# CHAPTER 1
# INTRODUCTION

## 1.1. Background of Study

The last two decades have been the most dynamic in the history of wireless communication [1]. Today's wireless technologies offer an immense range of capabilities to the user. Wireless communication system availabilities are increasing due to investment in fixed infrastructure, as well as reduced device cost and size.

Wireless technology is currently used in different applications. It has a great impact on our daily life in different applications. Recently there are researches that are being done by universities and Research Departments to work on supplying power to electrical and electronic equipment using wireless power transmission technology. By eliminating the need for power cables, accidents related to them can be avoided. Moreover, the technology is an important advantage as there will be no need to place the electrical equipments near the power cords. In addition, charging batteries that are used to power different types of electronics can be done anywhere without the need of classical power sources.

Radio Frequency is the range of electromagnetic frequencies above the audio range and below infrared light (from 10 kHz to 300 GHz) [2]. Except for infrared (IR) transmission, all wireless transmission uses RF, including AM and FM radio, TV, satellites, portable phones, cell phones and wireless networks. RF signals can be focused in one direction (directional) or they can transmit in all directions (omnidirectional). Refer to Table 1 in APPENDIX A for details on the RF ranges and applications.

## 1.2. Problem Statement

A wide range of wireless devices and products have been manufactured that became very important to normal consumer, industrial, and military needs. Unfortunately, with existing technology, wireless devices are constrained by their inability to operate independently of centralized power sources for an infinite duration. As a result, the usefulness of wireless devices, as well as the potential range of applications, is severely restricted by relatively slow advancements in rechargeable battery technology. Consequently, a clear market need exists that either allows wireless devices to operate for longer durations away from centralized power sources or increases the amount of power that can be supplied to a wireless device.

There have been researches done in the area of shrinking the charger in order to make it easier to carry along with the chargeable electronic devices. But as small as the charger becomes, it still needs to be plugged in to a wall outlet.

The new electronic equipment technologies aim to decrease both the size and power consumption. This decrease in size and power gives rise to new methods of using electronics, with many small devices working collaboratively or at least with strong communication capabilities using RF signals. Currently, these devices are powered by batteries. However, batteries present several disadvantages such as: the need to either replace or recharge them periodically and their big size and weight compared to high technology electronics.

Energy waves are propagating everywhere. Radio and television towers, satellites orbiting earth, and even the cellular phone antennas are constantly transmitting energy. Finding a way to harvest the energy that is being transmitted and use it as a source of power is the main target of this project.. By gathering and storing this energy, it can be used to power other circuits. In the case of small electronic devices, this power could be used to recharge a battery that is constantly being depleted. The potential exists for cellular phones, and more complicated devices such as: pocket organizers, person digital assistants (PDAs), and even notebook computers, to be operated completely wirelessly.

This project presents one of the methods to design an RF energy harvesting device. This device can supply electrical power in places where sources of electrical energy can not be found.

On the larger scale, the project's concept can be used as an alternative source of energy especially in the current situation where most of the energy produced depends on the Oil and Gas sources.

## 1.3. Objectives and Scope of Study

The main objective of this project is to find a way to design a system that can harvest the ambient Radio Frequency energy through the conversion to electrical energy that can be used in charging. This is an alternative to the current power cable as RF signals are safe and are widely used in many applications concerning wireless technology.

This project needs studying and reading about latest researches on RF and wireless technologies. Moreover, Energy harvesting circuits need to be analyzed and improved in terms of the output voltage as well as the efficiency of power supplied.

This project is relevant to the field of wireless technology, Alternative energy resources, Energy Harvesting methods, and Power Electronics.

The time frame allocated for this project is two semesters where in the first semester researches were performed to fulfill the implementation of the project objectives. While the second semester is dedicated to start working on the design based on the available information.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1. Radio Frequency for Energy Harvesting

The use of Radio Frequencies (RF) for communication is considered a wireless related technology that already began a century ago. It is a milestone in modern life that has various types of applications. RF is one of a general class of energy carrying waves which is defined in the electromagnetic spectrum.

RF signal is widely used nowadays specially in the communication field. Although thousands of radio waves propagate in the air, they do not interfere with each other because each RF transmission transmits at different frequency. Besides, certain range of frequency is specified according to the application.

Energy Harvesting can be defined as conversion of ambient energy present in the environment into electrical energy. RF radiation is used to power ID cards by directing high power electromagnetic energy to the devices from a nearby source. In addition to energy, it is possible to share information as well.

However, the term energy harvesting implies that the device gets its energy by making use of available energies in the surrounding environment. In cities and very populated areas there is a large number of potential RF sources: broadcast Radio and TV, mobile telephony, wireless networks, etc. The concept of RF Energy Harvesting is to collect all these disparate sources and convert them into useful energy. The conversion is based on a rectifying antenna (*rectenna*), constructed with a Schottky diode located between the antenna dipoles.

The energy levels actually present are so low that no present electronic device can use them. The goal of this project is to work on the fabrication of devices that would “recycle” RF energy generated for other purposes by different elements.

After going through different papers, journals and researches related to RF energy harvesting the overall system can consisted of the following subsystems:

## 2.2. Charge Pump (Voltage Doublers) subsystem

A charge pump is an electronic circuit that uses capacitors as energy storage elements to create either a higher or lower voltage power source [2]. Charge pump circuits are capable of high efficiencies, sometimes as high as 90-95% while being electrically simple circuits.

Charge pumps use some form of switching device(s) to control the connection of voltages to the capacitor. For instance, to generate a higher voltage, the first stage involves the capacitor being connected across a voltage and charged up. In the second stage, the capacitor is disconnected from the original charging voltage and reconnected with its negative terminal to the original positive charging voltage. Because the capacitor retains the voltage across it (ignoring leakage effects) the positive terminal voltage is added to the original, effectively doubling the voltage.

Charge pumps work in stages that progressively increase the output voltage in a DC form. By increasing the number of stages of the charge pump it is theoretically possible to deliver any needed output voltage. The only constraint is that the circuit must obey Ohm’s law. In other words, by increasing voltage, current is sacrificed.

A basic charge pump is shown below in Figure 1.

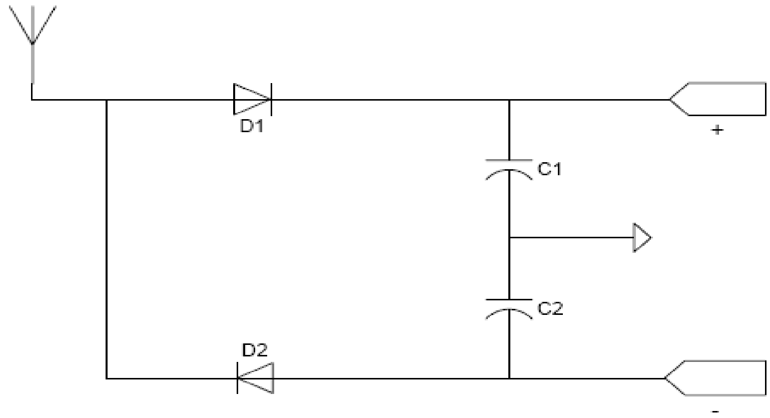


**Figure 1:** Charge Pump circuit

The illustrated circuit is a voltage doubler that operates as follows: Assuming a sinusoidal input, $V_{in}$=A Sin(ωt) and a peak amplitude larger than $V_{th}$ of the two diodes. With the first positive semi-cycle after $V_{in}=V_{th}$ capacitor $C_1$ begins to charge and continues to charge until the peak voltage of A-$V_{th}$ is reached. At that moment $V_{c1}$=A-$V_{th}$. When the semi-cycle begins to decrease, the capacitor $C_1$ retains its charge because it has no discharge path. At this point both diodes are behaving as open circuits. When Vin enters the negative semi-cycle diode $D_1$ operates as on open circuit and $D_2$ as a short circuit allowing capacitor $C_2$ to begin to charge the same way that $C_1$ charged. At this point both capacitors are charged and behave as DC voltage sources in series with an output voltage of $V_{out}=V_{c1}+V_{c2}=2(A-V_{th})$, which is approximately twice the input voltage.

The rectification subsystem will take the output from the antenna in the form of a sine wave and convert it to a steady direct current voltage. This circuit will also increase the output voltage to a level that will be usable by the supercapacitor charger. The problem with this for this application is that normal diodes have a turn-on voltage, $V_{th}$, of 0.7 V. This large turn-on voltage will consume most of the power that is harvested by the antenna and greatly reduce the operational efficiency of the system. To avoid this problem, Germanium diodes will be tried that have a $V_{th}$ of 0.3 V. Therefore charge pumps will be used to rectify the AC input and multiply the voltage before delivering it to the supercapacitor charger as a nearly pure DC voltage.

## 2.3. Antenna Subsystem

Antennas are metallic structures designed for radiating and receiving electromagnetic energy. An antenna acts as a transitional structure between the guiding device (e.g. waveguide, transmission line) and the free space. The official IEEE definition of an antenna the concept: “That part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves” [3].

Physically, an antenna is an arrangement of conductors that generate a radiating electromagnetic field in response to an applied alternating voltage and the associated alternating electric current, or can be placed in an electromagnetic field so that the field will induce an alternating current in the antenna and a voltage between its terminals [3].

### 2.3.1. Radiation Pattern and gain

An antenna’s radiation pattern and gain are perhaps the two antenna characteristics that most affect system coverage and performance. The radiation pattern of antenna simply describes how an antenna focuses or directs the energy it radiates or receives. All antennas, regardless of pattern shape or gain, do not radiate more total energy than is delivered to their input connector. The antenna does not act as an absolute power amplifier, rather, it acts as a directional amplifier, transmitting or receiving energy in one specific region of space more so than others.

Antenna radiation patterns are typically presented in the form of a polar plot for a 360-degree angular pattern in one of two sweep planes. The most common angular sweep planes used to describe antenna patterns are a horizontal or azimuth sweep plane and a vertical or elevation sweep plane. Radiation patterns are generally presented on a relative power dB scale. In the definition of the antenna gain level, an isotropic antenna is typically used as a reference standard. An isotropic antenna is a theoretical antenna radiating energy equally in all direction of space. This antenna would have a directivity of 0 dB since energy is distributed equally in all directions. Antenna directivity is simply the relative dB level of radiation intensity at the antenna pattern peak relative to that of the isotropic antenna. The gain of an antenna would be equal to its directivity if the antenna were 100% efficient. The gain of an antenna is therefore equal to the directivity less any losses in the antenna. With the exception of reflector antennas, antennas used in wireless communications systems typically have efficiencies that range from 85% to 95%.

### 2.3.2. Antenna Types [3]

Antennas come in different shapes and sizes to suit different types of wireless applications. The characteristics of an antenna are very much determined by its shape, size and the type of material that it is made of. Some of the commonly used antennas are briefly described below.

#### 2.3.2.1. Half Wave Dipole

The length of this antenna is equal to half of its wavelength as the name itself suggests. Dipoles can be shorter or longer than half the wavelength, but a tradeoff exists in the performance and hence the half wavelength dipole is widely used.

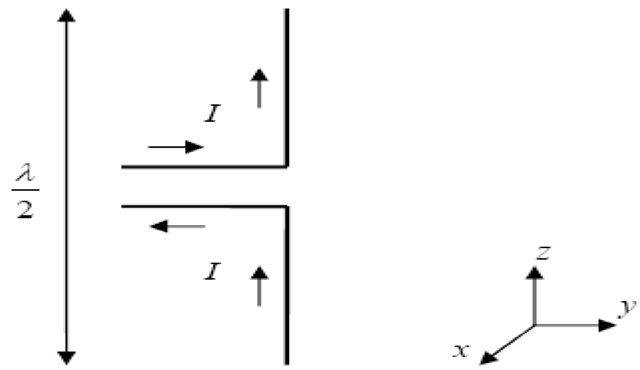


**Figure 2:** Half wave dipole

The dipole antenna is fed by a two wire transmission line, where the two currents in the conductors are of sinusoidal distribution and equal in amplitude, but opposite in direction. Hence, due to canceling effects, no radiation occurs from the transmission line. As shown in Figure 2, the currents in the arms of the dipole are in the same direction and they produce radiation in the horizontal direction. Thus, for a vertical orientation, the dipole radiates in the horizontal direction. The typical gain of the dipole is 2dB and it has a bandwidth of about 10%. The half power beamwidth is about 78 degrees in the E plane and its directivity is 1.64 (2.15dB) with a radiation resistance of 73 Ω. Figure 3 shows the radiation pattern for the half wave dipole.

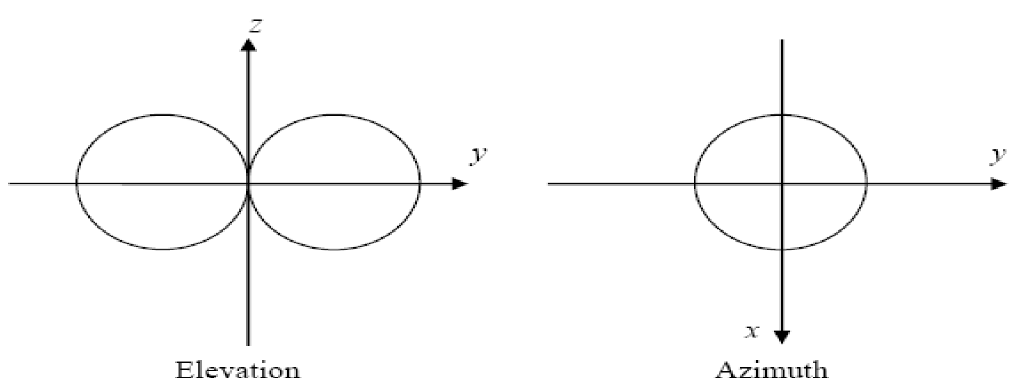


**Figure 3:** Radiation Pattern for Half wave dipole

#### 2.3.2.2. Monopole Antenna

The monopole antenna, shown in Figure 4, results from applying the image theory to the dipole. According to this theory, if a conducting plane is placed below a single element of length *L* / 2 carrying a current, then the combination of the element and its image acts identically to a dipole of length *L* except that the radiation occurs only in the space above the plane.

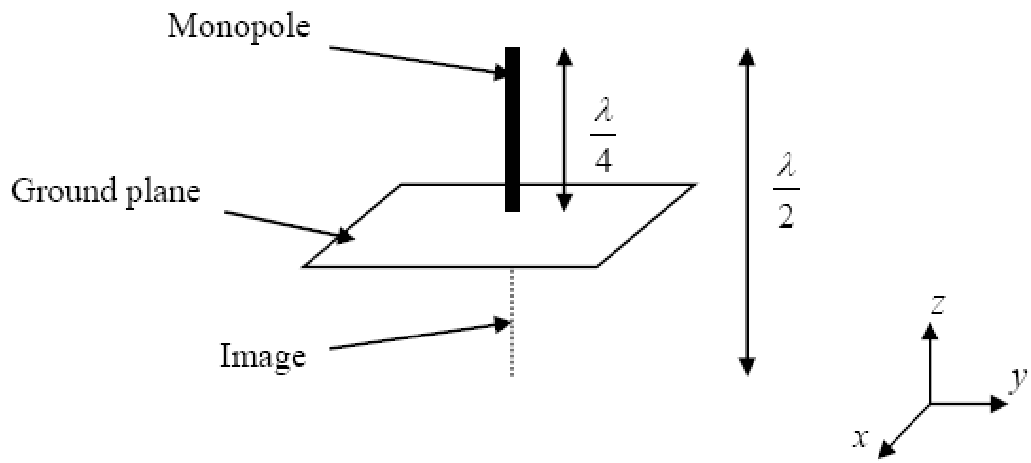


**Figure 4:** Monopole antenna

For this type of antenna, the directivity is doubled and the radiation resistance is halved when compared to the dipole. Thus, a half wave dipole can be approximated by a quarter wave monopole ($L / 2 = \lambda / 4$). The monopole is very useful in mobile antennas where the conducting plane can be the car body or the handset case. The typical gain for the quarter wavelength monopole is 2-6dB and it has a bandwidth of about 10%. Its radiation resistance is 36.5 Ω and its directivity is 3.28 (5.16dB). The radiation pattern for the monopole is shown below in Figure 5.

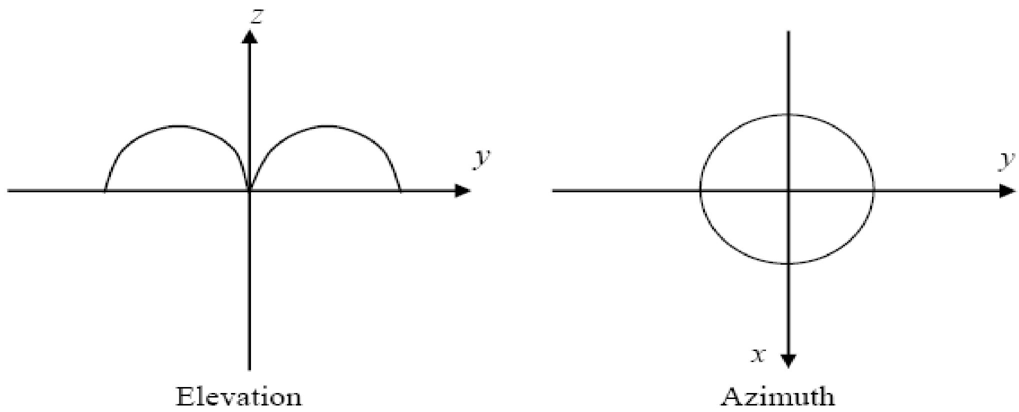


**Figure 5:** Radiation pattern for Monopole antenna

### 2.3.2.3. Loop Antennas

The loop antenna is a conductor bent into the shape of a closed curve such as a circle or a square with a gap in the conductor to form the terminals as shown in Figure 6. There are two types of loop antennas-electrically small loop antennas and electrically large loop antennas. If the total loop circumference is very small as compared to the wavelength ($L <<< \lambda$), then the loop antenna is said to be electrically small. An electrically large loop antenna typically has its circumference close to a wavelength. The far-field radiation patterns of the small loop antenna are insensitive to shape.

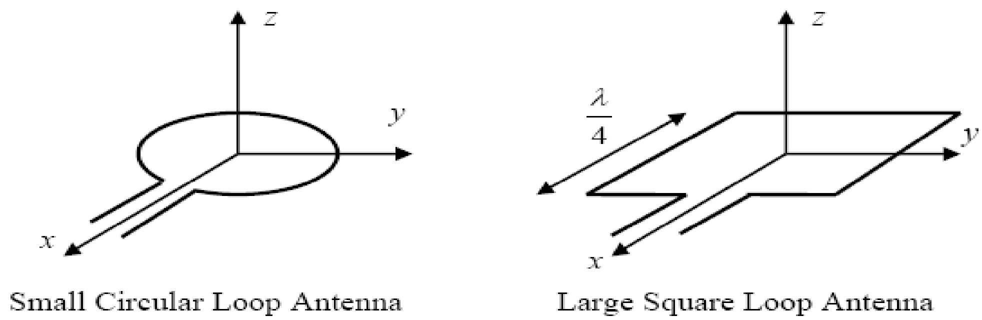


**Figure 6:** Loop antennas

As shown in Figure 7, the radiation patterns are identical to that of a dipole despite the fact that the dipole is vertically polarized whereas the small circular loop is horizontally polarized.

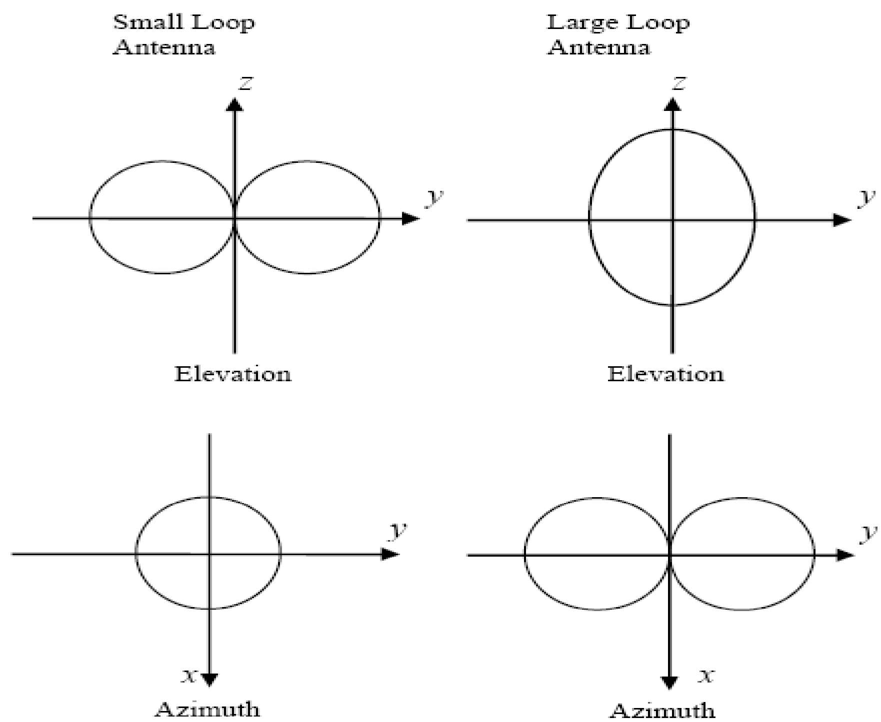


**Figure 7:** Radiation Pattern of Loop antennas

The performance of the loop antenna can be increased by filling the core with ferrite. This helps in increasing the radiation resistance. When the perimeter or circumference of the loop antenna is close to a wavelength, then the antenna is said to be a large loop antenna. The radiation pattern of the large loop antenna is different then that of the small loop antenna. For a one wavelength square loop antenna, radiation is maximum normal to the plane of the loop (along the z axis). In the plane of the loop, there is a null in the direction parallel to the side containing the feed (along the x axis), and there is a lobe in a direction perpendicular to the side containing the feed (along the y axis). Loop antennas generally have a gain from -2dB to 3dB and a bandwidth of around 10%. . The small loop antenna is very popular as a receiving antenna. Single turn loop antennas are used in pagers and multiturn loop antennas are used in AM broadcast receivers.

#### 2.3.2.4. Helical Antennas

A helical antenna or helix is one in which a conductor connected to a ground plane, is wound into a helical shape. Figure 8 illustrates a helix antenna. The antenna can operate in a number of modes, however the two principal modes are the normal mode (broadside radiation) and the axial mode (endfire radiation). When the helix diameter is very small as compared to the wavelength, then the antenna operates in the normal mode. However, when the circumference of the helix is of the order of a wavelength, then the helical antenna is said to be operating in the axial mode.

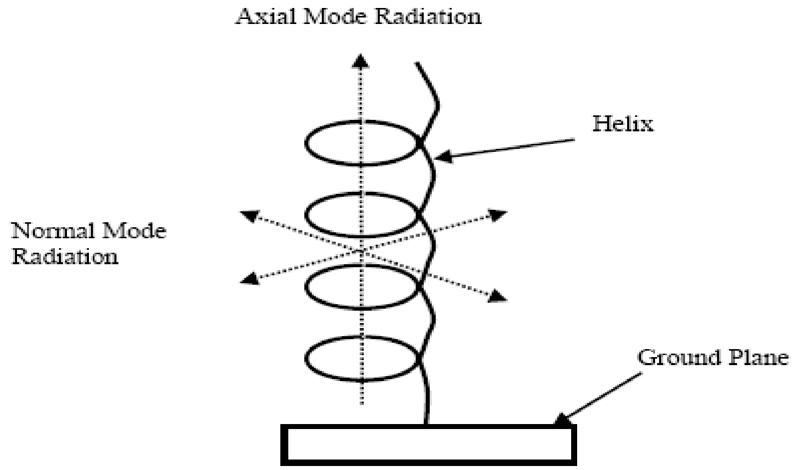


**Figure 8:** Helix antenna

In the normal mode of operation, the antenna field is maximum in a plane normal to the helix axis and minimum along its axis. This mode provides low bandwidth and is generally used for hand-portable mobile applications.

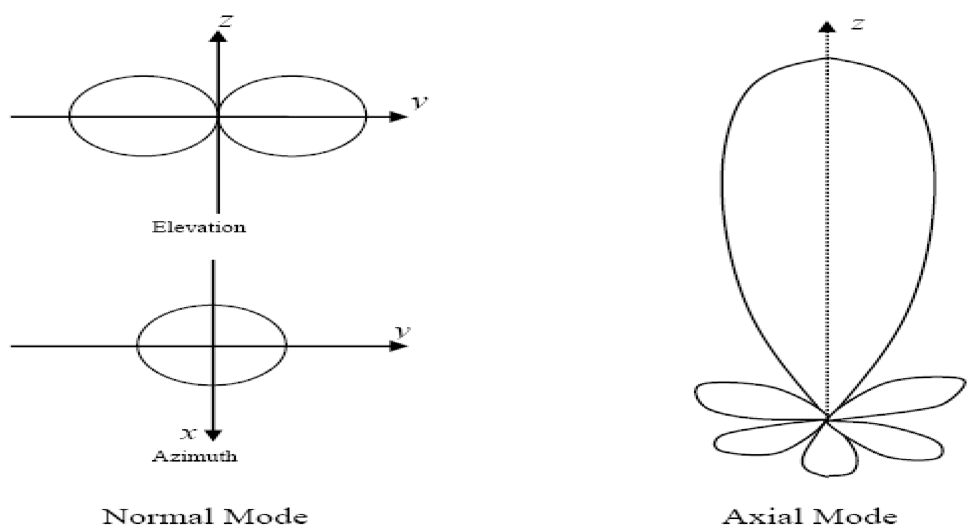


**Figure 9:** Radiation Pattern for Helix antenna

In the axial mode of operation, the antenna radiates as an endfire radiator with a single beam along the helix axis. This mode provides better gain (up to 15dB) and high bandwidth ratio (1.78:1) as compared to the normal mode of operation. For this mode of operation, the beam becomes narrower as the number of turns on the helix is increased. Due to its broadband nature of operation, the antenna in the axial mode is used mainly for satellite communications.

Figure 9 above shows the radiation patterns for the normal mode as well as the axial mode of operations.

### 2.3.3. Antenna Equivalent Circuits and impedance

To a generator feeding a transmitting antenna as in Figure 10, the antenna appears as a load. Similarly, a receiver connected to a receiving antenna's output terminals will appear to the antenna as load impedance. Such simple equivalent circuit representations of transmitting and receiving antennas are shown in Fig. 15.4.1, where in both cases V is the equivalent open-circuit Thevenin voltage. In the transmitting antenna case, the antenna is represented by a load impedance ZA, which in general will have both a resistive and a reactive part, $Z_A = R_A + jX_A$. The reactive part represents energy stored in the fields near the antenna, whereas the resistive part represents the power losses which arise because (a) power is radiated away from the antenna and (b) power is lost into heat in the antenna circuits and in the medium surrounding the antenna.

The generator has its own internal impedance $Z_G = R_G + jX_G$. The current at the antenna input terminals will be $I_{in}$ = V/(ZG+ZA), which allows us to determine (a) the total power Ptot produced by the generator, (b) the power PT delivered to the antenna terminals, and (c) the power PG lost in the generator's internal resistance RG. These are:

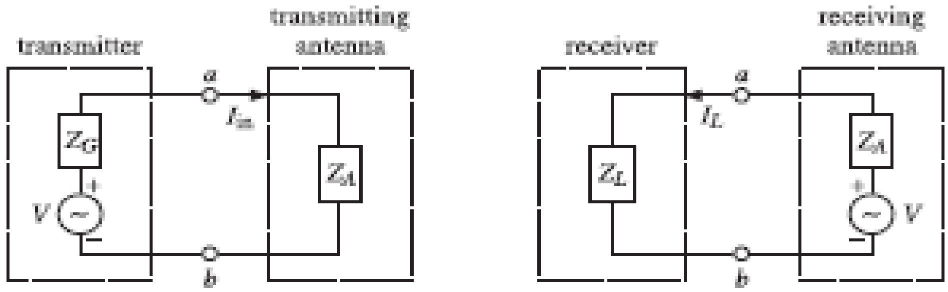


**Figure 10:** Equivalent Circuit for Transmitting and Receiving antennas

In the case of a receiving antenna, the induced currents on the antenna can be represented by a Thevenin-equivalent generator (the open-circuit voltage at the antenna output terminals) and an internal impedance ZA. A consequence of the reciprocity principle is that ZA is the same whether the antenna is transmitting or receiving. The current into the load is IL = V/(ZA + ZL), where the load impedance is ZL = RL + jXL. As before, we can determine the total power $P_{tot}$ produced by the generator (i.e., intercepted by the antenna) and the power PR delivered to the receiving load:

$$P_{\text{tot}} = \frac{1}{2}\text{Re}(VI_L^*) = \frac{1}{2}\frac{|V|^2(R_L + R_A)}{|Z_L + Z_A|^2}, \quad P_R = \frac{1}{2}|I_L|^2 R_L = \frac{1}{2}\frac{|V|^2 R_L}{|Z_L + Z_A|^2}$$

Under conjugate matching, $Z_L = Z^*_A$, we find the maximum power delivered to the load:

$$\boxed{P_{R,\max} = \frac{|V|^2}{8R_A}}$$

If the load and antenna are mismatched, we have:

$$P_R = \frac{|V|^2}{8R_A} \frac{4R_A R_L}{|Z_L + Z_A|^2} = P_{R,\max}(1 - |\Gamma_{\text{load}}|^2), \qquad \Gamma_{\text{load}} = \frac{Z_L - Z_A^*}{Z_L + Z_A}$$

It is tempting to interpret the power dissipated in the internal impedance of the Thevenin circuit of the receiving antenna (that is, in ZA) as representing the amount of power re-radiated or scattered by the antenna.

### 2.3.4. Effective Area

When an antenna is operating as a receiving antenna, it extracts a certain amount of power from an incident electromagnetic wave. As shown in Fig. 11, an incident wave coming from a far distance may be thought of as a uniform plane wave being intercepted by the antenna.

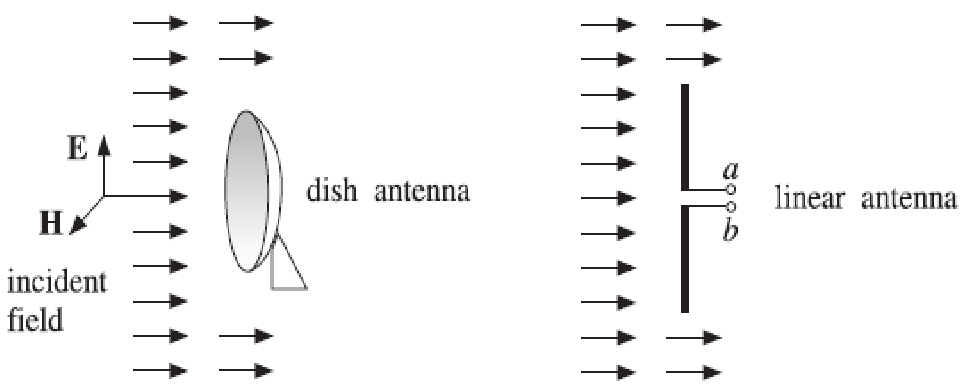


**Figure 11:** Effective Area of an antenna

The incident electric field sets up currents on the antenna. Such currents may be represented by a Thevenin-equivalent generator, which delivers power to any connected receiving load impedance. The induced currents also re-radiate an electric field (referred to as the scattered field), which interferes with the incident field causing a shadow region behind the antenna, as shown in Figure 11.

The total electric field outside the antenna will be the sum of the incident and reradiated fields. For a perfectly conducting antenna, the boundary conditions are that the tangential part of the total electric field vanishes on the antenna surface.

The power density of the incident wave at the location of the receiving antenna can be expressed in terms of the electric field of the wave, $P_{inc} = E_2/2\eta$. The effective area or effective aperture A of the antenna is defined to be that area which when intercepted by the incident power density $P_{inc}$ gives the amount of received power $P_R$ available at the antenna output terminals.

$$P_R = AP_{inc}$$

For a lossy antenna, the available power at the terminals will be somewhat less than the extracted radiated power $P_{rad}$, by the efficiency factor $P_R = eP_{rad}$. Thus, we may also define the maximum effective aperture Am as the area which extracts the power $P_{rad}$ from the incident wave, that is, $P_{rad} = A_m P_{inc}$. It follows that:

$$A = eA_m$$

In practice, the quoted effective area A of an antenna is the value corresponding to the direction of maximal gain Gmax. We write in this case:

$$G_{max} = 4\pi A/\lambda^2$$

Antennas fall into two classes: fixed-area antennas, such as dish antennas, for which A is independent of frequency, and fixed-gain antennas, such as linear antennas, for which G is independent of frequency. For fixed-area antennas, the gain increases quadratically with f. For fixed-gain antennas, A decreases quadratically with f.

## 2.4. Electromagnetic Concepts

The near and far field regions are generally used terms in antenna measurements. The near field and far field of an antenna or other isolated source of electromagnetic radiation are regions around the source where different parts of the field are relatively more or less important. The boundary between the two regions is only vaguely defined, and depends on the dominant wavelength (λ) emitted by the source. Roughly speaking, the near field is the region within a radius $r << \lambda$, while the far field is the region for which $r >> \lambda$. The two regions are defined simply for mathematical convenience, enabling certain simplifying approximations. These regions are sometimes also called the near zone and far zone. The latter is also frequently referred to as the radiation zone.

A more precise definition is given by the propagation properties. If the distance separating the transmitting and receiving antennas is larger than $2D^2/\lambda$ , where D is the largest dimension of the source of the radiation, then it is a far field measurement (Fraunhofer diffraction) and if the measuring distance is less $2D^2/\lambda$, it is a near field measurement (Fresnel zone).

The radiation zone is important because fields generally fall off in amplitude by 1 / r. This means that the total energy per unit area at a distance r is proportional to 1 / r2. But the area of the sphere is proportional to r2, so the total energy passing through the sphere is constant. This means that the energy actually escapes to infinite distance (it radiates).

### 2.4.1. Overview of Near and Far Fields

If sinusoidal currents are applied to a structure of some type, electric and magnetic fields will appear in space about that structure. If those fields extend some distance into space the structure is often termed an antenna. Such an antenna can be an assemblage of conductors in space typical of radio devices or it can be an aperture with a given current distribution radiating into space as is typical of microwave or optical devices. The actual values of the fields in space about the antenna are usually quite complex and can vary with distance from the antenna in various ways.

Since in many practical applications one is only interested in effects where the distance from the antenna to the observer is very much greater than the largest dimension of the transmitting antenna, the equations describing the fields created about the antenna can be simplified by assuming a large separation and dropping all terms which provide only minor contributions to the final field. These simplified distributions have been termed the far field and usually have the property that the angular distribution of energy does not change with distance; however the energy levels still vary with distance and time. Such an angular energy distribution is usually termed an antenna pattern.

Remarkably, by the principle of reciprocity the pattern observed when a particular antenna is transmitting is identical to the pattern measured when the same antenna is used for reception. Typically one finds relatively simple relations describing the antenna far field patterns, often involving trigonometric functions or at worst Fourier or Hankel transform relationships between the antenna current distributions and the observed far field patterns. While far field simplifications are very useful in engineering calculations, this does not mean the near field functions cannot be calculated, especially using modern computer techniques. An examination of how the near fields form about an antenna structure can give great insight into the operations of such devices.

The near-field is remarkable for reproducing classical electromagnetic induction and electric charge effects on the EM field, which effects "die-out" with increasing distance from the antenna (proportional to the cube of the distance), far more rapidly than do the classical radiated EM far-field (proportional to the distance). Typically near-field effects are not important farther away than a few wavelengths of the antenna. These near-field effects also involve energy transfer effects which couple directly to receivers near the antenna, affecting the power output of the transmitter if they do couple, but not otherwise (again, as in classical magnetic induction). In a sense, the near-field offers energy which is available to a receiver only if the energy is tapped, and this is sensed by the transmitter by means of answering electromagnetic near-fields emanating from the receiver. This is different with the far-field, which draws constantly energy from the transmitter, whether it is immediately received, or not.

# CHAPTER 3
# METHODOLGY

## 3.1. Tools and Equipment

Going through this project some software and hardware equipment were utilized to reach the project's goals.

Software:

- Multisim 10.0.1 Complete Edition
- Advance Design System(ADS)
- Ansoft Designer
- Ultiboard 10.0.1
- Eagle 5.1.0

Hardware:

- Electrical and Electronic equipment such as: BreadBoard, PCB, capacitors, resistors, wires, transmitters, receivers, antennas, Ac power supply, and function generator.

### 3.2. Project Stages

As stated before, the project will go through different stages in order to achieve the objective. The following chart illustrates these stages:

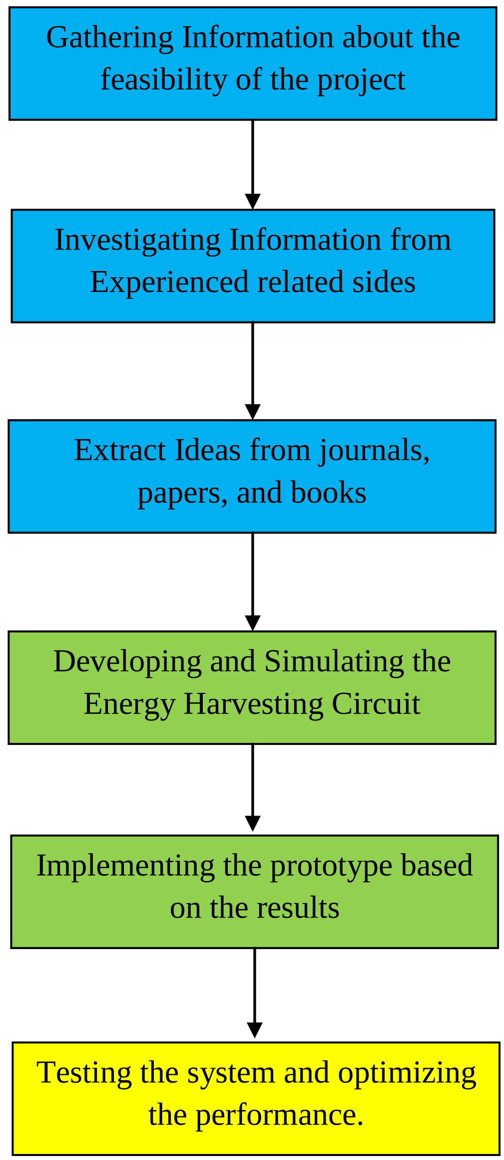


**Figure 12:** Flow Chart of the Project

## 3.3. Test Plan

The completion and testing the validity of the system will be done in three main stages. Upon completing these three stages, the minimum project goals will be fully achieved.

### Stage 1: Simulation

During this stage each of the subsystems will be tested separately from the other. Multisim 10.1 is used to simulate and predict the output voltage of the charge pump before proceeding with the real implementation of the actual circuit.

### Stage 2: Board Implementation

After simulating the charge pump all the values that were theoretically calculated and obtained will be verified and tested. Any modifications that need to be done to the design will be carried out. During this stage, a Light emitting diode (LED) will be used first to test the harvesting system. The circuit will be first implemented on a normal breadboard and the results will be analyzed. Then a PCB will be used to enhance the efficiency of the system.

### Stage 3: RF Transmission

The system will be tested using a 2.45 GHz transmitter that is available in the university. The prototype will be exposed to the RF energy at different distances from the transmitter. The output voltage produced by the charge pump will be analyzed. Changes will be applied to the design according to these outputs in order to reach the optimal performance of harvesting.

If the attached LED can be wirelessly powered from harvesting the RF energy, the next step will be adding an energy storage unit made of capacitors. This will store the DC output power delivered by the rectification subsystem in order to provide the electrical device with its power requirement.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1. System Overview

The RF energy harvesting device consists of two primary subsystems. The first subsystem is the receiving antenna, which is responsible for capturing the RF energy. The second subsystem is the rectification circuitry, which will efficiently convert the time varying input energy into a constant output voltage. Then the output of the rectification system can be fed to either capacitors to store the energy, and provide a constant output voltage to power a low powered device, or it can be connected directly to a load.

When the system is introduced to RF radiation, the antenna will collect as much RF energy as possible. That RF energy will be converted from an alternating current to a direct current and multiply the output voltage to be able to provide power for the load or the energy storage unit. So far several tasks had been completed in order to achieve the objectives of this project.

## 4.2. Charge Pump Design and Simulation

The rectification circuit (Charge Pump) was simulated using *Multisim 10.0.1* to determine the most efficient values of the capacitors and the suitable type of Diode to be used. Assuming an AC voltage input to the circuit of the value 0.5 $V_{rms}$, different types of Schottky Diodes were tested and the performance of the circuit was observed. In addition various values of capacitors were tried in the simulation to choose between them according to the maximum output delivered to the load.

The Voltage of the AC source was set to be 0.5 $V_{rms}$ at 2.4 GHz.

The output voltage can be calculated theoretically using the following equation:

$$V_o = nV_{in} - V_{th} - (n-1/fc) - I_{load}$$

There will be a small difference between the calculated output voltage and the simulated output as a result of the parasitic capacitances of the diodes and the saturation current.

The results of the simulation are shown below in the following figures:

**Test 1:** Different types of Schottky Diodes were used in a single stage charge pump with the capacitor values being constant:

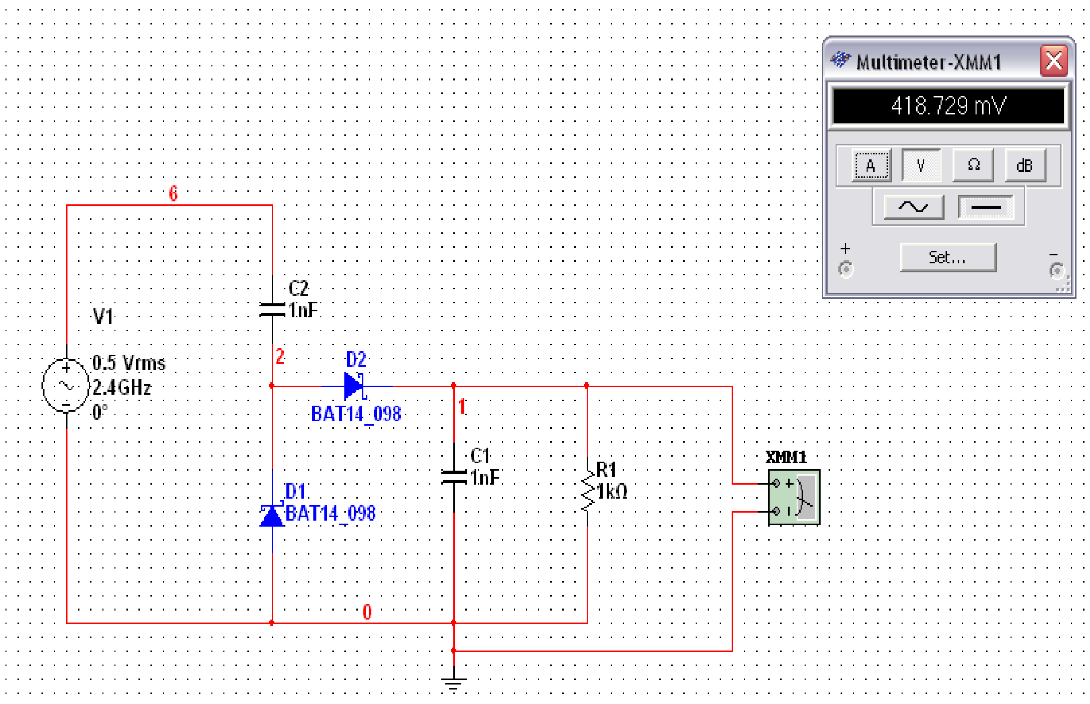


**Figure 13:** Single Stage Charge Pump with Schottky Diode: BAT14_098

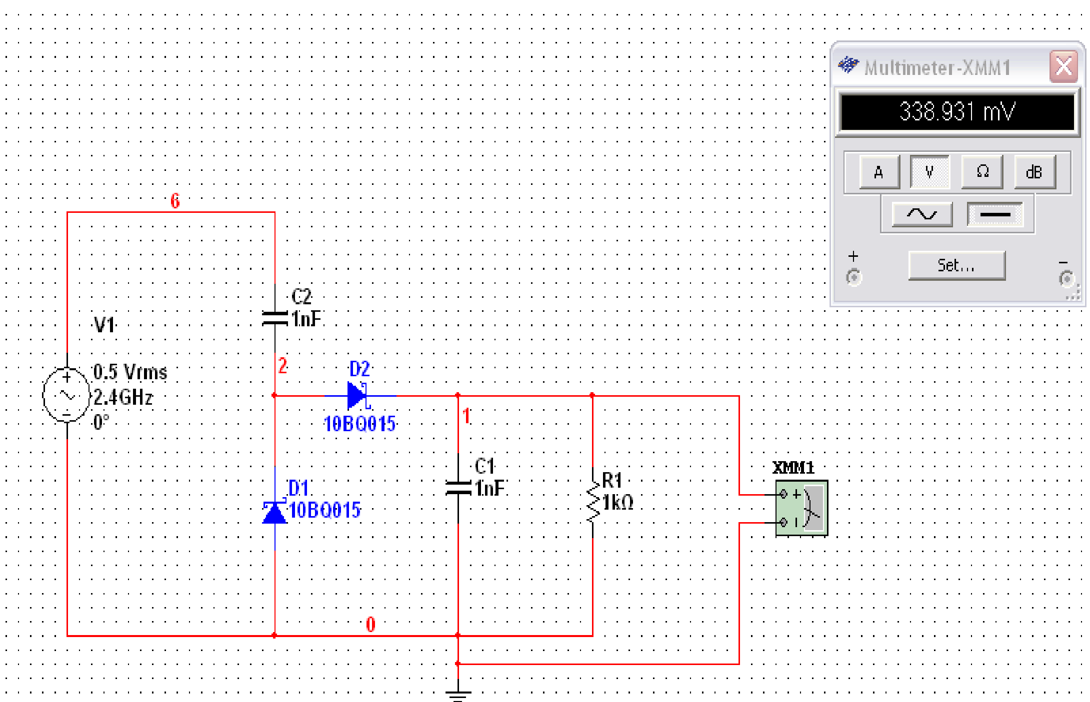


**Figure 14:** Single Stage Charge Pump with Schottky Diode: 10BQ015

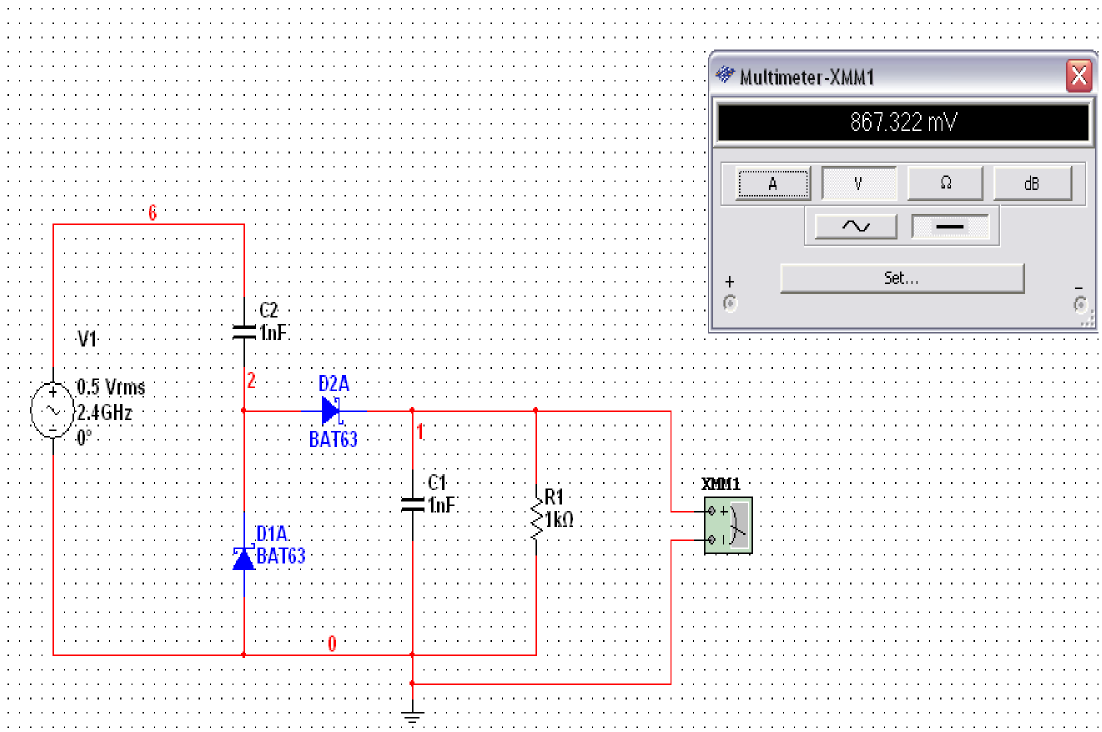


**Figure 15:** Single Stage Charge Pump with Schottky Diode: BAT63

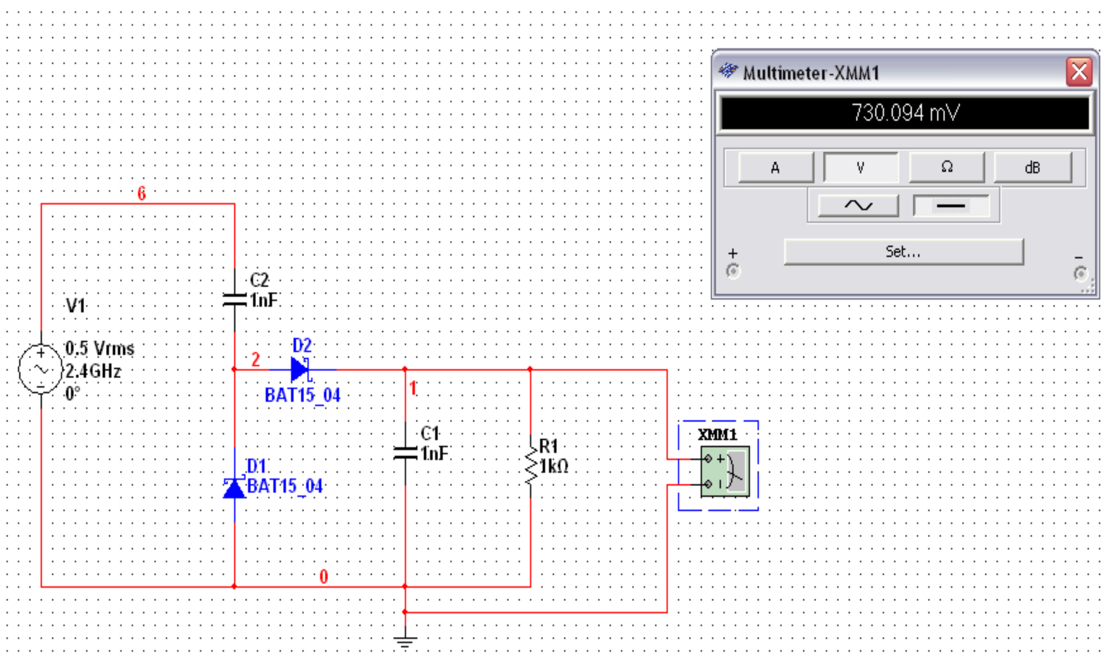


**Figure 16:** Single Stage Charge Pump with Schottky Diode: BAT15_04

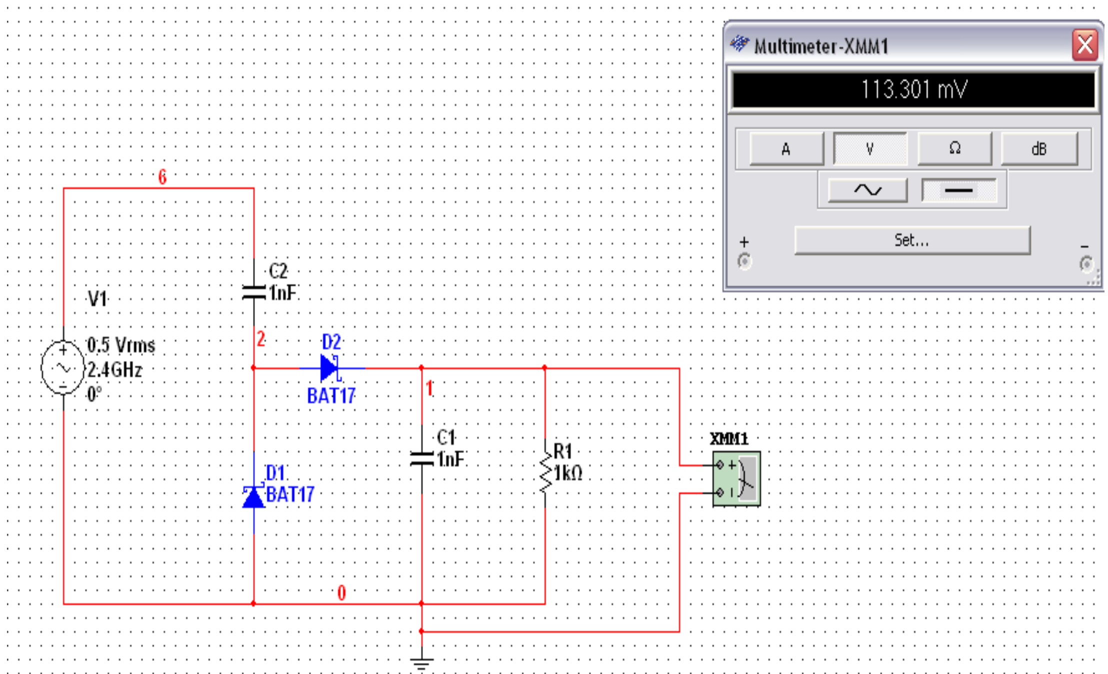


**Figure 17:** Single Stage Charge Pump with Schottky Diode: BAT17

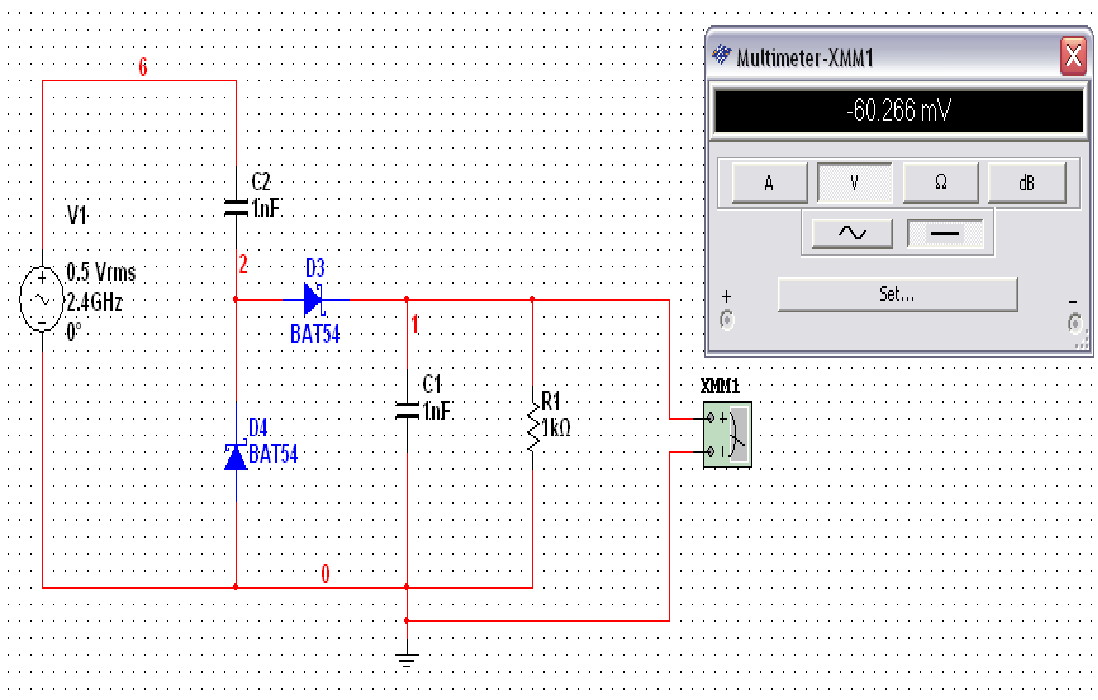


**Figure 18:** Single Stage Charge Pump with Schottky Diode: BAT54

From the results obtained, it was observed that Shottky Diode *BAT 63* gives the best output Voltage which is 867.322 mV. *BAT63* is Silicon Schottky diode (low barrier and can be used up to GHz frequencies) and manufactured by *SIEMENS* and *Infineon* technologies. *BAT63* datasheet is shown in APPENDIX B.

**Test 2:** Increasing the charge pump stages using BAT63 Diodes and 1 nF.

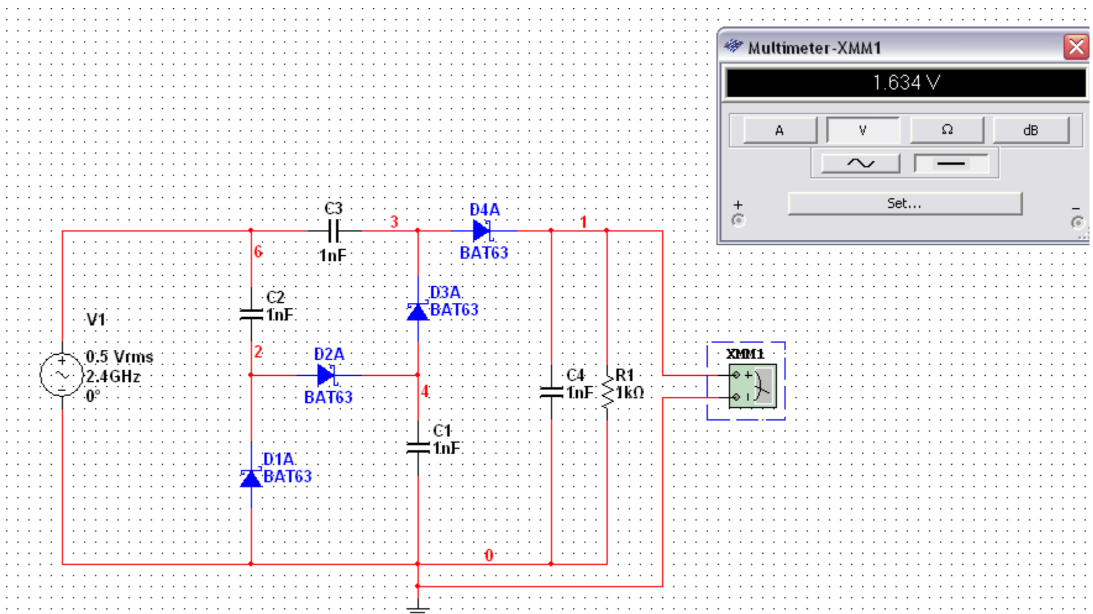


**Figure 19:** 3-Stage Charge Pump circuit

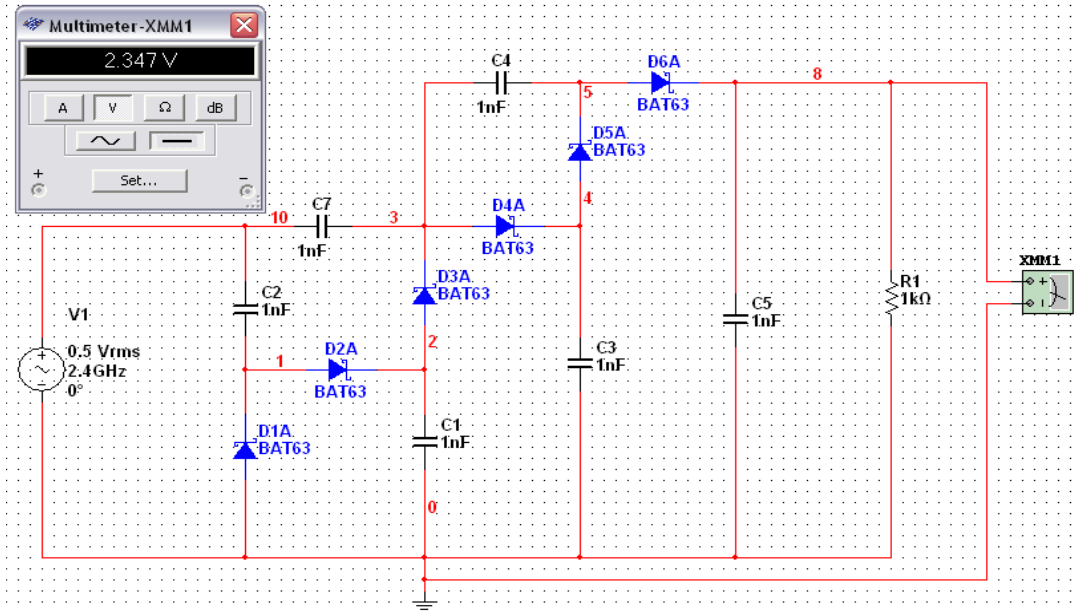


**Figure 20:** 5-Stage Charge Pump circuit

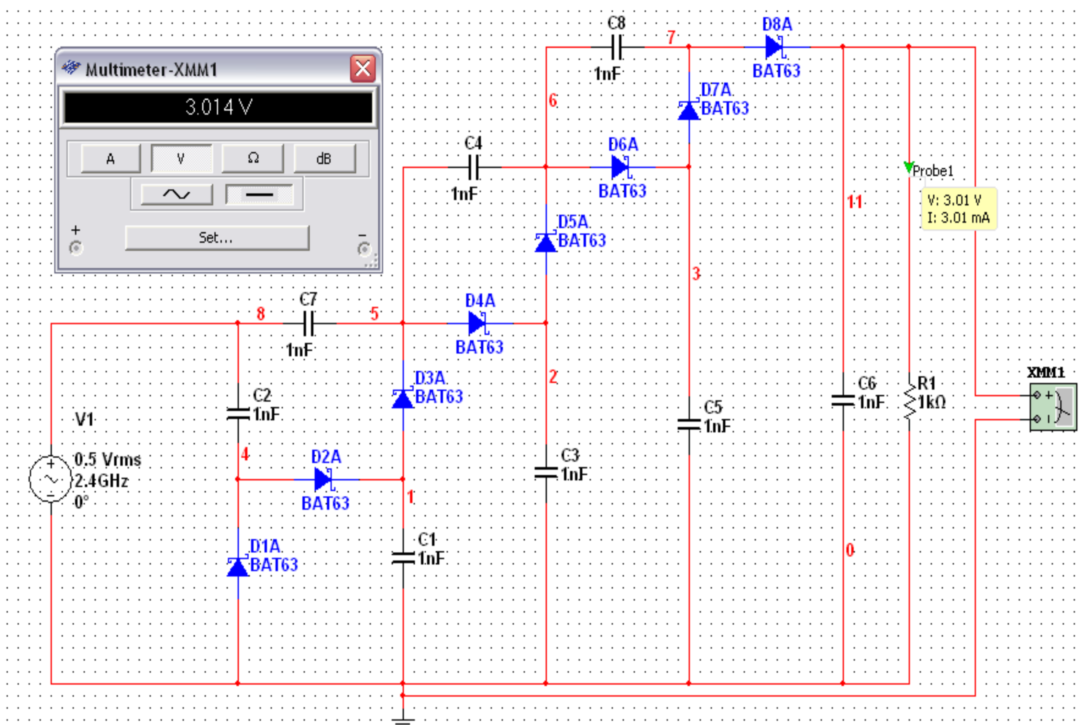


**Figure 21:** 7-Stage Charge Pump circuit

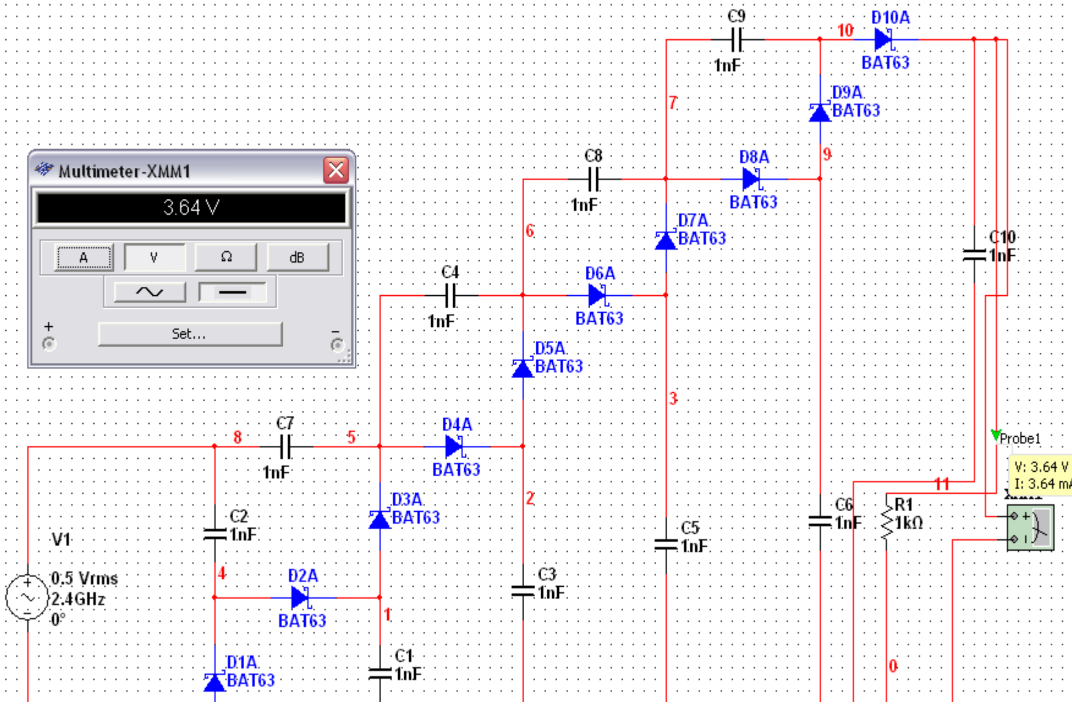


**Figure 22:** 9-Stage Charge Pump circuit

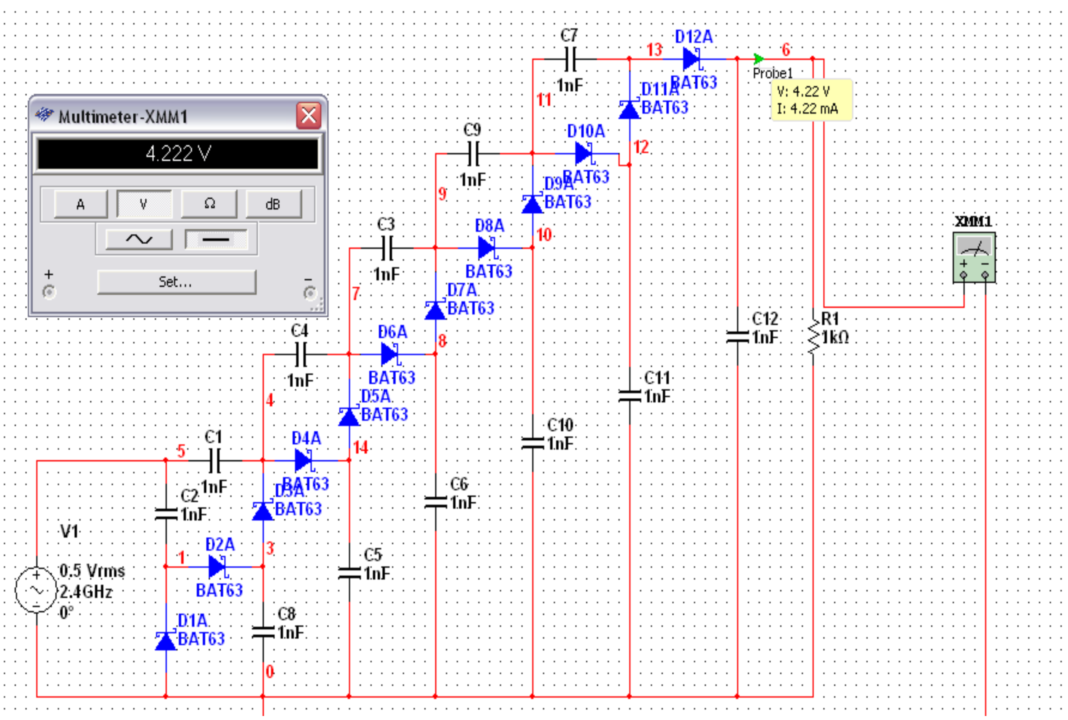


**Figure 23:** 11-Stage Charge Pump circuit

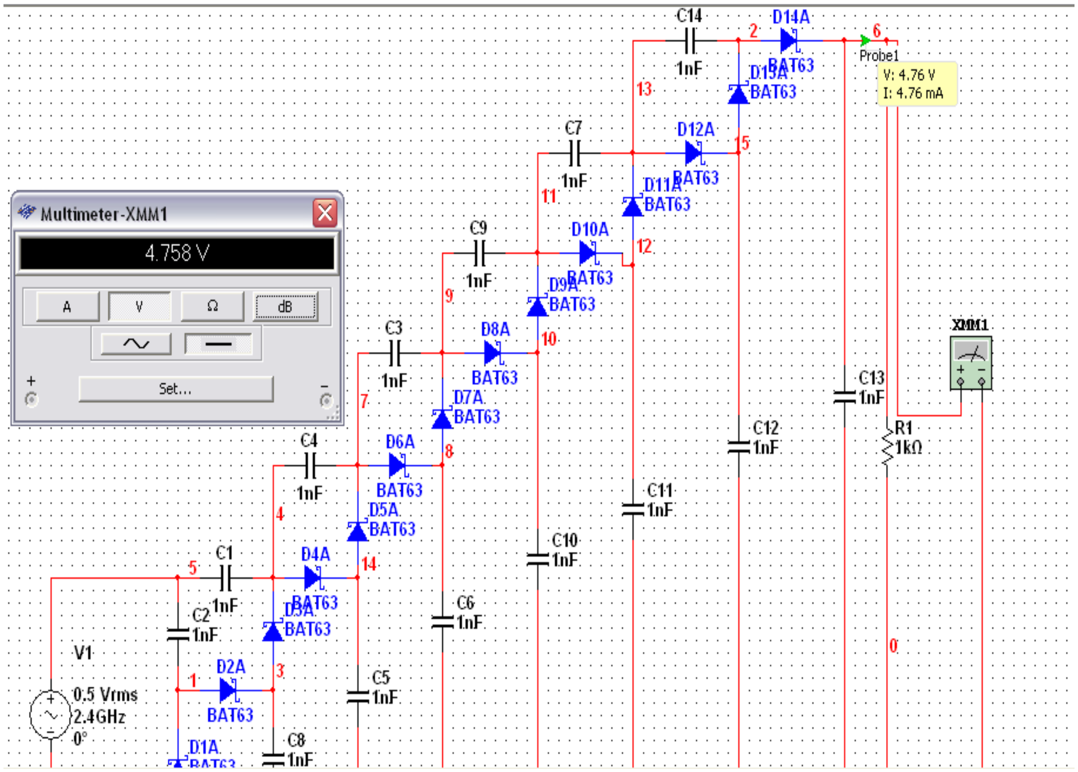


**Figure 24:** 13-Stage Charge Pump circuit

From the simulation results obtained, it was observed that the output voltage increases as we increase the number of stages of the charge pump. 7-stage, 9-stage, 11-stage, and 13-stage charge pumps produced a satisfying output voltage that is suitable to charge the third subsystem. However, as the number of stages increases, the size of the rectification circuit increases.

**Table 1:** Stages Number Effect on the output Voltages

| No. Of Stages | Vout (V) |
|---|---|
| 1 | 0.867 |
| 3 | 1.634 |
| 5 | 2.347 |
| 7 | 3.014 |
| 9 | 3.64 |
| 11 | 4.222 |

**Test 3:** The rectification circuit was simulated several times using different values of capacitors. The results proved that 1 nF, 750 pF, and 560 pF give the best output. The simulation results are shown in APPENDIX C.

**Table 2:** Stage Capacitor Effect on output Voltage

| Capacitor Value (F) | Vout(V) |
|---|---|
| 1 u | 0.419 |
| 470 n | 0.711 |
| 100 n | 1.789 |
| 1 n | 3.014 |
| 750 p | 3.004 |
| 560 p | 2.991 |

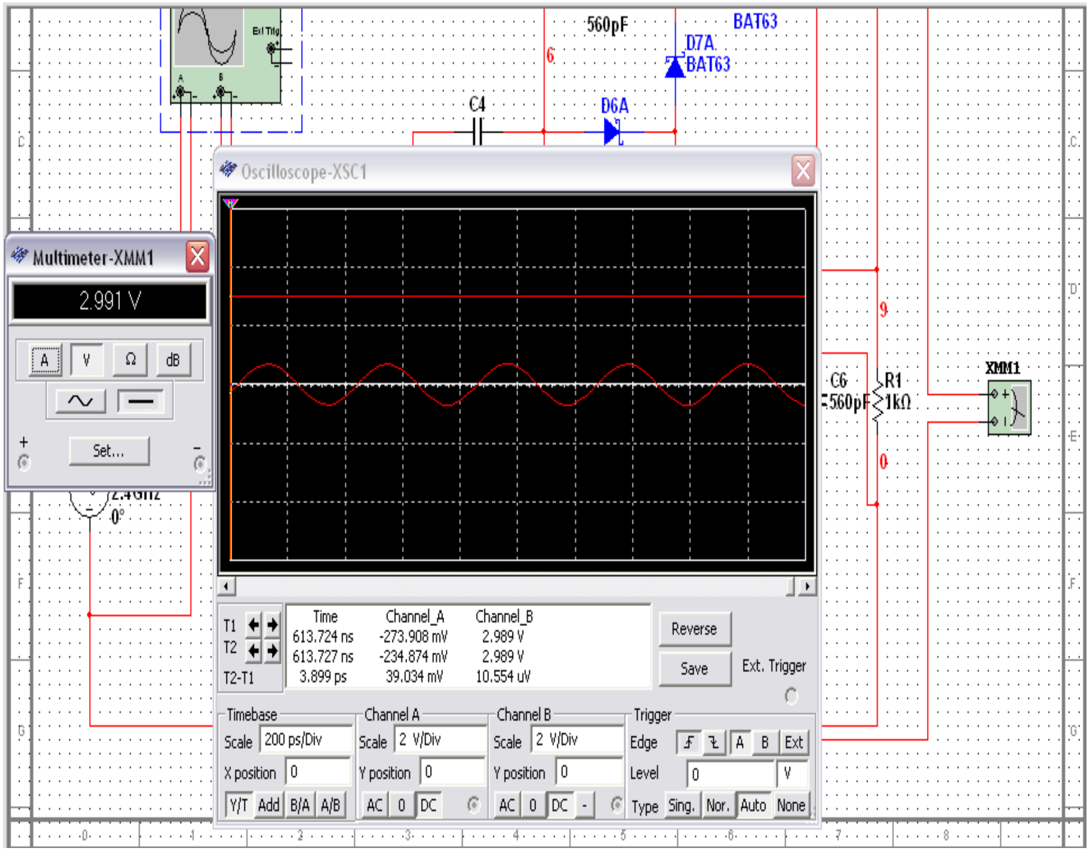


**Figure 25**: 7-Stage charge pump with 560 uF capacitors

**<u>Test 4:</u>** Different values of the input voltage were simulated to determine to what extent the system is valid to harvest the RF Energy transmitted.

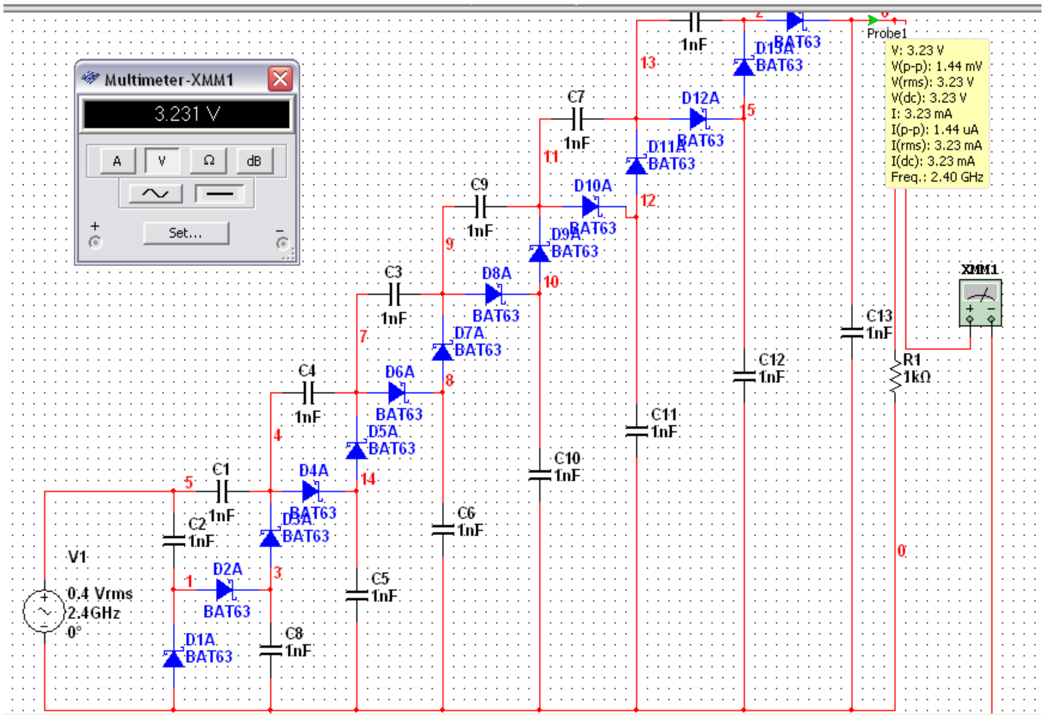

**Figure 26**: 9-Stage charge pump with 0.4 Vrms input

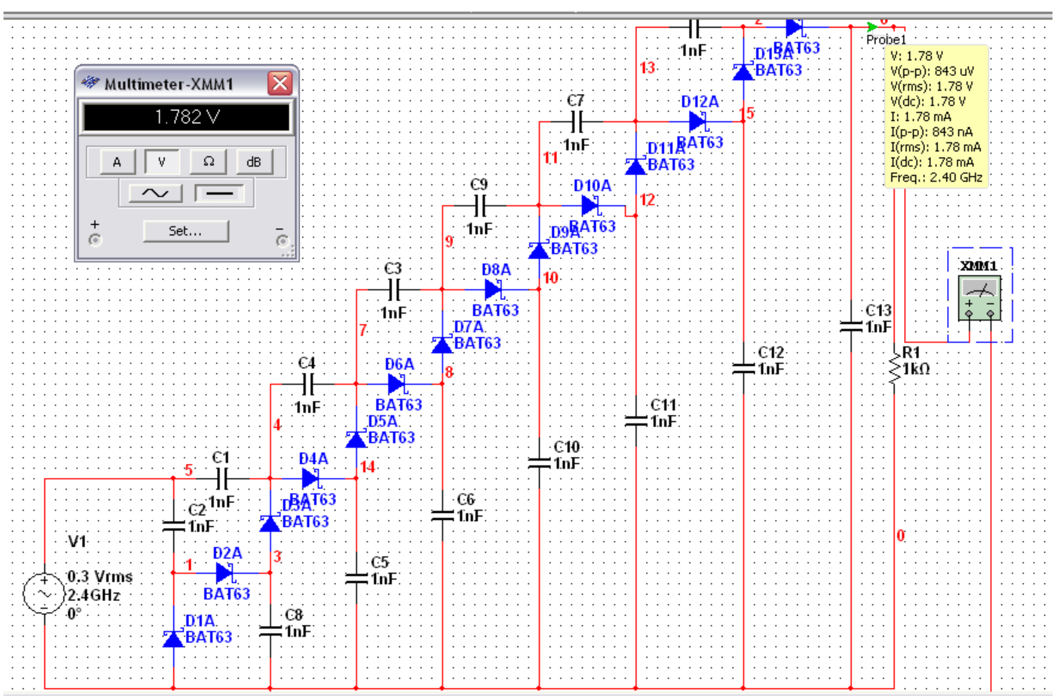

**Figure 27**: 9-Stage charge pump with 0.3 Vrms input

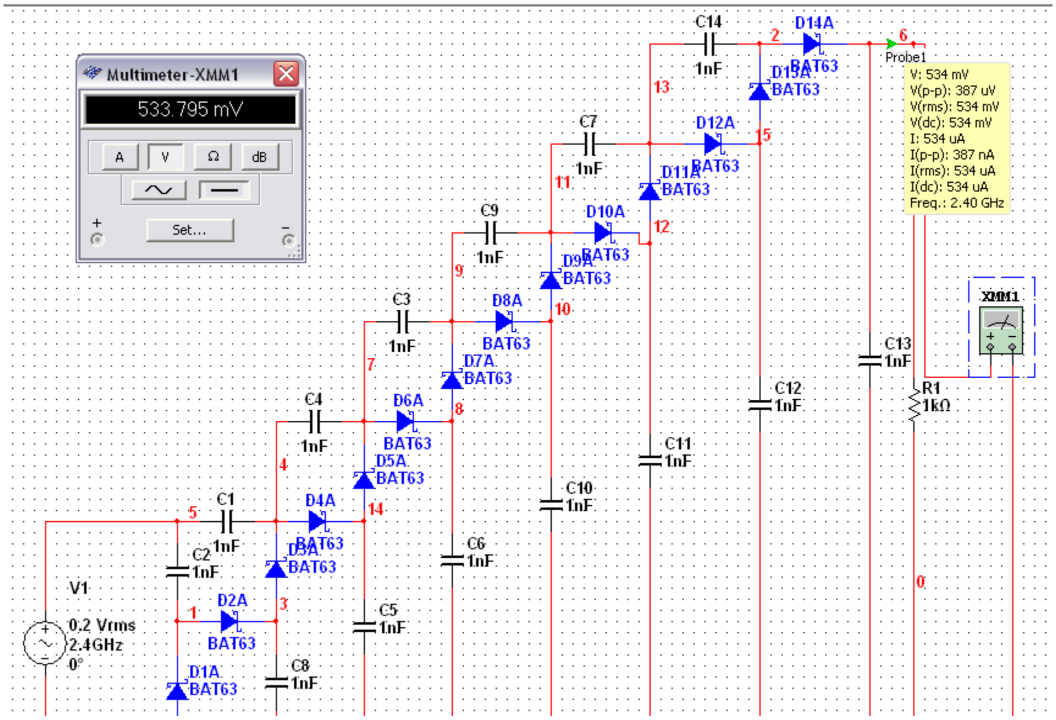


**Figure 28**: 9-Stage charge pump with 0.2 Vrms input

It can be concluded from test 4 that as the input voltage drops below 0.3Vrms and becomes 0.2 Vrms, the output of the charge pump becomes insufficient.

### 4.3. Antenna Design

The antenna subsystem provides the input for the rectification circuit. A monopole antenna is used to capture the RF Energy at 2.45GHz and deliver that alternating current produced by the incident wave to the Charge Pump to be rectified and multiplied. A monopole antenna basically consists of a piece of copper wire with one end connected to the circuit, and the other end left open. As discussed in the CHAPTER 2 it requires a ground plane in order to operate properly. It was decided to begin the experiment with a simple quarter wave monopole antenna.

A quarter wave monopole is a ground plane dependent antenna that must be fed single-ended. The antenna must have a ground plane to be efficient, and ideally the ground plane should spread out at least a quarter wavelength, or more, around the feed-point of the antenna. The size of the ground plane influences the gain, resonance frequency and impedance of the antenna.

To calculate the length of a quarter wave monopole antenna:

$$f = 2.45\text{GHz}$$

$$c = 3 * 10^8 \text{ m/sec}$$

$$\lambda = c / f$$

$$= \frac{300\text{ M}}{2.45\text{G}}$$

$$= 0.1224\text{ m} = 12.24\text{ cm}$$

Therefore a quarter wave monopole antenna would have the length of (0.25 * 12.24) = 3.06 cm.

Taking into consideration the demand for small size, this quarter wavelength monopole antenna can be implemented on PCB. A printed quarter wavelength monopole antenna can be tuned simply by slight changes in length. The antenna should be fabricated on standard FR4 printed circuit board (PCB).

The length of the monopole PCB trace mainly determines the resonant frequency of the antenna, but because of the very wide gain bandwidth of a quarter wave monopole, the antenna length is not too critical. But like any other antenna types, the gain of a quarter wave monopole will vary if parameters in the surroundings, such as case/box materials, distance to the ground plane, size of the ground plane, width and thickness of the PCB trace are varied. If any of these parameters are changed, a retuning of the monopole PCB trace length may be necessary for optimum performance in each application.

The antenna is fabricated on a standard FR4 substrate material with a typical dielectric constant $\varepsilon_r$ of 4.4 at 2.45GHz. The width of the monopole trace is W = 1.5mm. The wavelength in free air is $\lambda_o$ = 122mm. It may be approximated that the guided wavelength $\lambda_g$ on the FR4 substrate is

$$\lambda_g = 0.75 \cdot \lambda_o = 0.75 \cdot 122\text{mm} = 92\text{mm}.$$

The approximate, physical length of a printed quarter wave monopole antenna is then L = 92mm / 4 = 23mm

Provided that the size of the available ground plane is close to the ideal as discussed above and that the antenna trace is uniformly surrounded by the FR4 substrate. When implementing the monopole as a trace on the PCB, the length of the trace should be extended somewhat to allow for some fine-tuning of the antenna to resonance at 2.45GHz. If the size of available ground plane is approaching the ideal size and the antenna trace is uniformly surrounded by the FR4 substrate, then the length of the trace should be extended by about 20%.

# CHAPTER 5
# CONCLUSION AND RECOMMENDATIONS

Nowadays there is an active research area that is investigating a number of alternatives to extract energy from the environment and convert it to electrical energy that can be used to power an electronic device. Moreover, it is expected that energy harvesting will have a very important role in future microelectronic devices for a number of reasons: First, it is possible to increase the generated energy using new transducer designs or new materials, as well as innovative power conditioning circuits and energy storage elements. Also, the combination in the same device of several energy harvesting strategies will increase its capabilities to obtain energy in different situations. However, with the comparison between past evolution of batteries and electronic technology, it is in the part of electronic consumption that there are more possibilities to close the gap between generated and spent energy.

Electronic technology will continue its evolution of decreasing energy consumption thanks to continuing scaling down of devices, nanotechnology and eventually, molecular electronics. New processing and communication techniques will also help reducing power consumption. Finally, the trend of increasing mobility and autonomy of electronic devices has a natural step in the energetic independence from the user.

This project will be focusing on finding a way to harvest Radio Frequency Energy which is expected to play a major role in delivering power to several electronics wirelessly either by direct or indirect ways.

At the end of FYP I, the system was implemented using a monopole antenna and a charge pump composed of normal diodes found in the university. 315MHz and 430MHz transmitters were purchased and used to transmit the energy in order to test the rectification circuit and find whether it can harvest the transmitted energy through the antenna and deliver it t a connected load. However, the efficiency of the system was very low and it was decided to redesign the charge pump using different values of capacitors and different types of diodes. After finding the optimal values for the capacitors and the efficient type of the diode to be used, the circuit should be implemented on a PCB to maintain the efficiency of the system.

The prototype should be completed and tested by the delivery of the new components which were ordered online. It will be tested in different distances from the transmitter to determine the validity of the design.

Therefore it is recommended to provide more types and values of these components in the store in order to test the prototype in the early stages of the project so that there will be more time to work on increasing the efficiency and developing the system to reach the optimal performance.

It is recommended as well to have HFSS (High Frequency Simulation Software) so that the whole system can be simulated including both the antenna and the charge pump in high frequencies.

In addition there should be collaboration between UTP and some universities in US and UK which are working on developing this field of Technology.

In conclusion, this project tries to achieve the true meaning of mobility of electrical devices by eliminating the need for centralized power sources and depending on the RF Energy existing in the air to charge these electrical devices

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# APPENDICES

# APPENDIX A
# RADIO FREQUENCY RANGE

| Name | Symbol | Frequency | Wavelength | Applications |
|---|---|---|---|---|
| Extremely low frequency | ELF | 3–30 Hz | 10,000–100,000 km | Directly audible when converted to sound, communication with submarines |
| Super low frequency | SLF | 30–300 Hz | 1,000–10,000 km | Directly audible when converted to sound, AC power grids (50–60 Hz) |
| Ultra low frequency | ULF | 300–3000 Hz | 100–1,000 km | Directly audible when converted to sound, communication with mines |
| Very low frequency | VLF | 3–30 kHz | 10–100 km | Directly audible when converted to sound (below ca. 20 kHz; or *ultrasound* otherwise) |
| Low frequency | LF | 30–300 kHz | 1–10 km | AM broadcasting, navigational beacons, lowFER |
| Medium frequency | MF | 300–3000 kHz | 100–1000 m | Navigational beacons, AM broadcasting, maritime and aviation communication |
| High frequency | HF | 3–30 MHz | 10–100 m | Shortwave, amateur radio, citizens' band radio, skywave propagation |
| Very high frequency | VHF | 30–300 MHz | 1–10 m | FM broadcasting, amateur radio, broadcast television, aviation, GPR, MRI |
| Ultra high frequency | UHF | 300–3000 MHz | 10–100 cm | Broadcast television, amateur radio, mobile telephones, cordless telephones, wireless networking, remote keyless entry for automobiles, microwave ovens, GPR |
| Super high frequency | SHF | 3–30 GHz | 1–10 cm | Wireless networking, satellite links, microwave links, satellite television, door openers |
| Extremely high frequency | EHF | 30–300 GHz | 1–10 mm | Microwave data links, radio astronomy, remote sensing, advanced weapons systems, advanced security scanning |

**APPENDIX B**

**SIMULATION RESULTS**

**Figure 29:** Single Stage Charge Pump with 1 uF capacitors

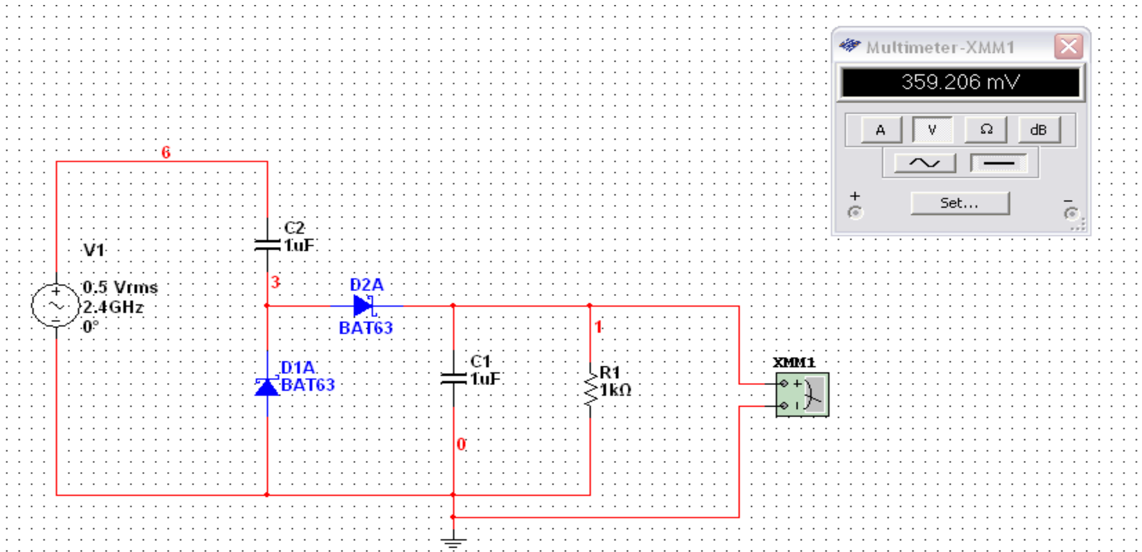



**Figure 30:** Single Stage Charge Pump with 1 nF capacitors

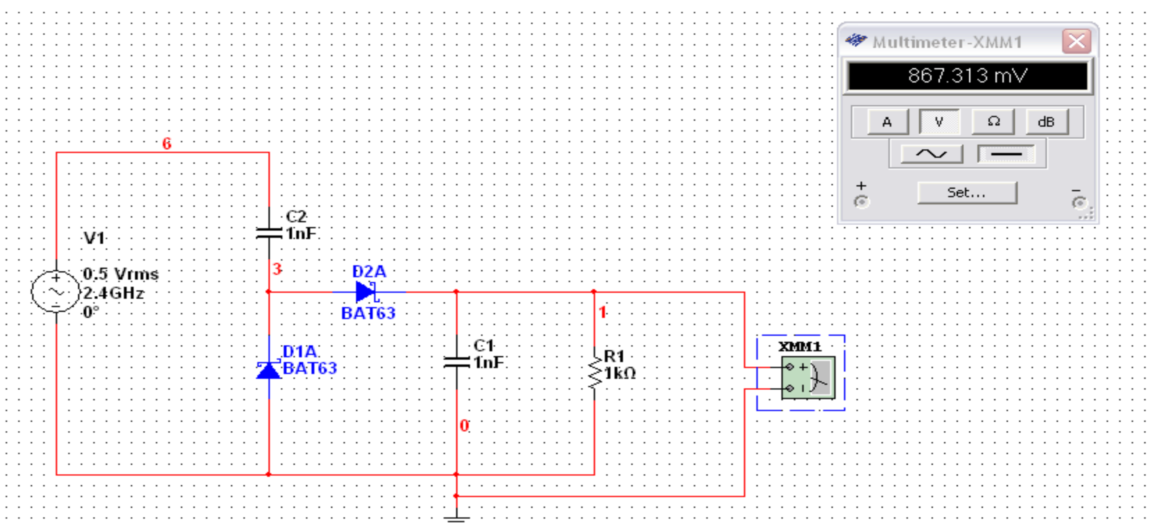


**Figure 31:** Single Stage Charge Pump with 750 pF capacitors

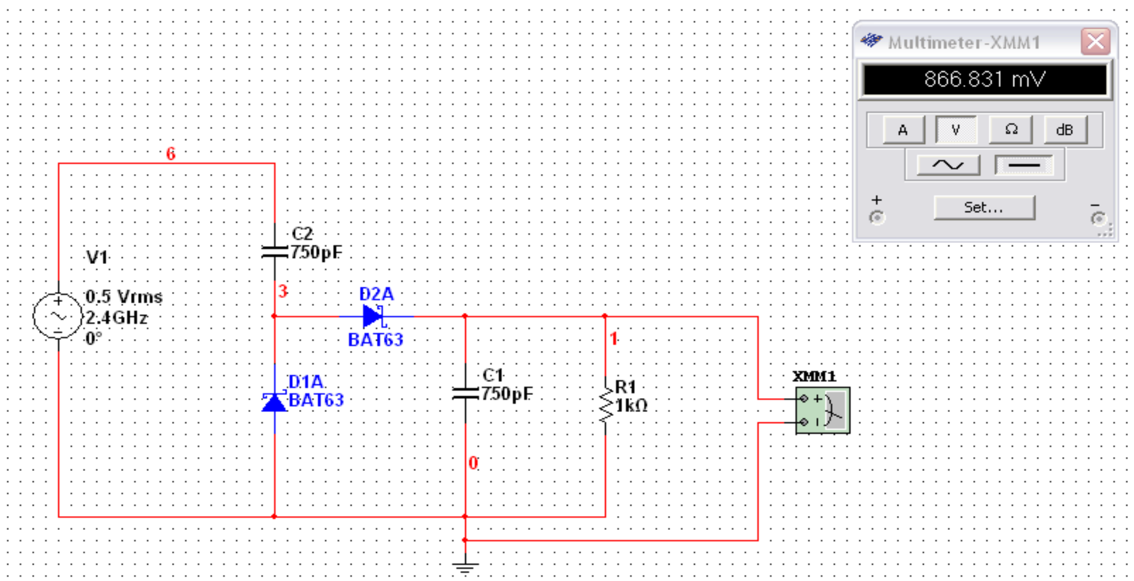
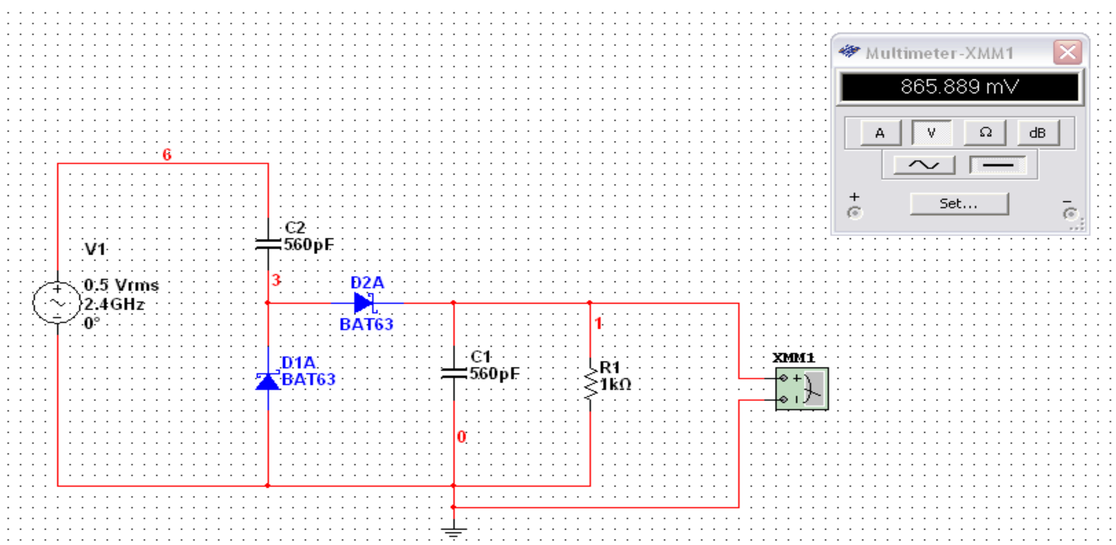


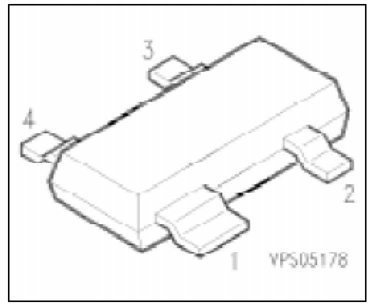

**Figure 32:** Single Stage Charge Pump with 560 pF capacitors



# APPENDIX C
# BAT63 DATASHEET

**Silicon Schottky Diode** **BAT 63**

- Low barrier diode for mixer and detectors up to GHz frequencies




| Type | Ordering Code (tape and reel) | Pin Configuration 1 | 2 | 3 | 4 | Marking | Package |
|---|---|---|---|---|---|---|---|
| BAT 63 | Q62702-A1004 | A1 | C2 | A2 | C1 | 63 | SOT-143 |

**Maximum Ratings**

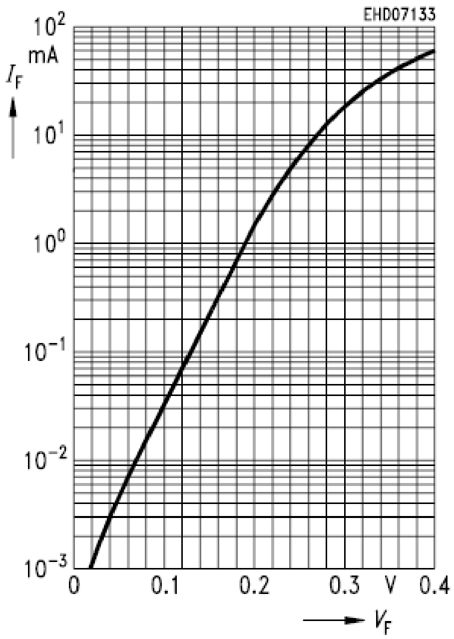
| Parameter | Symbol | Values | Unit |
|---|---|---|---|
| Reverse voltage | $V_R$ | 3 | V |
| Forward current | $I_F$ | 100 | mA |
| Junction temperature | $T_j$ | 150 | °C |
| Storage temperature range | $T_{stg}$ | – 55 … + 150 | °C |
| **Thermal Resistance** | | | |
| Junction-ambient[1)] | $R_{th\,JA}$ | ≤ 450 | K/W |

1) Package mounted on aluminum 15 mm x 16.7 mm x 0.7 mm.

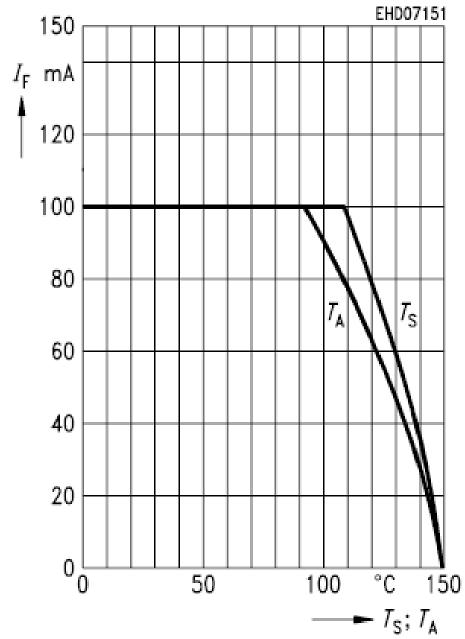
**Electrical Characteristics**
at $T_A$ = 25 °C, unless otherwise specified.

| Parameter | Symbol | Value | | | Unit |
|---|---|---|---|---|---|
| | | min. | typ. | max. | |
| **DC Characteristics** | | | | | |
| Reverse current<br>$V_R$ = 3 V | $I_R$ | – | – | 10 | nA |
| Forward voltage<br>$I_F$ = 1 mA | $V_F$ | – | 190 | 300 | mV |
| Diode capacitance<br>$V_R$ = 0.2 V, $f$ = 1 MHz | $C_T$ | – | 0.65 | 0.85 | pF |
| Case capacitance | $C_C$ | – | 0.1 | – | pF |
| Differential resistance<br>$V$ = 0, $f$ = 10 kHz | $R_0$ | – | 30 | – | kΩ |
| Series inductance | $L_S$ | – | 2 | – | nH |

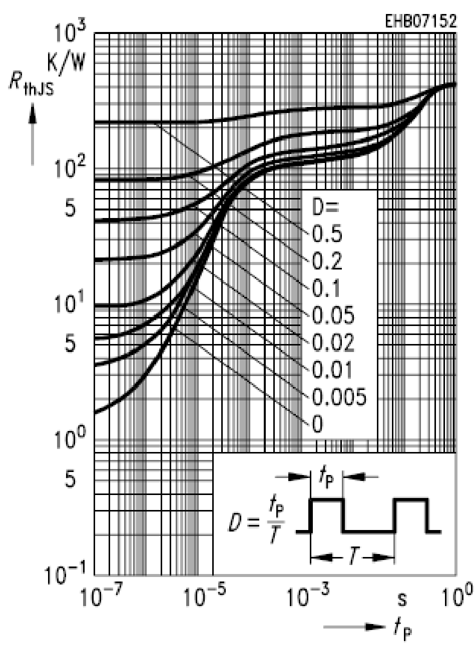
**Forward current** $I_F = f(V_F)$




**Forward current** $I_F = f(T_S; T_A)$




**Permissible Pulse load** $R_{thJS} = f(t_p)$




**Permissible Pulse load** $I_{Fmax} / I_{FDC} = f(t_p)$
$T_A$ = 25 °C