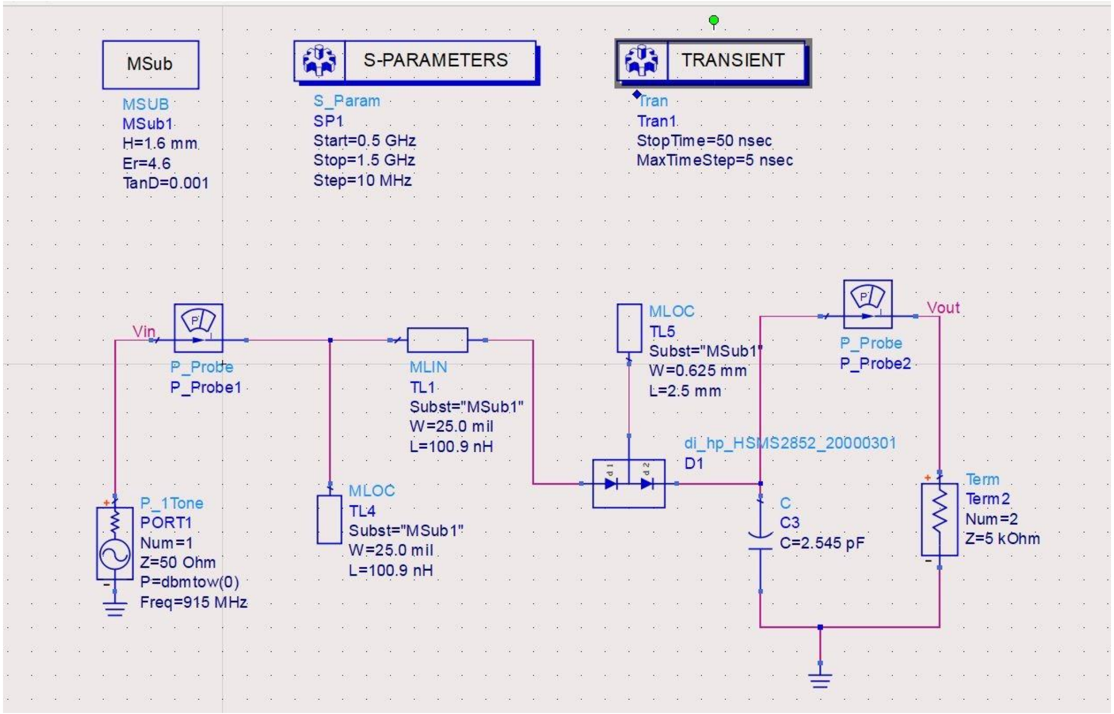


Figure 6.23 Schematic of matched single band rectifier circuit

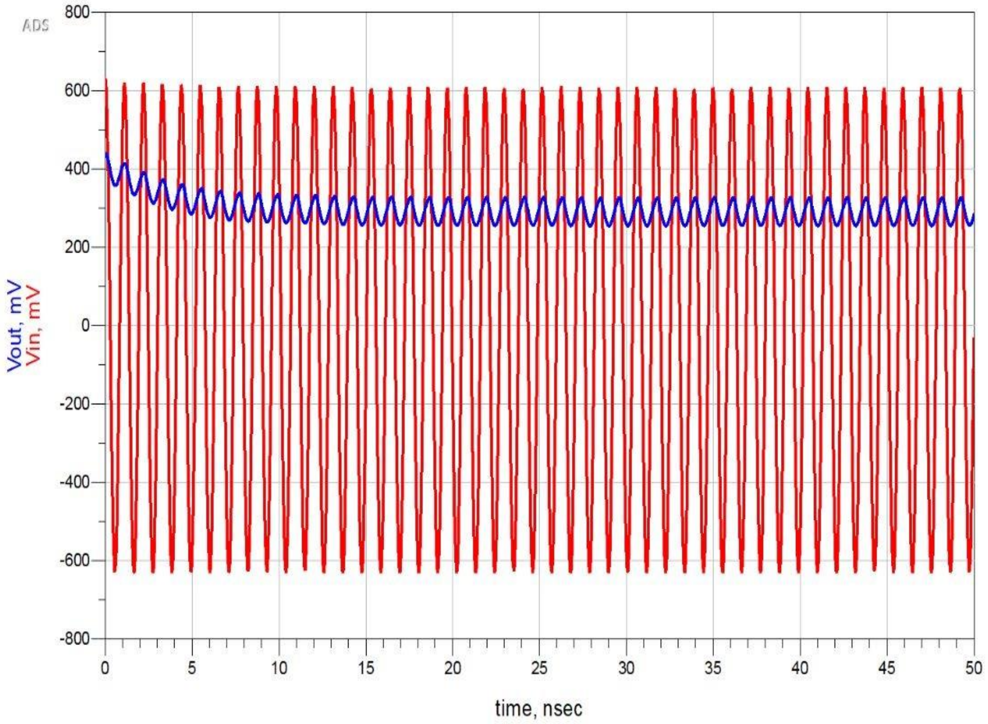
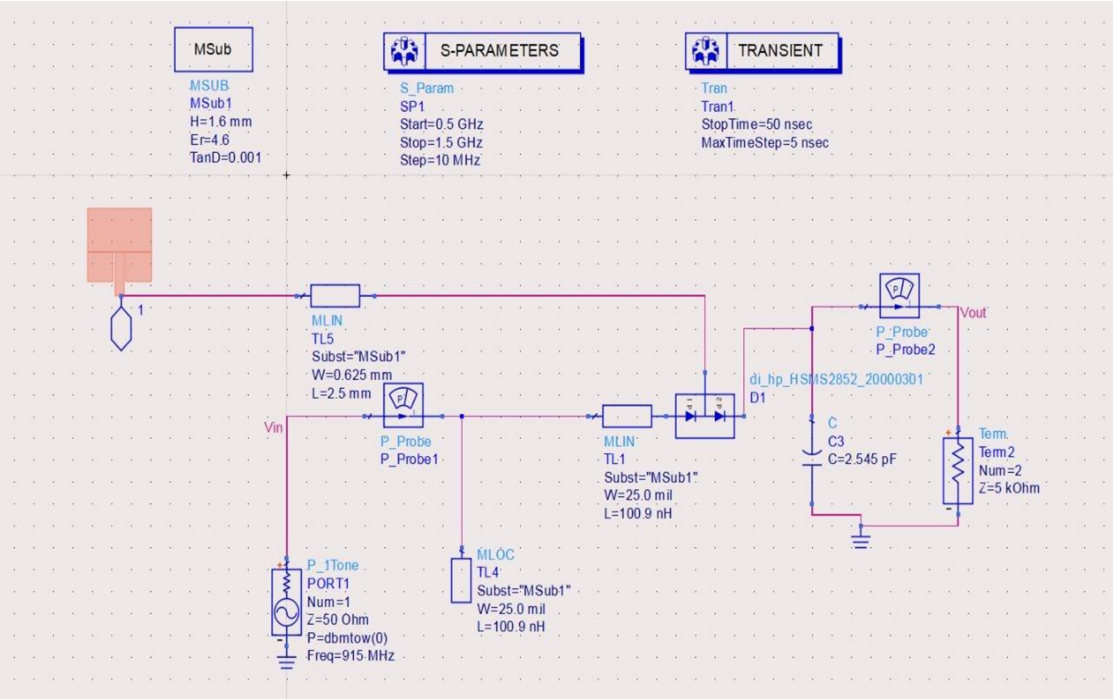


Figure 6.24 Schematic of matched single band rectifier circuit

6.5 RF Energy Harvesting Circuit:



MSUB
MSub1
H=1.6 mm
Er=4.6
TanD=0.001

S_Param
SP1
Start=0.5 GHz
Stop=1.5 GHz
Step=10 MHz

Tran
Tran1
StopTime=50 nsec
MaxTimeStep=5 nsec

MLIN
TL5
Subst="MSub1"
W=0.625 mm
L=2.5 mm

P_Probe
P_Probe1

MLIN
TL1
Subst="MSub1"
W=25.0 mil
L=100.9 nH

di_hp_HSMS2852_20000301
D1

P_Probe
P_Probe2

C
C3
C=2.545 pF

Term
Term2
Num=2
Z=5 kOhm

P_1Tone
PORT1
Num=1
Z=50 Ohm
P=dbmtow(0)
Freq=915 MHz

MLOC
TL4
Subst="MSub1"
W=25.0 mil
L=100.9 nH

Figure 6.25 Schematic of RF Energy Harvesting Circuit

6.6 Matching Network:

An impedance-matching circuit maximizes the power transfer from the receiving antenna to the rectifier and a multi-stage rectifier converts the incoming RF signals to an output DC voltage. In an RF Energy harvester circuit or any other AC circuit, there is a maximum transfer of power from the source to the load, when the load impedance (ZL) is equal to the source impedance (ZS). Fixed LC impedance matching circuits are used to match the input impedance of the rectifier to the output impedance of the antenna. A fixed impedance matching circuit is implemented onto a printed circuit board (PCB) to fine tune the impedance match between the antenna and the rectifier.

Fig. 6.26 Typical Impedance Matching Network

Chapter 7

PHOTOGRAPHS RELATED TO THE PROJECT

FR4 Sheets:

This Sheet was used in the fabrication of the antenna. We use FR4 because of it's stable properties, lack of water absorption and extremely high mechanical strength make it the perfect choice for circuit board printing. It also has advantages like cost-effectiveness, excellent mechanical and electrical properties, and high strength-to-weight ratios.

Fig.7.1

Ferrous Chloride Powder

This $FeCl_3$ powder is used for the process of etching. Etching is traditionally the process of using strong acid or mordant to cut into the unprotected parts of a metal surface to create a design in intaglio in the metal.

Fig.7.2

FR4 Sheet inside $FeCl_3$ solution

Fig.7.3

This is the process of etching. Here, the excess amount of copper was removed using $FeCl_3$ solution.

Fabricated Antenna:

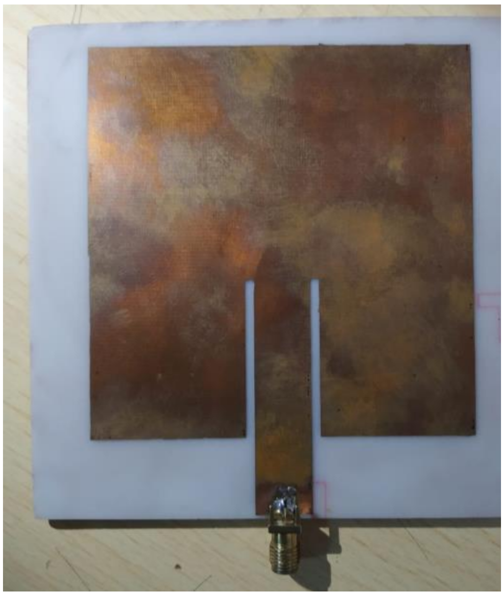
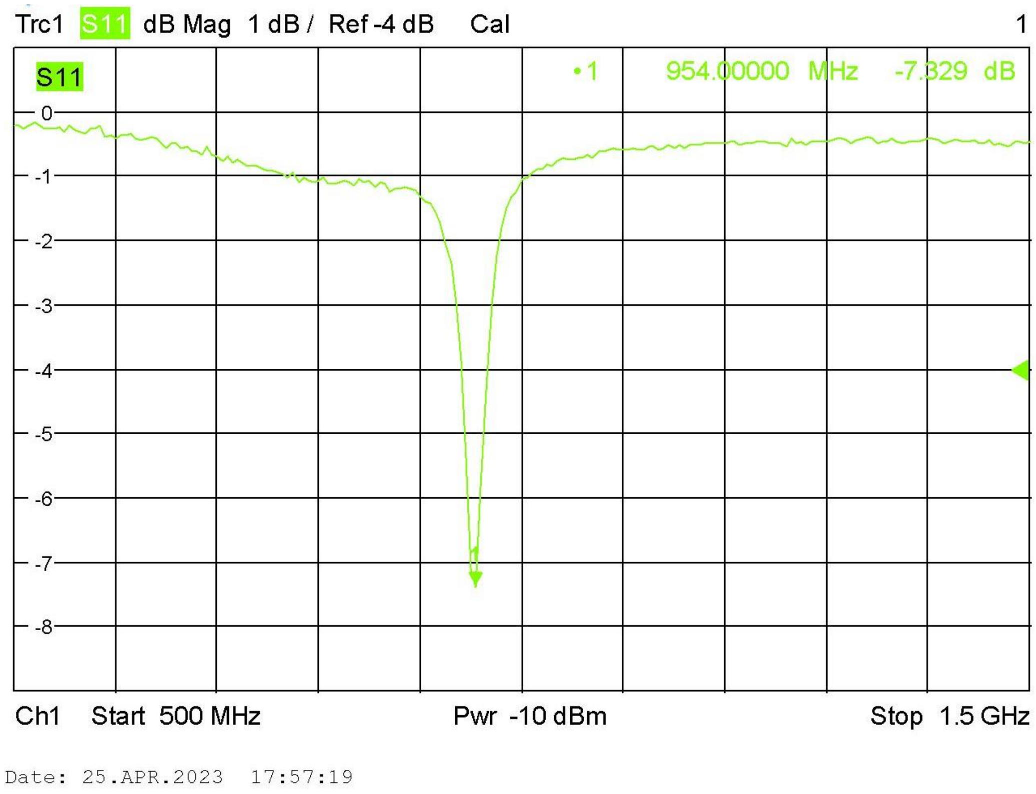


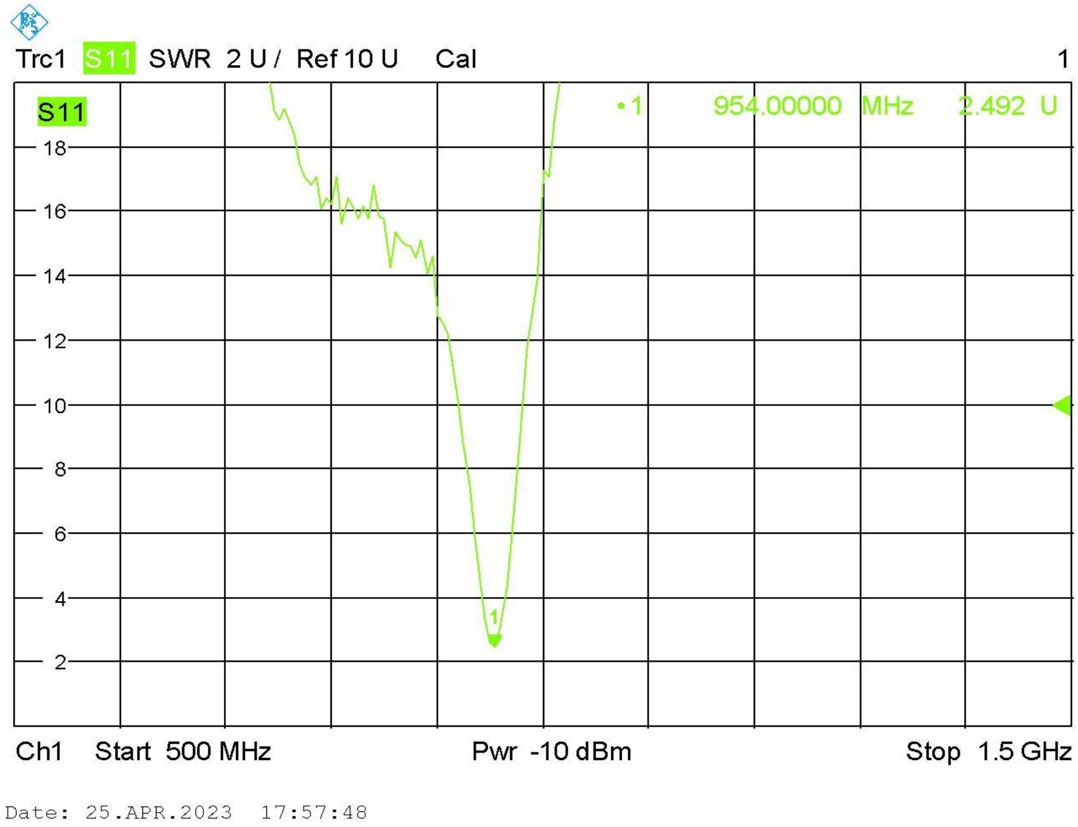
Fig. 7.4

This is the fabricated antenna.

Obtained Results: On Vector Network Analyzer



Date: 25.APR.2023 17:57:19



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CONCLUSION

In conclusion, the project focused on the design and fabrication of antennas for RF energy harvesting at a frequency of 915 MHz, along with the implementation of rectifiers and matching circuits using ADS (Advanced Design System) software.

Using ADS, the antennas were designed to resonate at the desired frequency of 915 MHz, ensuring efficient energy capture. The design process involved considering factors such as antenna size, impedance matching, and radiation pattern to optimize the energy harvesting efficiency.

Rectifiers and matching circuits were also designed and implemented using ADS to convert the captured RF energy into usable electrical power. These components are crucial in maximizing power transfer and minimizing losses during the energy harvesting process.

Overall, the project aimed to harness RF energy at a frequency of 915 MHz through the design, simulation, fabrication, and testing of antennas, rectifiers, and matching circuits. By efficiently capturing and converting RF energy into usable electrical power, such technology holds the potential for various applications, including powering low-power devices, wireless sensors, and IoT (Internet of Things) devices, thereby contributing to energy efficiency and sustainability.

FUTURE SCOPE

Wireless energy harvesting has a lot of potential for projects like home automation and the Internet of Things. Devices with advanced embedded technology that typically operate at a microwatt input power can be produced using smart sensor technology. The automotive, industrial, and home automation sectors all make use of wireless temperature, humidity, and proximity sensors. Without wire charging of any gadgets gadget would be conceivable with headways in remote energy reaping innovation. Wireless charging technology will be available for use as an alternative power source in our upcoming mobile devices. Wireless energy will be used to power wearable devices and medical sensors. Wireless energy harvesting is a method by which power can be used by enhanced security devices that incorporate smart sensor technology. It has advantages due to its small size, wire-free wireless transmission, and ease of implementation.

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6] Microstrip Patch Antenna For 2.4GHz Using Slotted Ground Plane, Karthikeya Anusury, Haneesh Survi, Paritosh Peshwe, (10th ICCCNT - 2019 July 6-8, 2019, IIT - Kanpur, India)

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