Electromagnetic Energy Harvesting

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ABSTRACT

Energy harvesting is the process of extracting energy from external sources (e.g. thermal energy, solar energy, wind energy etc). The process of “electromagnetic energy harvesting” in particular, harvests energy from ambient electromagnetic waves. Owing to the ubiquity of electromagnetic waves in the present era, this offers an effective, real time, portable, low power energy source that can lessen our dependence on rechargeable batteries.

Electromagnetic energy harvesting enables energy recycling by employing three subsystems. Firstly, we have the receiving antenna, with maximized power capturing capability. This antenna then feeds energy to the rectification subsystem, which converts the high frequency AC signal into DC. Last is the storage subsystem, which stores the harvested energy, and then provides a continuous voltage output. The storage system also acts as a backup, once the real time harvested energy is insufficient.

In this EM harvesting approach, energy has been harvested from multiple frequency bands, namely GSM 900, GSM 1800 and ISM band. Secondly, multiple element Microstrip patch antennas have been designed that maximize captured energy. For the rectification part, charge pumps have been utilized that both rectify and up convert the RF signal. For the storage subsystem, super capacitors with enhanced storage capacity, have been employed.

DECLARATION

No portion of the work presented in this dissertation has been submitted in support of another award or qualification either at this institution or elsewhere.

DEDICATION

This project is dedicated to our families, who have helped us throughout with their unwavering support, patience and prayers.

ACKNOWLEDGEMENT

This project would not have been possible without the help and guidance of several individuals who in one way or another extended their valuable assistance in the preparation and completion of this project.

First and foremost, our utmost gratitude to Dr. Farooq Ahmed Bhatti, whose sincerity and encouragement our group will never forget. He has been our inspiration as we have overcome all the hurdles in the completion of this project.

Secondly we would like to thank “FAB (Frequency Allocation Board)” who provided us with their monitoring vehicle that conducted an RF survey of our university campus.

We also would like to thank “Rhodes & Schwartz, Testing department” who throughout the course of our project gave us invaluable guidance.

Not to forget the support of “Rogers Corp” for providing us with the free sample of substrates “RT Duroid 5880” without their assistance we would not have achieved our desired goals. Our University Engineering students, who in one way or another assisted us especially whenever a bottleneck in our project was observed.

Last but not the least, our family and the one above all of us, the omnipresent God, for answering our prayers for giving us the strength to plod on despite our constitution wanting to give up, thank you so much Dear Allah

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ABBREVIATIONS USED

EM	ElectroMagnetics
RF	Radio Frequency
VNA	Vector Network Analyser
FAB	Frequency Allocation Board
H FSS	High frequency Structure Simulator
ADS	Adavance Design System
IEEE	Institute Of Electrical & Electronics Engineers
MW	Microwave

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the present era of telecommunication, EM waves have become ubiquitous. We are perpetually surrounded by EM waves, be them in any of their various forms. Radio signals, wireless internet (Wi-Fi), radar, mobile networks etc, are just a few of the services that rely on EM waves. Hence we are always surrounded by ambient energy that is ready to be tapped. By developing a system that extracts the energy of EM waves and converts it into DC, immeasurable utility for handheld portable devices has been obtained. We have strived to come up with an energy garnering setup that, once integrated makes portable devices self charging.

1.2 Background

Within the past decade, a wide range of wireless devices have been introduced that provide efficient and practical solutions to consumer, industrial, and military needs. Unfortunately, with existing technology, wireless devices are constrained by the amount of time they can be operated without rechargeable batteries. As a result, the usefulness of wireless devices, as well as their applications are restricted by relatively slow advancements in rechargeable battery technology. As a result, a clear market need exists that either allows wireless devices to operate for longer durations away from centralized sources or increases the amount of power that can be supplied to a wireless device. [1]

Furthermore, there exists a severe energy shortfall in our country, and there is a dire need to recycle all forms of energy. Although, the amount of energy in ambient waves is not sufficient enough to overcome the energy crisis, but still it provides a means by energy is reused. By reusing invaluable energy, we can lessen our energy consumption and hence conserve it.

Moreover, there exist locations where electricity supply is unreachable. However, these areas are still served by radio and cellular communications. For these areas EM harvesting can provide to be an alternate means to charge our portable devices.

Therefore, nowadays electromagnetic energy harvesting proves to be the preferred choice for remote and portable powering of low power devices.

1.3 EM Harvesting Applications

In the present age, of low power and portable consumer devices, the potential of EM harvesting is limitless. The power that scavenged from EM waves is available round the clock, is wireless and is ubiquities. These qualities lead to numerous applications of Electro Magnetic Energy Harvesting.

The most useful application is the wireless charging of the portable devices like mobiles, mp3 players, digital cameras, PSP`s, Laptops and likewise many other handheld low power devices. These systems can have an in built EM Harvesting system and there batteries would remain charged and topped up always. There would be no need to charge these devices daily and find electricity sockets. In a country like Pakistan which is plagued by load shedding, such invention would be of the utmost utility for the nation.

Furthermore in the technical world, Wireless sensor networks are used. They serve multiple purposes like weather logging, medical reporting etc. WSN's run on small batteries which need to be changed frequently. WSN's are often deployed in remote areas too, where battery replacement can be a problematic affair. With EM harvesting systems installed in WSN, their usability is enhanced tenfold. If our WSN is in an inaccessible region/ terrain, still it will work perpetually as it will have ambient energy as its power source.

A medical advantage of EM harvesting is the charging of pacemakers in heart. There batteries need to be changed with time and if not replaced these could prove fatal for human beings. Now rather than installing batteries in them, we can use EM harvesting. This would prove to be a non invasive method of powering up technological implants in the human body. Also all sorts of implanted biosensors can be wirelessly, remotely charged.

There has always been a concern about the radiation hazards of EM waves. EM harvesting is the best method for recycling these radiations and putting them to good use. Not only we are reducing the hazards of EM waves but instead we are utilizing it for our benefits.

In short EM harvesting has a great future and potential because of its small size, flexibility and mobility. On large scale manufacturing, the costs of EM harvesting devices would also rapidly decrease . All Low power devices can be powered by integrated EM harvesting systems increasing their life span and reducing maintenance expenditure. In a nutshell, EM harvesting promises countless advantages out of literally nothing at all.

1.4 EM Harvesting : Approach

The particular approach that has been adopted in this electromagnetic energy harvesting design, is based on subsystems. The overall system is subdivided into three constituents, which are then integrated to achieve the overall functionality. The following block diagram shows the EM harvesting design formed by its constituent elements.

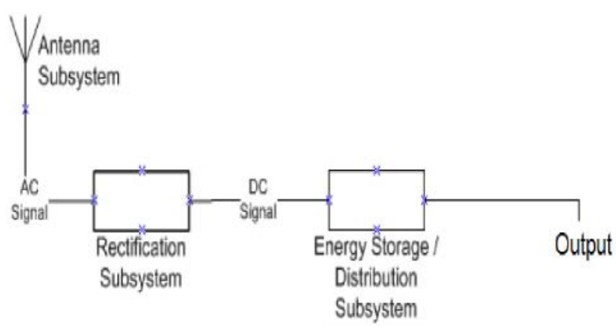


Figure 1 EM Harvesting Block Diagram

The three subsystems of the EM harvesting design are:

Receiving antenna subsystem

The receiving antenna is designed to capture the ambient RF energy. The goals of antenna design are to firstly maximize the amount of power captured and secondly, to provide the captured power to the next subsystem with minimal amount of losses.

Rectification subsystem

The rectification subsystem is for converting the high frequency AC signal captured by the antenna, into DC. Since the energy content in EM waves is in the form of high frequency AC signal, we need to rectify it into DC, so that it is useable for electronic devices. Hence, an efficient and fast rectification system is very important.

Storage subsystem

Owing to the varying and inconsistent amplitude of ambient EM waves, we cannot always ensure that sufficient harvestable energy will be present. For this the EM harvesting design, also incorporates a storage and distribution system, which is supposed to act as a temporary backup power solution for cases when the real time harvested energy is insufficient. The design goals here are to have minimal losses, and minimum leakage of stored energy.

In this subsystem oriented approach, the integration is of utmost We need to ensure that the system is optimally connected and a ll connecting joints junctions are lossless. Once integrated, the system can both harvest and store electromagnetic energy.

1.4 Objectives

The objectives of this EM harvesting design are

To maximize the amount of ambient harvestable energy

To ensure that the losses in the system are minimum

To work towards designing a system that is manageable in terms of size and portability

To ensure that costs are kept to a minimum

To ensure easy integration with electronic devices

CHAPTER 2

DEVELOPMENT OF PREMISE

2.1 Literature Survey

There exists a reasonable amount of published research relating to EM harvesting. IEEE has many publications on the potential and various design approaches of EM harvesting. A comprehensive treatment of the subject is found in [Hamid Jabaar] who investigates the general potential of EM harvesting designs and circuitry. Similarly advanced methodologies have been explored in [Triet Le] by Triet Le. [booucchia] showcases work presented in a conference on renewable energy sources in Spain and explores different antenna types to extract maximum power. Besides research papers, there exists a undergraduate implementation of ambient energy scavenging by students at the university of San Diego California[1]. Furthermore, a master's level dissertation has been written by a student of university of Pittsburgh who explores the potential of EM harvesting for wirelessly and remotely charging cell phones [2]. Complete integration of cell phones charging appliances with ambient energy scavenging devices has also been presented. Due to the increased need to power, portable electronics remotely, and to lessen our dependence on rechargeable batteries, substantial research is being carried out in the field of EM harvesting.

Significant points that have repeatedly surfaced in published research are

The need of a multiple element antenna, high gain antenna ,to capture EM energy [3]

The need of a rectification system that operates efficiently and with minimal losses at high frequencies

Cellular network bands as offering more power density than other frequency bands [4]

In lieu of the above mentioned points which are highlighted in many publications on EM harvesting, the best approach has been decided upon.

Links for further reading and related literature regarding the subject is presented in the appendix.

Prior to the design of the individual subsystems that comprise the EM harvesting design, some details had to be finalized. Based on these fundamental details, the rest of the EM harvesting system is designed. The most important decision was that what frequency bands should energy be harvested from.

EM energy and EM waves occupy the complete electromagnetic spectrum.

Figure 2 Electromagnetic Spectrum

We obviously cannot harvest energy from the entire frequency spectrum, because our harvesting system like any electronic system has a certain frequency bandwidth on which it ideally operates on. Therefore, we had to select a definite frequency band from which energy is to be scavenged. For this, there were two main deciding factors.

1) Power density in the frequency band is maximum
2) The antenna size and type are both manageable at the selected frequencies.

Keeping in mind the first factor, thorough research was done through internet, published material, and experts in the professional field, as to what frequency band has the maximum ambient EM energy. According to WHO, commercial FM radio, and commercial VHF video transmission offer the maximum energy. However, these do not prove to be adequate harvestable frequencies, since the antenna size at such RF frequencies can be large. Furthermore, at these frequencies recent antenna technologies like Microstrip patch antennas could not be used. 100-600 MHz frequencies do not allow us use of patch antennas, as their dimensions become unmanageable large.

Further research revealed that the cellular mobile network frequencies, offer both a substantial amount of RF energy, and also have frequencies that permit practical antenna sizes. Furthermore, in the university campus, we have a “UFONE GSM” BTS operating in the 900 MHz band and so the GSM 900 band was selected. Also the other GSM band, i.e. the 1800 MHz band was also selected. This had the same advantage of high energy content at a reasonable antenna size. To further establish our theoretical findings we wanted to practically carry out an RF survey of our college. However our college laboratory equipment was lacking in this regard. No RF meters were available. So for this purpose, we established a correspondence with “frequency allocation board (FAB)” to assist us in determining the best frequencies to harvest. We requested our university administration to request the monitoring vehicle from FAB which is capable of determining the powers being transmitted in the spectrum. The range specification of this monitoring vehicle was from 0 to 3 GHz. It is used to measure the Received power level on this frequency range from an omni directional antenna.

2.2 FAB MONITORING VEHICLE SURVEY

On 4th May, 2011 MR Salman Assistant Director with FAB Monitoring vehicle came to MCS, for the RF Survey. Detailed readings were obtained at different locations in our university. The collective summary of the result has been tabulated.

S/No	Frequency	Received Power level
1	100 MHz	-65 dBm
2	400 MHz	-60 dBm
3	2.42 MHz	-69 dBm
4	944.4 MHz	-53 dBm
5	1817 MHz	-62 dBm

According to the RF survey it is clear that the highest energy component is at 944.4 MHz which comes from a 900 GSM cellular operator, Ufone, whose BTS is located in the backyard of our university. The second highest component was at 1817 MHz which lies in the 1800 GSM range.

By results of the monitoring vehicle, we discovered that our university also has strong power density in the 2.4 GHz WIFI band. A number of routers are installed in each building of MCS campus and this provides sufficient ambient energy in the whole university area.

These findings made us decide on the eventual frequency bands we are going to work on. Furthermore, this survey also pinpointed to us the frequency peaks that occur within these bands. This is important since we need to decide the exact resonant frequency of our antennas and subsequent matching networks. The final operating frequencies were

Frequency Band	Frequency Peak	Bandwidth Requirement
GSM 900	944.4 MHz	20 MHz
GSM 1800	1817 MHz	20 MHz
WI-FI 2.4	2.417 GHz	20 MHz

~~*Source:* FAB Monitoring Vehicle Results 4th May 2011~~

After selection of the frequencies to harvest, we proceeded to design the three subsystems.

CHAPTER 3

DESIGN OF ANTENNA SUBSYSTEM

3.1 Antenna Type

Since the fundamental requirement of our design is portability and compactness, the antenna type we chose to use is microstrip patch antenna. Many types of antennae are available, but we did not choose them since all of them have disadvantages we cannot afford to have. For instance

Yagi-Uda Array: High size, difficult integration, old technology

Horn Antenna: expensive, large size, difficult integration

Monopole/ Dipole: Varying lengths, difficult handling, difficult integration etc

The antenna that is most suited to our requirement is indeed Microstrip patch since it provides us the following advantages [5]

Small size

Low manufacturing and equipment cost

Ease of installation

Aerodynamic profile

Versatile in terms of selecting resonant frequency and impedance

Besides all this advantages, Microstrip patch antenna also offers an added advantage of being of manageable size in our frequencies. It is a rule of antenna theory, that the antenna size is directly proportional to wavelength and the wavelengths we are operation on are conducive to design of Microstrip patch antennas.

3.2 Design Of GSM 900 Antenna

The antenna that was to be designed in the GSM 900 band had to have its exact resonant frequency as 944.4 MHz. It is a fact of antenna theory, that the captured power by an antenna is directly proportional to its effective area, which in turn is directly proportional to its

[redacted]

[redacted]

These two equations show us the relationship between received power and effective area. Equation one tells us that in order to maximize the received power Po, with incident power P, effective area should be high [Wikipedia]. The second equation tells us th at to maximize effective area, we need to maximize antenna gain. So the overall conclusion is that in order to increase the received power, we need to maximize the antenna gain.

There exist numerous methods to increase the gain of Microstrip antennas [ga in enhancement]. However the method we proceeded to use is design of an array antenna, owing to its simplicity, inexpensiveness, and ease of fabrication.

3.2.1 Single element antenna design

In designing an array the first step is to design the single elem ent patch antenna. The substrate we are using is “Rogers RT Duroid 5880”. It is by far the most superior performing laminate in the industry, with extremely low loss and permittivity [data sheet]. The thickness that we are using for the GSM 900 antenna is 3.175mm. As a general rule, thicker substrates offer higher bandwidth and hence are preferable for antenna designing [Balanis]. 3.175mm is the maximum thickness substrate that is offered by Rogers Corporation. According to the formulas given in [5] we obtain the following dimensions for the single patch.

3.2.2 Design Specifications:

Height	Permittivity	Resonant Frequency
	2.2	944.4 MHz

Calculated dimensions:

Length	Width
10.56 cm	12.56 cm

Next proceeds the design of the feed method of the antenna

3.2.3 Designing Feed of antenna

Generally there are two types of feeding methods for a microstrip patch antenna [6].

- Microstrip feed line
- Coaxial feed

The feed method we have used for our design is the microstrip feed line. Its main benefit is that it allows for very easy integration with electronic circuits. Furthermore it also has an enhanced bandwidth than the coaxial method.

To optimize antenna performance, it is very important that our antenna is properly matched to the feed line. The characteristic impedance we are using for the transmission line is and have to match with is

$$Zo=50$$

The edge impedance for our patch is 144 ohms for design. Therefore to ensure that the return loss and the reflection coefficient was kept to a minimum, it had to be determined that point on the antenna where the impedance is same as the transmission line impedance of 50 ohms. For this we use the inset feed method given in [5]. By this we extend the feed line to within the patch antenna, where a point of 50 is reached. The width Wo and separation between inset feed and patch is kept the same to keep the resonant frequency constant. The width Wo is calculated for a 50 ohm transmission line using formulas given in [7]. All the calculations were verified by Microstrip calculators online. [8]

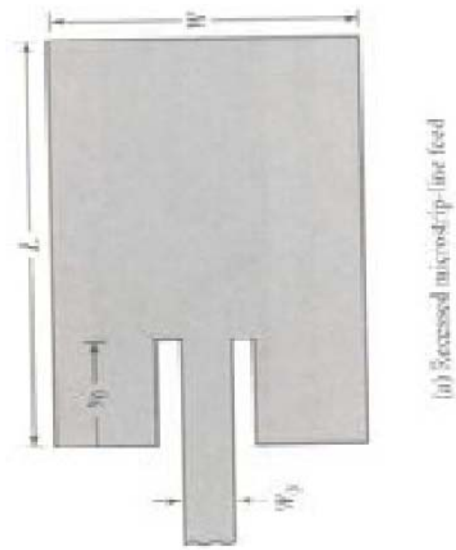


Figure 3.1 Inset fed antenna

The Microstrip patch antenna was simulated using both HFSS and ADS.

3.2.4 Optimizing Antenna

The return loss of our antenna simulations was satisfactory, but not very good. To improve on the return loss we needed to improve the quality of our match. The basic concept behind inset feed is that, the 50 ohm point within the body is located by using the inset. A return loss of less than -20 here shows that the 50 ohm point has not been accurately located. So we had to vary the offset length to locate the exact 50 ohm point to obtain the best match.

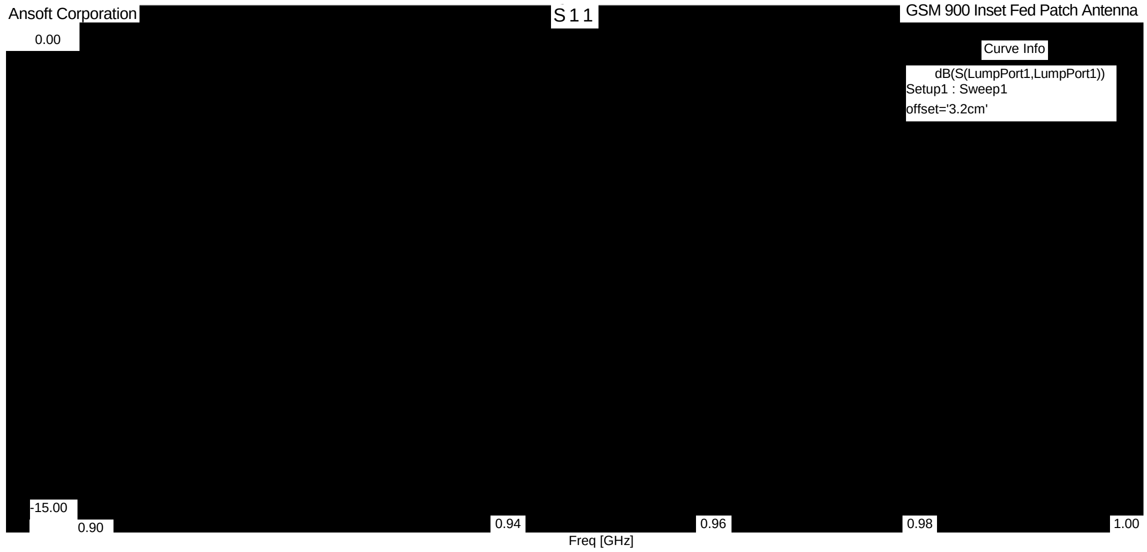
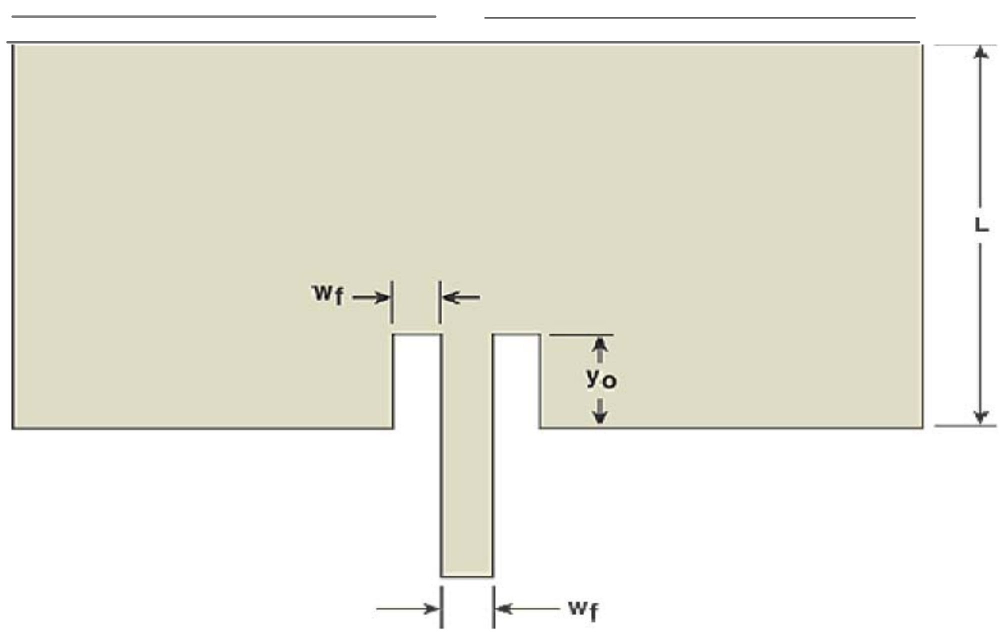


Figure 3.2 Return Loss at calculated dimensions

The offset/inset distance is portrayed in the following figure



1. The basic parameters for a microstrip-line inset-fed patch antenna, include width (W), length (L), and distance of feed line from the edge (y0).

Figure 3.3 Parameters for inset fed antenna

The Yo we have calculated is according to the formula given in [Balanis].

Calculated **Yo = 2.53 cm**

However as our simulations showed, the exact 50 ohm point had not been located. So to improve the match we employed the feature of HFSS known as optimetrics.

3.2.5 Optimetric analysis of antenna in HFSS

HFSS has a package known as “optimetrics” which allows the designer to repeatedly vary some value or parameter of its design and repeatedly see the results. A variable ‘offset’ was assigned to the distance Yo.

It was decided to vary the value of this variable from 2.3 cm to 3.3 cm and see whether we obtain better results at some other value of Yo, than the calculated one.

Figure 3.4 Effect of varying offset distance on resonant frequency

As evidenced in the graph, by varying the offset distance in small steps, different values for the return loss are obtained. This in turn tells that the quality of match at the junction is being changed, which further tells us that the 50 ohm point is being better located.

Amongst these graphs, we see that the return loss has its minimum value of -44 dB and it is at the value of 2.9 cm. This is the best value amongst the shown return losses and hence 2.9 cm offset length is selected in order to maximize the energy transfer from the feed to the antenna.

3.2.6 Adjusting Resonant Frequecny

At the initial simulation, the resonant frequency of the antenna was displaced. At the calculated value of length, the resonant frequency was incorrect correct. For this purpose, optimetric analysis was applied on the length of the antenna; L, until the correct resonant frequency was obtained. When the right frequency and match was obtained, the length and offset parameters was finalized. The following graph shows optimetric analysis on the length

Figure 3.5 Effect of varying offset distance on resonant frequency

Using the simulation results, the single element antennas dimensions were finalized, with fixed resonant frequency and return loss.

3.2.7 Array Design GSM 900

In designing an array antenna the most important factor is the number of elements. As the number of elements would increase, so would the effective area. However, since one of the fundamental design objectives was to keep the overall size of our system manageable, the number of elements cannot exceed a certain value. This is a very important trade off throughout the design.

Since the size of the single element patch antenna is not very small, we cannot afford to go to more than two elements. The wavelength is also sufficiently long, and hence the optimum amount of elements that were decided upon our two. These two elements are arranged in a corporate feed network.

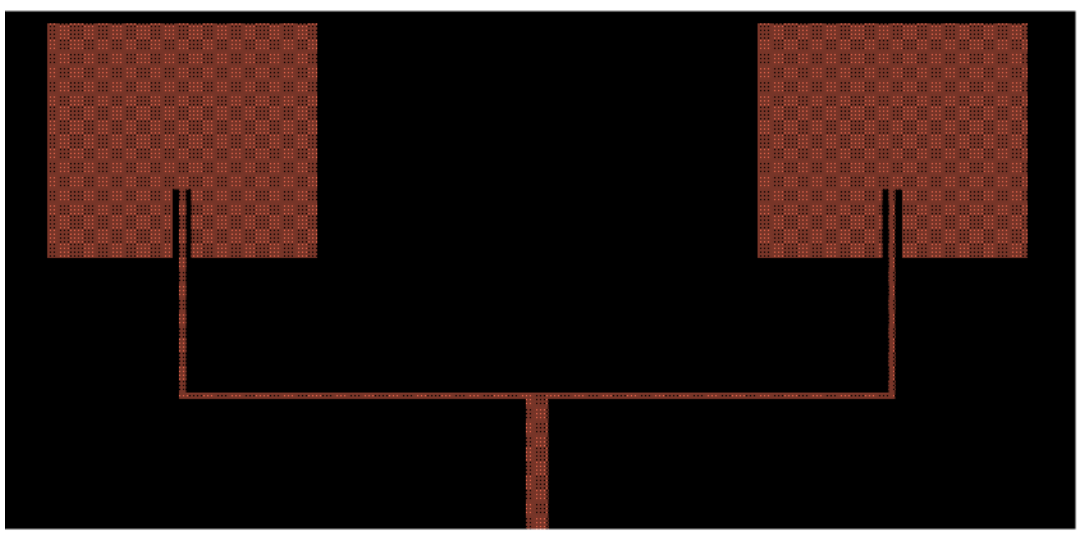


Figure 3.6 1 x 2 Corporate Fed Array GSM 900

The element spacing used was one free space wavelength edge to edge between the elements.

The matching network of the array is very intricately designed.

1. Firstly the patch elements are inset matched at 100 ohm point.
2. The 100 ohm line is connected at its centre with a 50 ohm line.
3. Since the impedance at the centre of a transmission line is halved, the 100 ohm and the 50 ohm lines are matched automatically at the 100 ohm lines junction.
4. The 50 ohm line is matched perfectly with connection to the 50 ohm SMA connector.

This step by step matching network gives a simulated return loss in ADS as

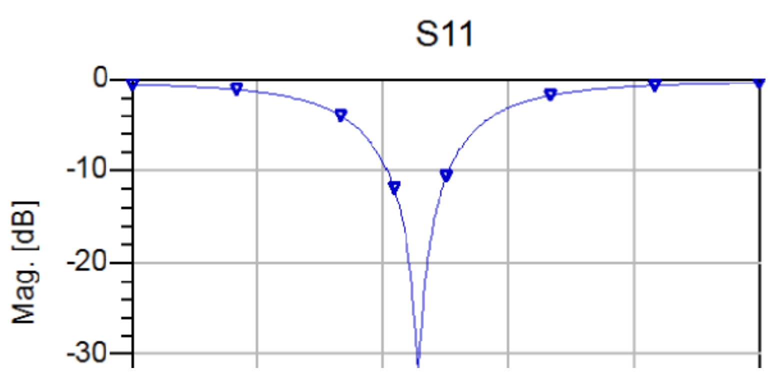


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Figure 3.7 Array Return Loss

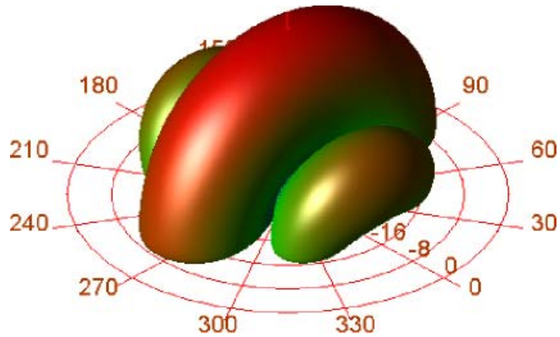


Figure 3.8 Array 3D Radiation Pattern

The gain of the antenna came out to be 10.3 dBi. The overall simulation results are tabulated

Geometry	1 x 2
Radiation Pattern	Moderately directional
Maximum Gain	10.3
Return Loss	-32 dB
Impedance Bandwidth	12 MHz

3.3 Array Design GSM 1800

The second antenna that needed to be designed was for the GSM 1800 band. The substrate that was selected was again Rogers RT Duroid 5880, for its superior performance characteristics. However the thickness at this frequency was 0.787mm. The reason for this thickness was to ensure more manageable and thinner transmission line widths. The gain enhancement technique decided here was again using a multiple element array. Since the wavelength is smaller in the GSM 1800 band, the antenna sizes are smaller and more manageable. This allows us freedom in selecting more number of elements. The number of elements chosen, hence are four, with the geometry being 1 x 4, in a corporate fed network.

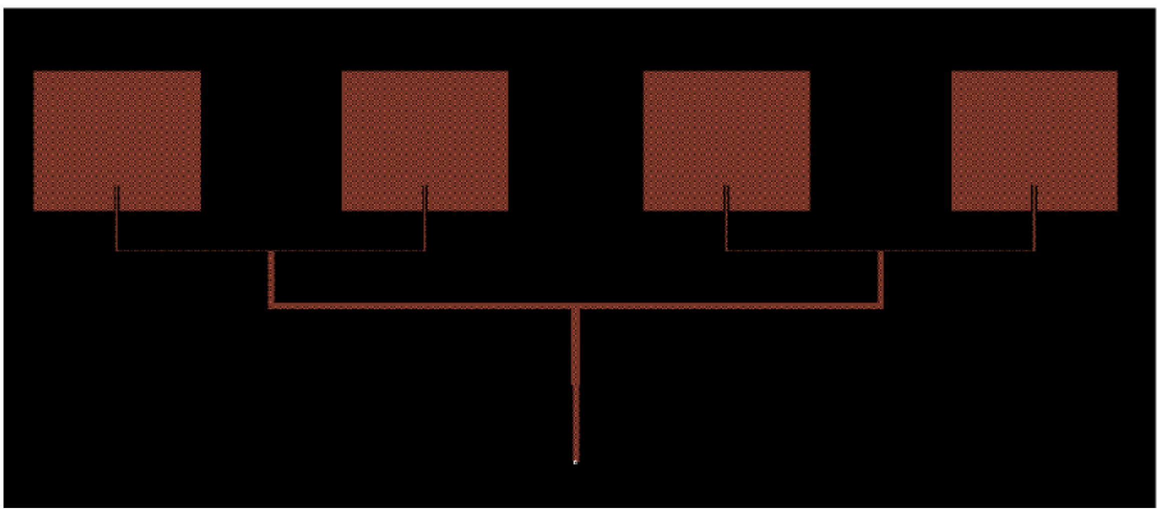


Figure 3.9 1 x 4 Corporate Fed Network

The element spacing here is 0.75 free space wavelengths, edge to edge, since it maximizes gain of the antenna.

The matching of the antenna proceeds as follows.

1. The patches are inset matched at 100 ohms.
2. The centre of the 100 ohm line, coming from the patches is matched to a 50 ohm line, hence they are automatically matched.

3. At the centre of the 50 ohm line, the impedance is 25 ohms. This is matched to the final 50 ohm line and SMA port by using a quarter wave transformer. The transformer impedance by the quarter wave formula was calculated to be 35.36 Ohms.

This matching network gives us a return loss in ADS as

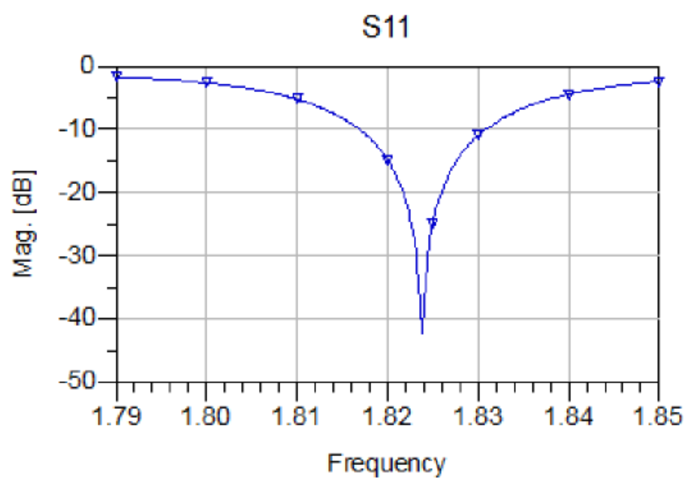


Figure 3.10 GSM 1800 array return loss

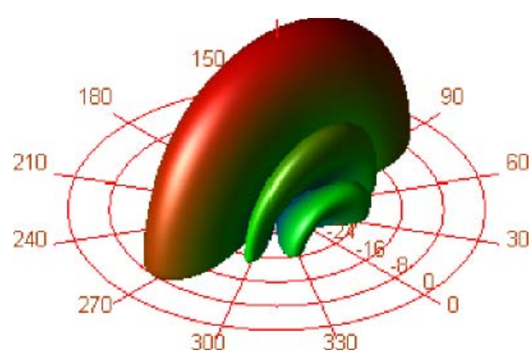


Figure 3.11 Array 3D Radiation Pattern

The gain of the antenna in our simulations came out to be 23 dB. The overall results are tabulated below.

Antenna type	**Microstrip Patch Antenna**
Geometry	**1 x 4**
Radiation Pattern	**Highly directional**
Gain	**23 dBi**
Return Loss	**-41 dB**
Impedance Bandwidth	**30 MHz**

3.4 Wi-Fi Antenna:

For the Wi-Fi antenna, only a single element patch antenna has been designed. With the Wi-Fi harvesting system, the goal was to show how miniaturized the system can get. The substrate used was Rogers RT Duroid 5880, with thickness 0.787mm. The single element antenna was again designed using [Balanis] and online calculators [EM Talk], with the results as follows.

Height	**Permittivity**	**Resonant Frequency**
0.787 mm	**2.2**	**2.4 GHz**

Length	Width
41.8 mm	49.4 mm

Figure 3.13 Return Loss of single element patch antenna WiFi

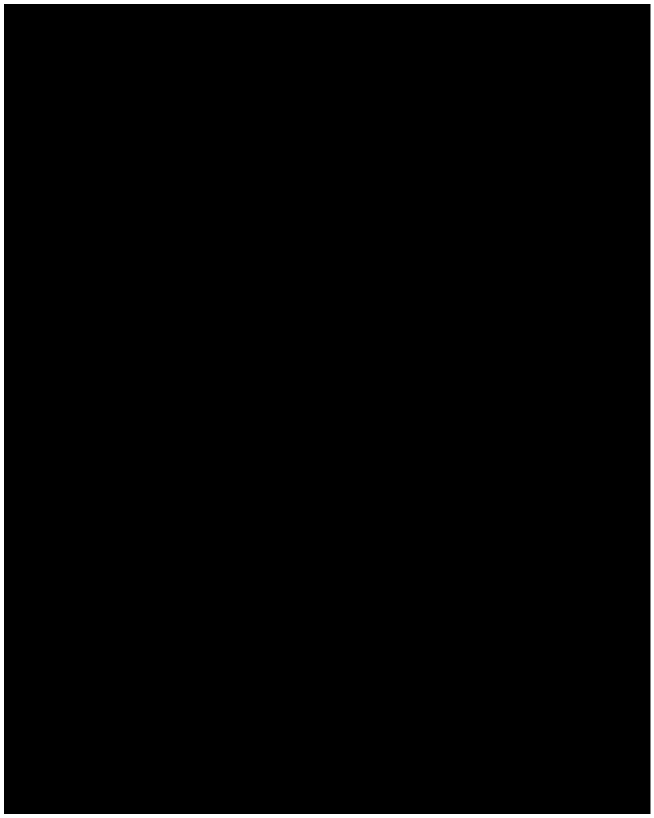
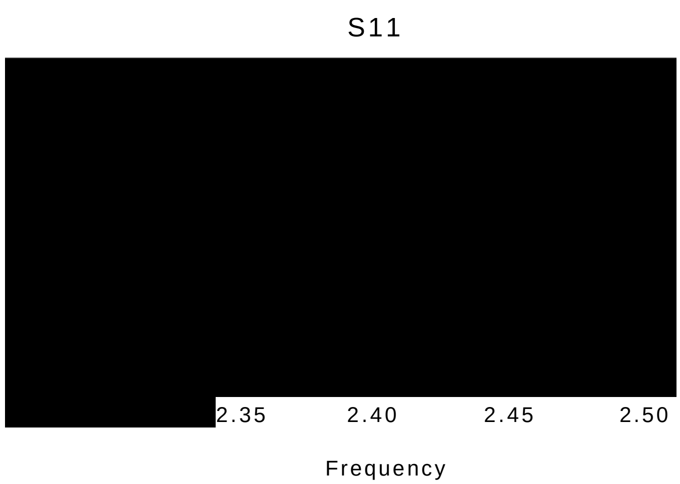


Figure 3.12 Single Element Patch antenna WiFi



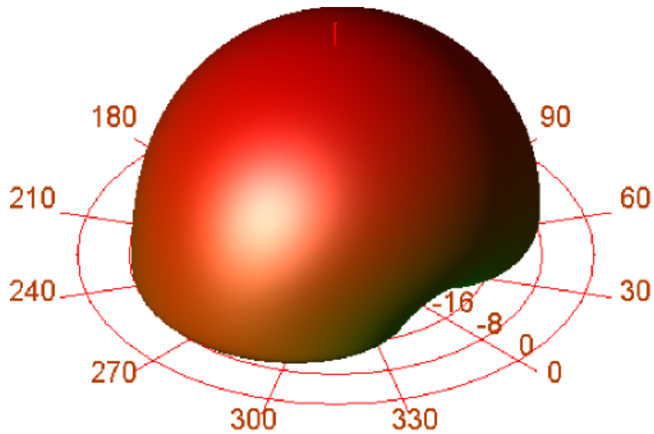


Figure 3.14 3D Radiation Pattern of the single element patch

The simulated gain of the antenna came out to be 6.5 dBi.

Antenna type	**Microstrip Patch Antenna**
[redacted]	
Return Loss	**-39 dBi**
Impedance Bandwidth	**10 MHz**

This concludes the antenna designs of the EM harvesting subsystems of the project.

Figure 3.13 Return Loss of single element patch antenna WiFi

CHAPTER 4

RECTIFICATION SUBSYSTEM DESIGN

4.1 Overview

The signal captured by the antenna is a high frequency AC signal. To power or charge a low power portable device this signal must be rectified since such devices operate on DC signal. The electronic subsystem therefore consists of a passive electronic circ uit comprising of capacitors and diodes.

4.2 Rectification/Cockcroft Walton Generator

The aim of the rectifier was to generate high DC voltage from a low voltage AC signal. This means that the rectifier designed to increase the voltage level besides recti fying the AC signal. Cockcroft Walton generator commonly known as charge pump is an electric circuit which generates a high DC voltage from a low voltage AC or pulsing DC input.[wikipedia]

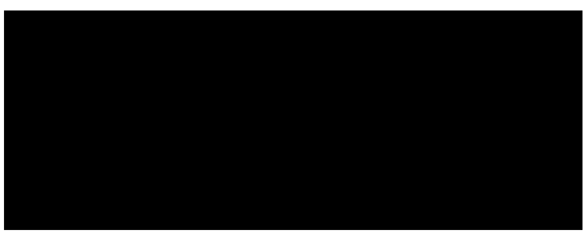


Figure 4.1 ladder network of diodes and capacitors

The table below shows the comparison of the CW generator with the common rectifiers. Thus CW generator was chosen due to its advantages over was chosen over the common rectifiers. It consists of a ladder network of capacitors and diodes to generate high vo ltages.

Features	Cockcroft Walton Generator	Common Rectifiers
Rectification	Yes	Yes
Voltage Up [redacted]	Yes	No
Energy Lost	Less	More
Component Cost	Less	More

It consists of stages of voltage doublers. To get an insight into the circuit's working principle consider the two stage CW generator shown in figure 2. During the positive half of the cycle D2 and C2 rectify the incoming AC signal (RF in this particular case) while D1and C1 rectify during the negative half cycle. But, C1 transfers the voltage stored on it to C2 during the positive half-cycle. Thus, C2 has a voltage twice the peak voltage of the RF source minus the turn-on voltage of the diode, hence the name voltage doubler. The most attracting feature of this circuit is that these stages can be cascaded to get more voltage. This is explained by the fact that the output is not exactly DC. It is actually an AC signal with a DC offset.

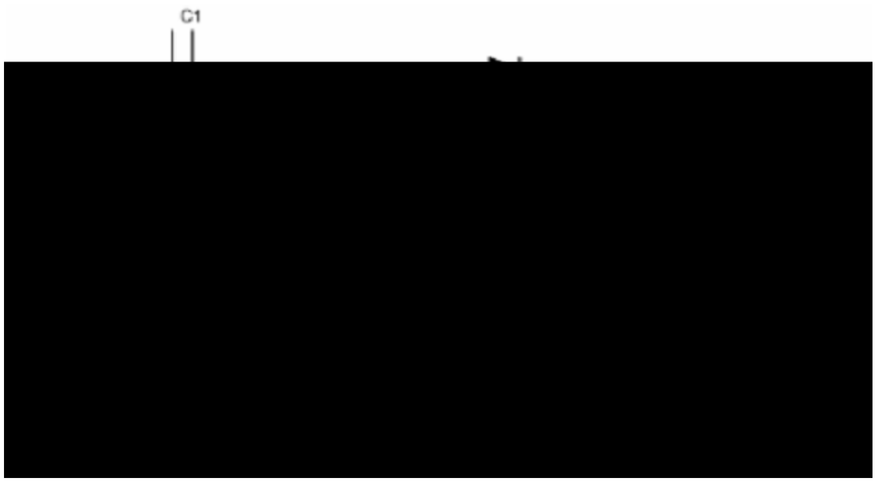


Figure 4.2 Two stage Cockcroft/Walton Generator

By adding a second stage in cascade with the first, the second stage sees only the AC part of the output given by the first stage. This gets doubled and adds up to the DC of the first stage. Thus, more the stages more the output voltage. The output voltage of an n stage cascade is given by

$$V_0={}^{2n}V_{in}$$

Figure 4.3 Output of a two stage CW generator

This means that by the choice of appropriate number of stages any voltage can be reached theoretically. But this is only valid for negligible current draw. In the presence of output current, an AC current passes through the capacitors, resulting in a voltage drop and a lower input voltage for subsequent stages. However increasing the number of stages to such high value like 10 or 20 is neither used in practice nor is sensible reason being a sag in the voltage level as the number of stages is increased. To be more specific the formula for the voltage drop is

$$\Delta U = \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n\right)$$

This shows that by increasing the number of stages the voltage drop is increased thus limiting the number of stages to a specific value.

4.3 Design Approach

As explained in the previous section the circuit design consists of capacitors and diodes. Thus choosing the right diodes and capacitors for the circuit were an essential part of the design. So keeping all this in mind, an extensive research was done to choose the right type of components for the design. Considering the requirement of the circuit, schottky diodes were chosen due to its fast recovery time and low forward voltage drop (0.15-0.45V). The diode chosen was the Agilent's HSMS 2860 due to its low forward voltage drop as low as 0.25V. Avago's HSMS~286x family of DC biased detector diodes have been designed and optimized for use from 915 MHz to 5.8 GHz. They are ideal for RF/ID and RF Tag applications as well as large signal detection, modulation, RF to DC conversion or voltage doubling [HSMS 2860 datasheet]. Since this diode supports a wide frequency range so this was chosen for all the charge pumps (GSM 900, GSM 1800 and ISM 2.4).

Figure 4.3 Output of a two stage CW generator

The capacitors chosen were the multilayer ceramic capacitors. These capacitors have various types of dielectrics. The main differences between ceramic dielectric types are the temperature coefficient of capacitance, and the dielectric loss. Table 1 shows the comparison between various dielectric types. The best suited for the purpose was class I capacitors but due to limited budget class II capacitors were chosen. One of the most important part of designing this circuit was the selection of right values for the capacitors. This is based upon two factors, equivalent series resistance (ESR) and transient response. ESR is the sum of in-phase AC resistance[wikipedia]. It includes resistance of the dielectric, plate material, electrolytic solution, and terminal leads at a particular frequency. ESR acts like a resistor in series with a capacitor (thus the name Equivalent Series Resistance). Increasing the capacitance decreases the ESR, keeping the frequency constant. However, increasing the capacitance increases the transient time. This means there is a tradeoff between the transient time and the ESR. Simulations were conducted in ADS (Advanced Design System) to select the optimum value of capacitors.

Features	Class I	Class II	Class III
Dissipation factor	0.15%	2.5%	4%
Voltage stability	Best	Medium	Poor
Accuracy	High	Average to Poor	Poor
Cost	High	Medium	Low

4.4 Simulations and Results

For the simulations an input signal of 50mV was assumed from the antenna. The simulations were conducted keeping the number of stages constant to 7. Table 2 shows the simulation results for the different capacitor values.

Stage capacitors (nF)	No of [redacted]	Input AC Voltage (mV)	Output DC voltage (V)
0.47	7	50	0.5
1.0	7	50	1.4
2.2	7	[redacted]	
[redacted]			
10	7	[redacted]	

Since at 10nF the best results are obtained as the ESR is reduced. Question might arise that why the capacitance isn't increased beyond this point? The answer to this lies in the fact that further increasing would increase the transient time, so 10nF is a good tradeoff between the ESR and the transient time. Hence 10nF was chosen as the final value. The charge pumps were designed at three frequencies as discussed in the previous section. All the simulations were conducted in ADS. The simulations and results for each charge pump are shown and discussed in this section.

4.4.1 GSM 900 Charge Pump

The charge pump was designed at 944MHz, since this was resonant frequency of the antenna.

A screenshot of the charge pump is shown in figure 4. It consists of 7 stages. This is because increasing the number of stages beyond this becomes useless since the voltage begins to sag and also the voltage drop begins to increase. So a 7 stage charge pump serves the purpose in terms of output voltage and voltage sag.

[redacted]

Figure 4.4 7 Stage GSM 900 charge pump in ADS

The simulation results for this charge pump are shown in figure 5. The charge pumps is capable of producing 2.4V DC signal with a 50mV input AC signal.

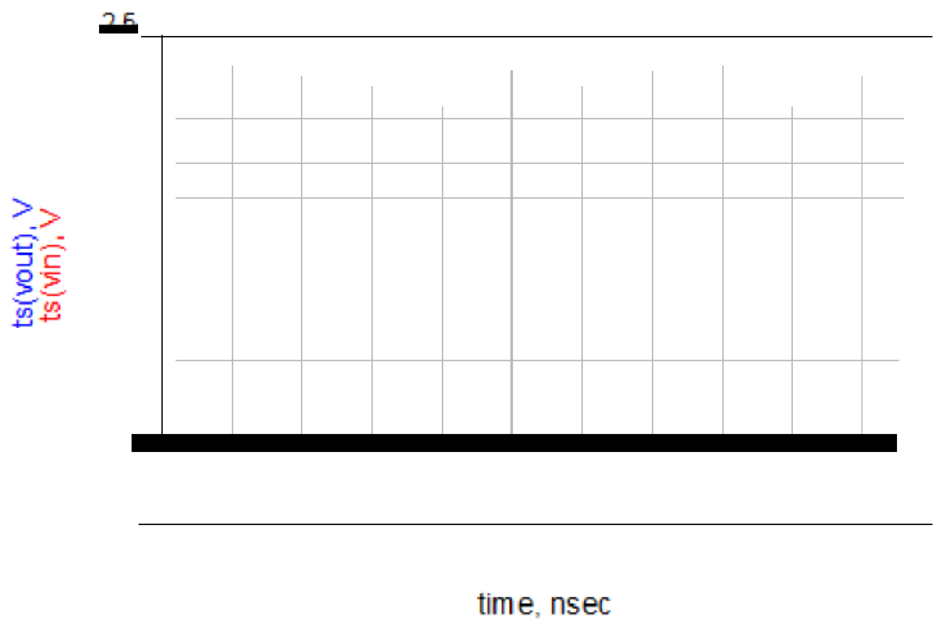


Figure 4.5 7 Stage GSM 900 charge pump results

4.4.2 GSM 1800 Charge pump

The charge pump was designed at 1817MHz, since the antenna resonates at this frequency.

Figure 6 shows a screenshot of the charge pump. It consists of 7 stages. This is because increasing the number of stages beyond this becomes useless since the voltage begins to sag and also the voltage drop begins to increase. So a 7 stage charge pump serves the purpose in terms of output voltage and voltage sag.

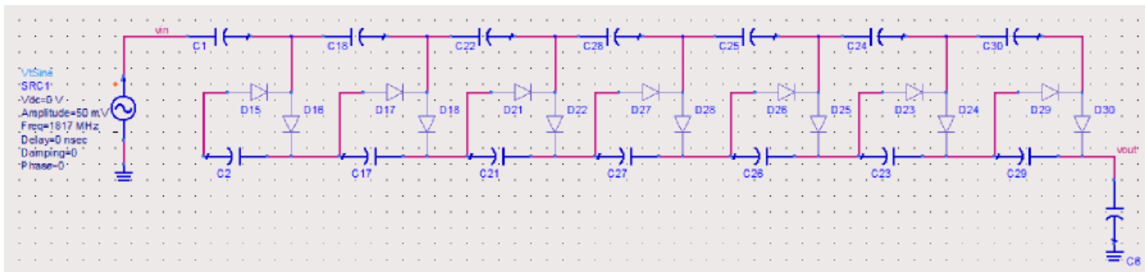


Figure 4.6 7 Stage GSM 1800 charge pump

The simulation results for this charge pump are shown in figure 7. The charge gives 200mV DC signal with a 50mV input AC signal.

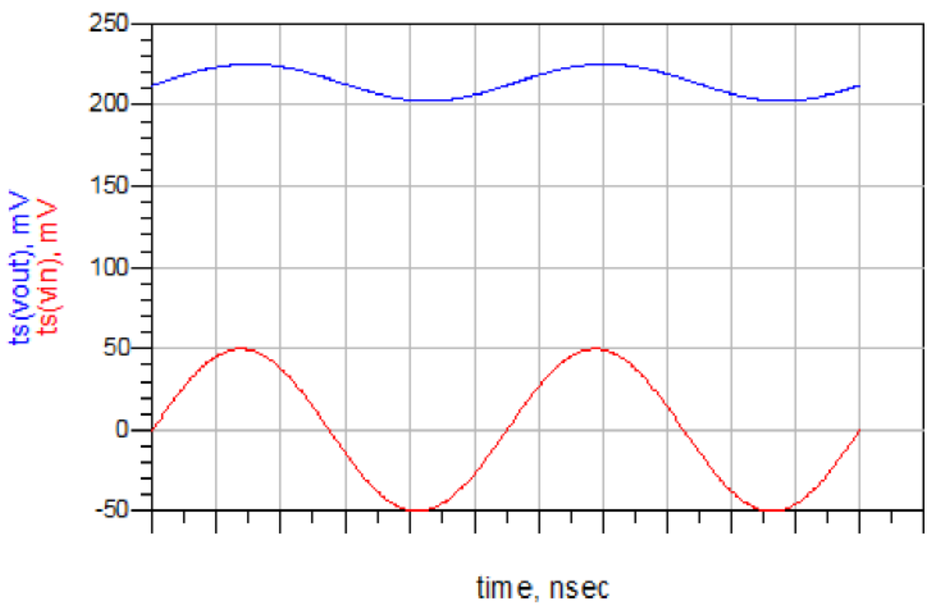


Figure 4.7 7 stage GSM 1800 charge pump Result

4.4.3 ISM 2.4 GHz Charge Pump

The charge pump was designed at 2.417 GHz in accordance with the antenna's resonant frequency.

A screenshot of the charge pump is shown in figure 8. This was a three stage charge pump because at higher stages the voltage drop was becoming significant in accordance with the formula given in the previous section 4.2.

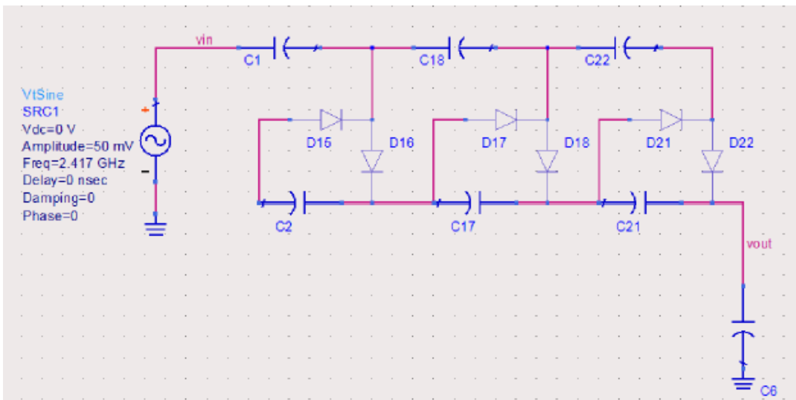


Figure 4.8 7 stage 2.4GHz charge pump

The simulation result for this charge pump is shown in figure 9. The charge pump produces 1 80mV DC signal from a 50mV AC signal.

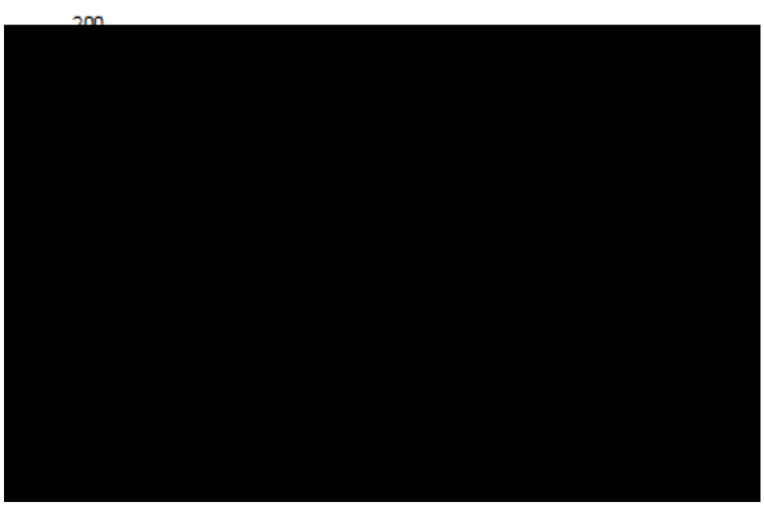


Figure 4.9 7 stage 2.4GHz charge pump result

It must be noted that the output of both the charge pumps that is 1800MHz and 2.4GHz is less than that of 900MHz. This is because as the frequency increases the voltage drop begins to increase in accordance with the formula given in section 4.2.

4.5 Conclusion Rectification Subsystem

In the light of the above mentioned study and simulation results the design for the charge pump was finalized. Table below shows the final components used for the rectification subsystem. The reason for the selection of these components has been discussed previously in this section.

[redacted]

[redacted]

Part Number	HSMS 2860
Mounting	Surface mount (SOT 23)
Forward Voltage	0.25V

Maximum frequency 5.8GHz

CHAPTER 5

STORAGE SUBSYSTEM

5.1 Overview

The storage subsystem is basically employed since the real time harvested energy cannot always be enough. For this purpose, we have chosen to design a storage subsystem that would act as a supply battery backup.

5.2 Supercapacitors

The main feature of our storage subsystem is supercapacitor technology. The supercapacitor, also known as *ultracapacitor* or *double-layer capacitor,* differs from a regular capacitor in that it has a very high capacitance. A capacitor stores energy by means of a static charge as opposed to an electrochemical reaction. Applying a voltage differential on the positive and negative plates charges the capacitor. This is similar to the buildup of electrical charge when walking on a carpet. Touching an object releases the energy through the finger.

The modern supercapacitor is not a battery per se but crosses the boundary into battery technology by using special electrodes and electrolyte. Several types of electrodes have been tried and we focuse on the double-layer capacitor (DLC) concept. It is carbon-based, has an organic electrolyte that is easy to manufacture and is the most common system in use today.

All capacitors have voltage limits. While the electrostatic capacitor can be made to withstand high volts, the supercapacitor is confined to 2.5–2.7V. Voltages of 2.8V and higher are possible but they would reduce the service life. To achieve higher voltages, several supercapacitors are connected in series. This has disadvantages. Serial connection reduces the total capacitance, and strings of more than three capacitors require voltage balancing to prevent any cell from going into over-voltage. This is similar to the protection circuit in lithium-ion batteries.

Advantages	Virtually unlimited cycle life; can be cycled millions of time High specific power; low resistance enables high load currents Charges in seconds; no end-of-charge termination required Simple charging; draws only what it needs; not subject to overcharge Safe; forgiving if abused Excellent low-temperature charge and discharge performance
Limitations	Low specific energy; holds a fraction of a regular battery Linear discharge voltage prevents using the full energy spectrum High self-discharge; higher than most batteries Low cell voltage; requires serial connections with voltage balancing High cost per watt

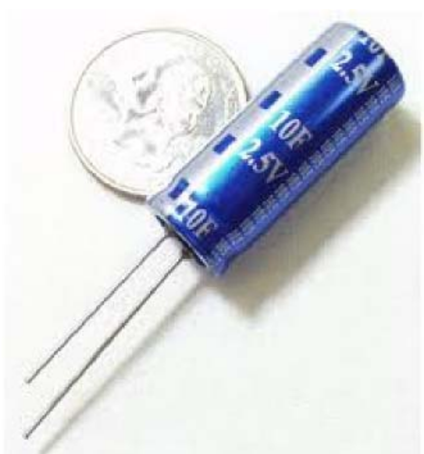


Figure 5.1 A sample Supercapacitor compared with the size of a coin

5.3 Supercapacitor Charger

We also plan to use an IC provided by linear technology that will be used to charge the supercapacitors. The IC is LTC3225. According to linear technology's website

The L TC3225/L TC3225- 1 are programmable supercapacitor chargers *designed to charge two supercapacitors in series to a selectable fixed output voltage (4.8V/5.3V for the LTC3225 and 4V/4.5V for the LTC3225-1) from input supplies as low as 2.8V to 5.5V. Automatic cel balancing prevents overvoltage damage to either supercapacitor. No balancing resistors are required.*

The advantages of the supercapacitor charger are numerated

Low Noise Constant Frequency Charging of Two Series Supercapacitors

Automatic Cel Balancing Prevents Capacitor Overvoltage During Charging

Programmable Charge Current (Up to 150mA)

5.4 Conclusion

The storage subsystem is meant to be the last subsystem of the EM harvesting design. It will be the subsystem that will bridge the connection between the harvested energy and component integration. Therefore we have designed the storage system on a breadboard to allow flexibility in the design. Furthermore, since the signal has been converted into DC, it is compatible with working with a breadboard.

CHAPTER 6

SYSTEM INTEGRATION AND MANUFACTURE

6.1 Integration

Our antennas need to be integrated with the electronic cicrcuitry, so as to optimally feed the power to the electronic rectification. For the GSM 900 antenna, the antenna is connected with a fine RG-174 Coax cable to the PCB board that consists of the rectification circuitry. Similar methodology is used for the GSM 1800 frequency. For the WiFI harvesting system, however, the patch antenna is directly fed to the circuitry using a Microstrip transmission line. This was done in view of mininituraizing the system to as small as possible.

A very important aspect of the integration phase, were the matching networks.

6.1.2 Design of matching networks

For the GSM 900 antenna, a SMA port of 50 ohm is used. Similarly, the PCB containing the charge pump at this frequency is also attached with a 50 ohm SMA connecter. The circuitry hence needed to be matched to the 50 ohm connector. For this purpose schematic simulation of ADS was used to firstly calculate the input impedance of the circuitry. Then using impedance transformation using the matching network we convert the load impedance to the 50 ohm impedance of the port. The Zin of the rectification circuitry for GSM 900 system is shown below.

freq	Zin1

900.0 MHz	10.440 - j40.117
901.0 MHz	10.267 - j39.008
902.0 MHz	10.101 - j37.920
903.0 MHz	9.941 - j36.851
904.0 MHz	9.788 - j35.801
905.0 MHz	9.641 - j34.768
906.0 MHz	9.501 - j33.754
907.0 MHz	9.366 - j32.756
908.0 MHz	9.236 - j31.774
909.0 MHz	9.111 - j30.807
910.0 MHz	8.992 - j29.856
911.0 MHz	8.877 - j28.91 9
912.0 MHz	8.767 - j27.995
913.0 MHz	8.661 - j27.086
914.0 MHz	8.559 - j26.189
915.0 MHz	8.462 - j25.304
916.0 MHz	8.368 - j24.432
917.0 MHz	8.278 - j23.571
918.0 MHz	8.191 - j22.721
919.0 MHz	8.108 - j21.883
920.0 MHz	8.028 - j21.054
921.0 MHz	7.952 - j20.236
922.0 MHz	7.878 - j19.427
923.0 MHz	7.808 - j18.628
924.0 MHz	7.740 - j17.838
925.0 MHz	7.675 - j17.056
926.0 MHz	7.613 - j16.283
927.0 MHz	7.553 - j15.518
928.0 MHz	7.496 - j14.761
929.0 MHz	7.441 - j14.012
930.0 MHz	7.389 - j13.270
931.0 MHz	7.339 - j12.535
932.0 MHz	7.291 - j1 1.807
933.0 MHz	7.246 - j1 1.085
934.0 MHz	7.202 - j10.370
935.0 MHz	7.161 - j9.661
936.0 MHz	7.121 - j8.957
937.0 MHz	7.084 - j8.260
938.0 MHz	7.048 - j7.568
939.0 MHz	7.015 - j6.881
940.0 MHz	6.983 - j6.199
941.0 MHz	6.952 - j5.522
942.0 MHz	6.924 - j4.850
943.0 MHz	6.897 - j4.183
944.0 MHz	6.872 - j3.51 9
945.0 MHz	6.849 - j2.860
946.0 MHz	6.827 - j2.205
947.0 MHz	6.807 - j1.554
948.0 MHz	6.788 - j0.906
949.0 MHz	6.771 - j0.262
950.0 MHz	6.755 + j0.379
951.0 MHz	6.741 + j1.016

Figure 6.1 Input impedance vs frequency

The frequency we chose to match at is 944.4 MHz. This matching was done using smith chart and matching network calculators online [SAN

DIEGO website]. It was chosen to work with minimum number of lumped elements for the matching network, since the lesser the number of elements the lesser would be the dissipation. Stubs were employed for providing inductance since, inductor values were subject to availability and often could not be realizable. For the GSM 900 circuit the matching network consisted of a variable capacitor from 0-30pf and a short circuited stub.

Using similar methodology for the GSM 1800 circuitry, the matching network consisted of a variable capacitor and a transmission line length.

The matching network employed for the WI-Fi harvesting system was free of lumped components and it wholy was composed of a transmission line length and an open circuited stub.

Simulations in ADS schematic and momentum show us satisfactory results for our matching networks giving sufficient bandwidth.

6.2 Manufacture

The first step in manufacture is to design the PCB layouts and GERBERS. For this ADS momentum was used.

Trace thickness used was 1 mm keeping in mind the pad lengths of the components etc. Also extensive simulations were done varying the line lengths to obtain sufficient bandwidths and performance. As the frequencies were microwave we needed to fine tune all dimensions of our circuitry.

The GERBER layouts are displayed below.

Figure 6.2 Gerber Layout of GSM 900 Antenna

Figure 6.3 Gerber Layout of GSM 900 Charge Pump

Figure 6.4 Gerber Layout of GSM 1800 Antenna

Figure 6.5 Gerber Layout of GSM 1800 Charge Pump

Figure 6.6 Gerber Layout of WI-FI Harvesting System

These GERBER files and the laminates were given to National Institute of Electronics for manufacture. The soldering of the components was done manually.

The ports and the wires were also soldered and constructed manually.

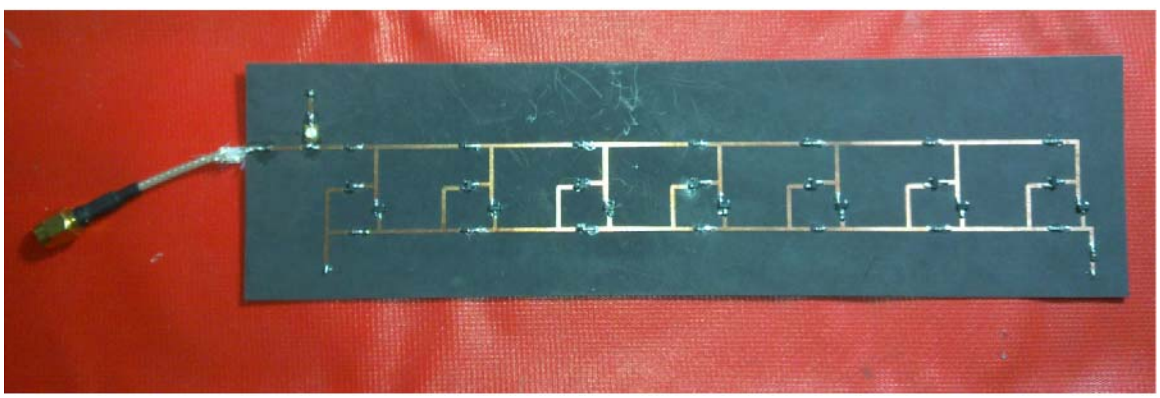


Figure 6.7 Manufactured GSM 900 Charge Pump

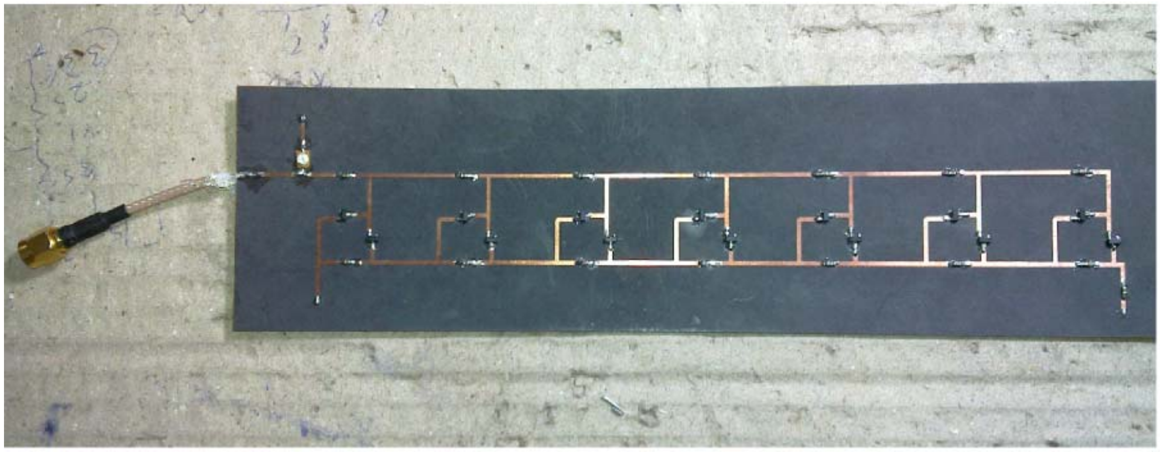


Figure 6.8 Manufactured GSM 1800 Charge Pump

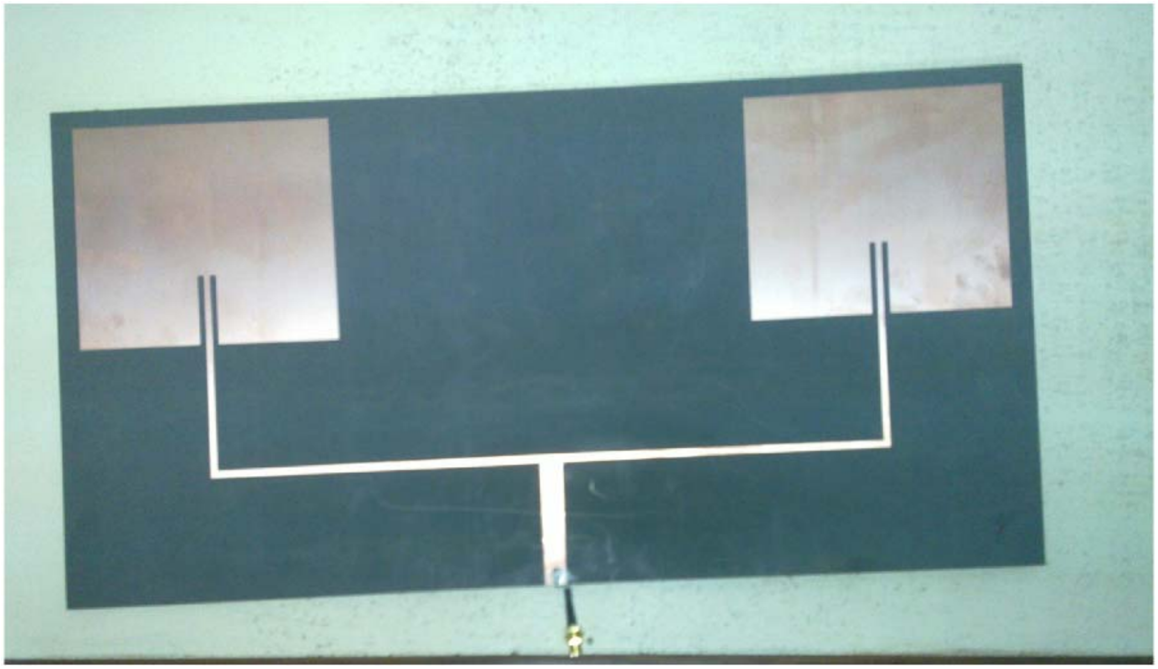


Figure 6.9 Manufactured GSM 900 Antenna

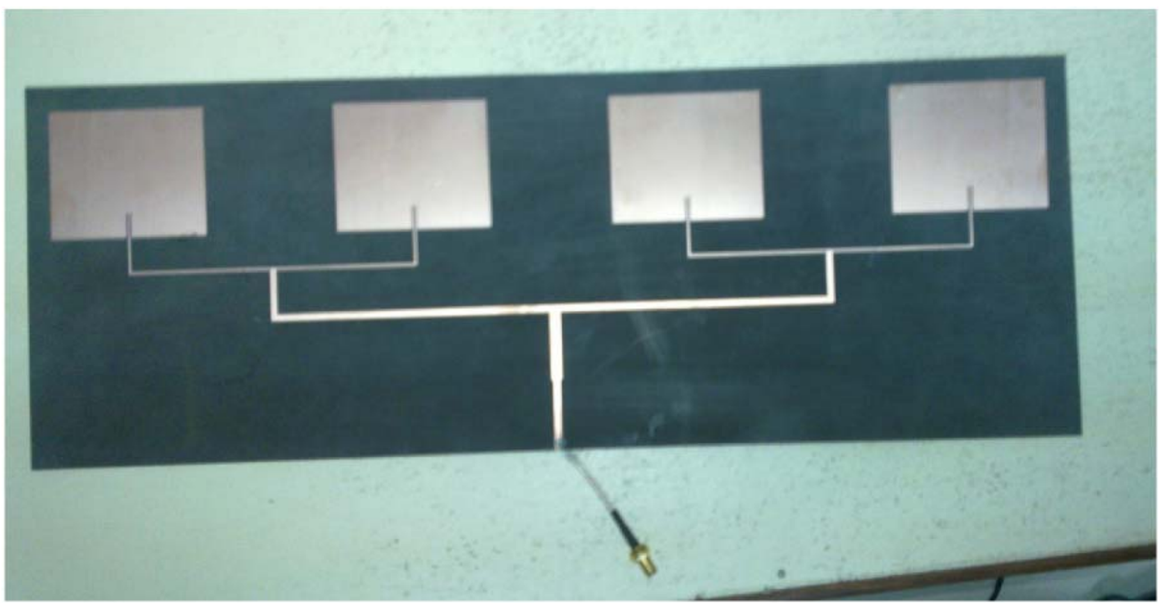


Figure 6.10 Manufactured GSM 1800 Antenna

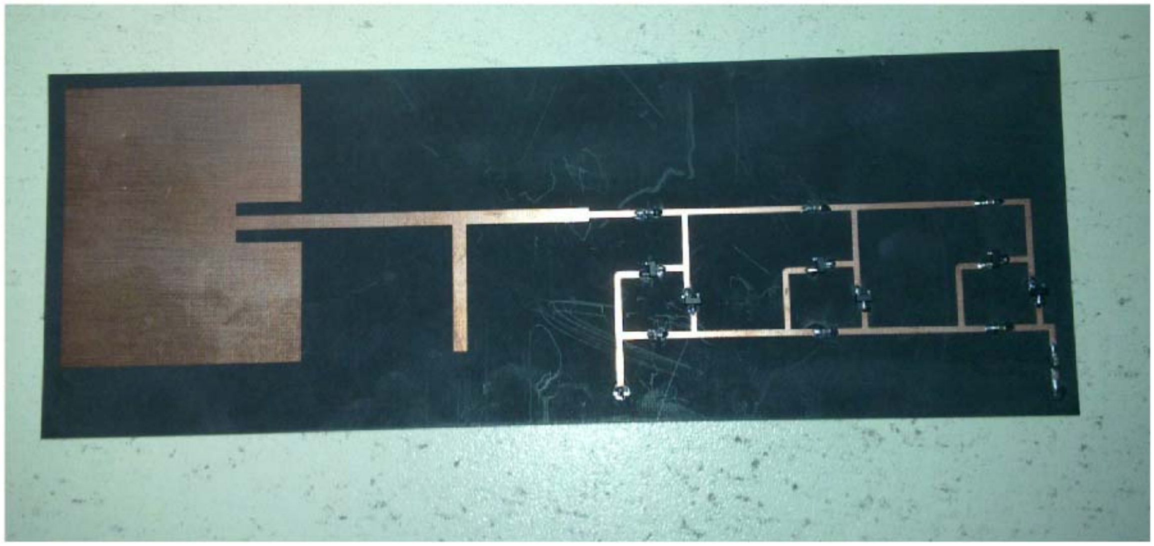


Figure 6.11 Manufactured WiFI harvesting System

CHAPTER 7

TESTING AND VALIDATION

7.1 Testing Techniques

The testing of the equipment was carried out in the RF research lab in MCS. The testing methodology used was first to test the individual components using the VNA. By using the VNA we can determine the return losses, resonant frequencies and the impedance bandwidth.

In the next phase each of the individual PCBs are to be tested In a standalone setting.

Finally the overall testing was to be carried out, where each harvesting system performance is seen completely.

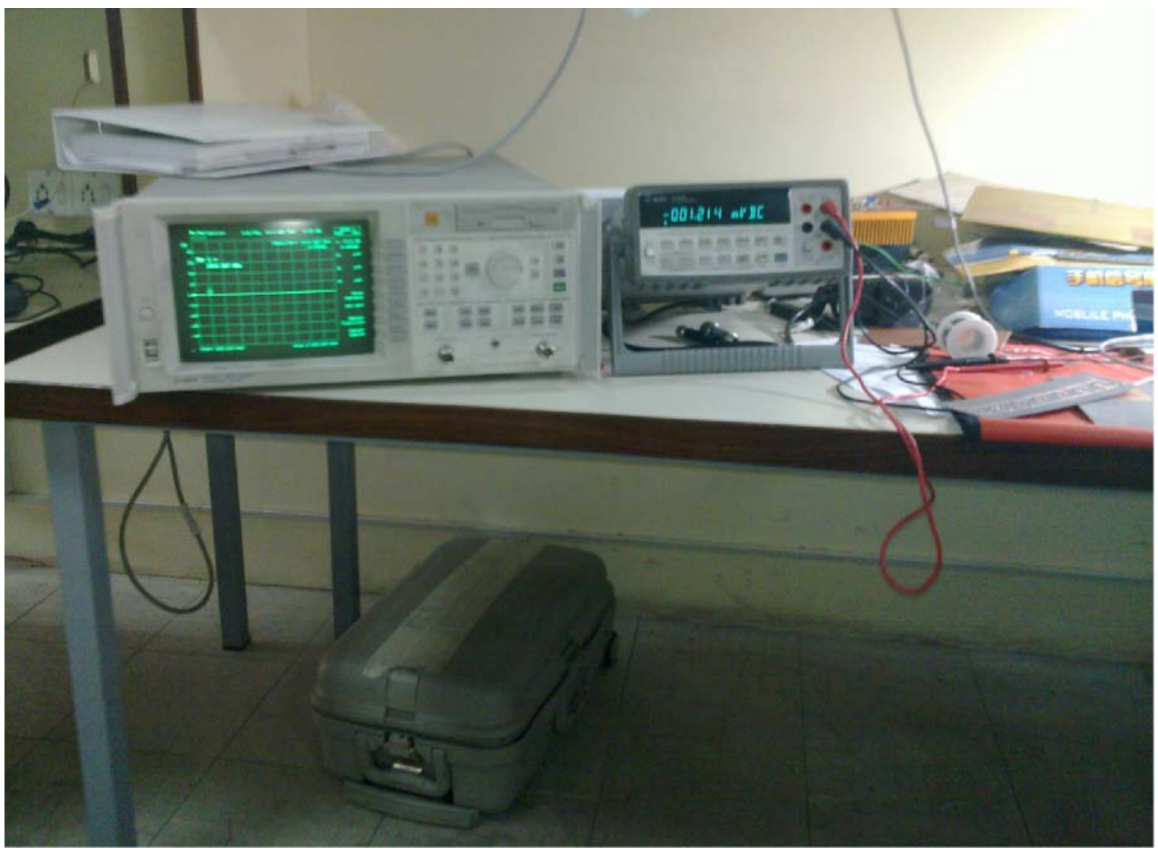


Figure7.1 Testing Equipment

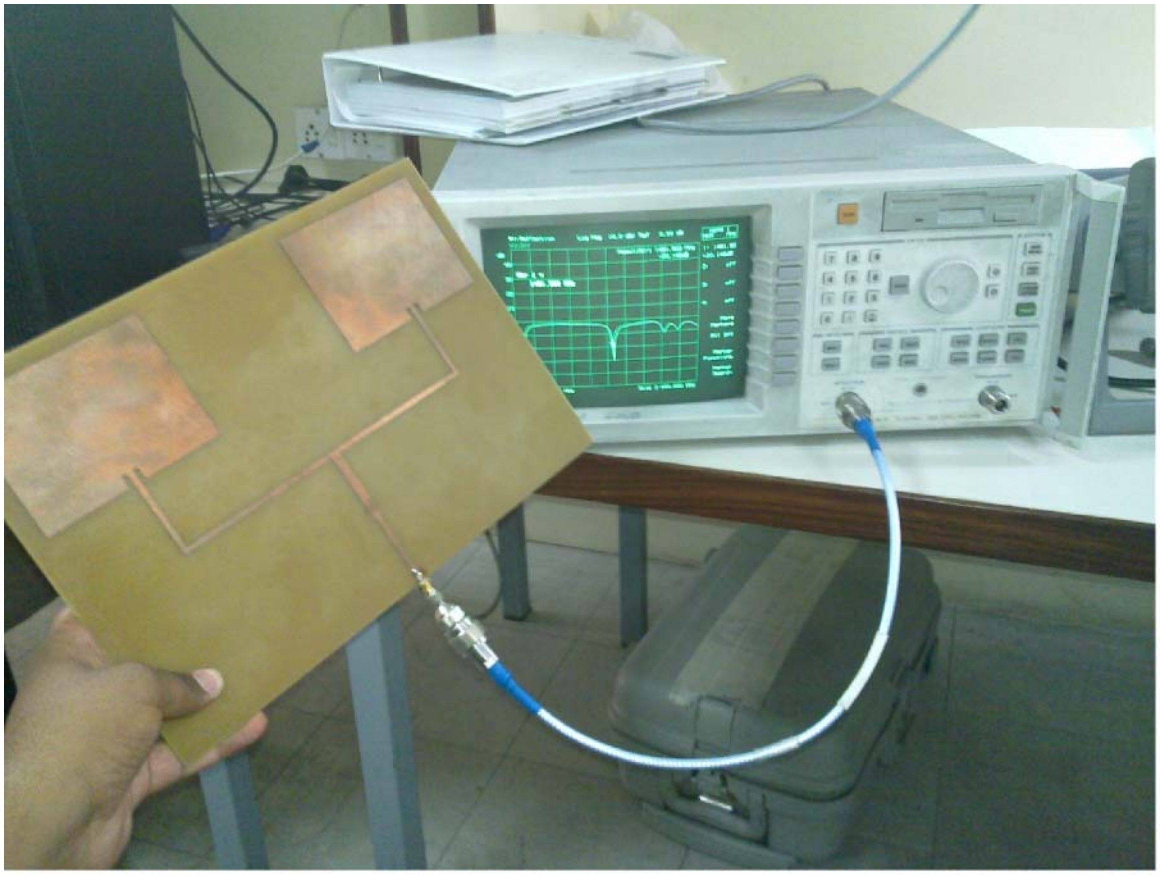


Figure 7.2 FR4 Test Antenna resonating at 944.4 MHz

7.2 Testing use VNA

The VNA results have been generally satisfactory.

GSM 900	Simulated	Actual
Return Loss	**-42 dB**	**-21 dB**
Resonant Frequency	**944.4 MHz**	**948.2 MHz**
Impedance Bandwidth	**22 MHz**	**18 MHz**

GSM 1800	Simulated	Actual
Return Loss	-36 dB	-24 dB
Resonant Frequency	1817 MHz	1824 MHz
Impedance Bandwidth	25 MHz	18 MHz

GSM 1800 Antenna Results

GSM900 Charge Pump	Simulated	Actual
Return Loss	-22 dB	-24 dB
Resonant Frequency	944.4 MHz	936 MHz
Impedance Bandwidth	25 MHz	13 MHz

GSM 900 Charge Pump Results

GSM1 800 Charge Pump	Simulated	Actual
Return Loss	-22 dB	-27 dB
Resonant Frequency	1817 MHz	1790 MHz
Impedance Bandwidth	25 MHz	15 MHz

GSM 1800 Charge Pump Results

The WI-FI harvesting system could not be tested since it is completely manufactured on the PCB and no ports can be connected to it.

7.3 Testing Fabricated Circuit Boards

The individual charge pumps were tested using Agilent Signal Generator available in Lab which operates up till 2 GHz. By using SMA coupling we fed our charge pumps high frequency AC signals according to the frequency of the antennas. We observed the output to be slightly less than the simulated results. Satisfactory results were obtained.

7.4 Overall Testing

After coupling all the SMA connecters together, the overall systems were tested as to how much ambient energy they could harvest. The amount of energy harvested was varying however energy ranging to a few milliwatts was obtained.

7.5 Testing Conclusion

Overall, the testing phase needs to be progressed further and the system is in the process of being further optimized, and will continue be doing so after the submission of this dissertation.

CHAPTER 8

FUTURE WORK AND CONCLUSION

8.1 Potential Future Work and Improvements

As the power harvested from EM Energy harvesting system is in Milli Watts. Only low power devices can be operated with such output. The main aspects on which future work should be done are:

Power output of the EM Harvesting,

Size of the antennas,

Rectification and stepping up system

Storage subsystem

The size of the EM harvesting at the present moment is on 18x12 inches lamination sheet on which most of the space is taken by the antenna. As we harvested the power from lower frequency bands that is GSM 900 Mhz band and GSM 1800 Ghz band. Harvesting from a higher frequency like from Wimax (3.5 Ghz) and Wifi (2.4 GHz) would reduce the antenna size considerably from GSM 900 (12.56 cm x 10.56 cm) to WiMax (3.2 cm x 2.6 cm). This simple frequency selection has reduced the size by almost 4 times. Not only the antenna size would reduce also the spacing between the elements of array would reduced as at higher frequency the wavelength reduce by the formula v=fý. The spacing between the elements we selected was one wavelength. Also this spacing of one wavelength can be reduced to 0.5 wavelengths with some better array designing.

The next thing which can be done in future as far as EM Harvesting system is concerned is to increase the power output. Frequencies from TV boosters and aeronautical radars have a very higher power density as compare to that of GSM 900 and GSM 1800. Harvesting from such frequency band would yield in a higher output and such output power can

be achieved which can charge handhelds and will keep there batteries topped up and power in some high Milli Watts and even in few Watts could be achieved. Also gain enhancement techniques should be used like stacking the antenna`s, this would increase the gain almost by 10 dBs minimum and with many more gain enhancement techniques available we can increase the gain which will increase the output power of the EM harvesting system.

The antenna designed is very directive which reduces the performance when antenna not directly face the waves from the transmitters. Antenna should be designed such that it should not be directive and should harvest more ambient waves. Also the concept of shorting pins can be used to reduce the size of the antenna comparatively without reducing its efficiency.

The antenna bandwidth designed in EM harvesting system was very less that is up to very few MHz. Techniques to increase the bandwidth should be used so that whole range of the frequency can be harvested which will directly increase the amount of energy received. Broadband antennas should be used in future harvesting to get the maximum possible bandwidth which will in other words will give us the maximum output power.

More the number of components more are the losses in the electronics subsystem. Though surface mount components were used but still a total of 30 components were used in one charge pump and every component take some part of the energy harvested. Hence a better electronic subsystem should be designed with less number of components for rectifying and stepping up the voltage.

Another way in which EM harvesting system can be improved is by improving the matching network. Matching network used in today`s EM harvesting system is by single stub and a simple capacitor. Matching via surface mount inductors and capacitors would enhance the performance of the future EM harvesting systems. Multi stage matching system can also be implemented so that the system is perfectly matched and no losses take place between the subsystems.

Proper storage system was not designed for the EM harvesting system. A proper storage subsystem should be designed so that it can store power and side by side power can also be used for the desired purpose.

Also multiple sources EM Harvesting should be done so that the power from different multiple sources can be harvested at a single time. Like harvesting from three different frequencies will increase the power by three times.

Limitations of the project are the lack of equipment in the laboratories of MCS to measure frequency response at higher frequencies and accurately. The computers are unable to run heavy software's of frequency simulations. Moreover the substrates like Roger RT Duroid are not available in the market and are pretty expensive and testing cannot be done on such laminates as budget issue will come in to play. More over surface mount diodes are also not available in the market with zero bias and testing equipment would cost heavy on pocket.

Also a single millimeter change in any of the dimension will cause the system to run on any other frequency and the system will not work properly and whole system will be a waste. Hence systems should be fabricated from China as that will cost less and there accuracy is far better than the companies who fabricate in Pakistan.

8.2 Conclusion

The main application objective of our project was to work on the following

- Energy Issues
- Limited Battery Times
- Wireless solution
- Powering low power portable devices
- Energy recycling of EM waves

Keeping in mind what we have studied throughout our four year degree programme, the following were our academic goals:

- Antenna
    - Simulations and design
    - High Gain
- RF Electronics
    - High frequency Circuit Design
- Manufacturing and testing
    - High frequency laminates
    - Network and spectrum analyzers
    - RF surveys

At the end of our project the EM harvesting team was able to make accurate microstrip patch antennas with matched electronic subsystem and getting 2.5 V at the output. Low power devices can be charged from the EM Harvesting system and the whole system is mobile, easy to use with small size and over all the cost of the project was reasonable considering the advantages one gain from EM harvesting. At the end of the day the group was able to complete the project well in time and all the academic and applications goals were achieved.

APPENDIX A1

DATA SHEETS

APPENDIX A1

Rogers RT Duroid 5880 Data Sheet

ROGERS
CORPORATION

Advanced Circuit Materials

Advanced Circuit Materials Division
100 S. Roosevelt Avenue
Chandler, AZ 85226
Tel: 480-961-1382, Fax: 480-961-4533
vvarw.rogerscorp. com

Data She&
RT/duroid 5870!5880 Laminates

RT/duroid°5870 /5880 High Frequency Laminates

Features:

- Lowest electrical loss for reinforced FTFE material,
- Low moisture absorption.
- Isotropic
- Uniform electrical properties over frequency,
- Excellent chemical resistance.

Some Typical Applications:

- C mmercial Airline Telephones
- Microstrip and Strlpline Circuits
- Millimeter Wave Applications
- Military Radar Systems
- Missile Guidance Systems
- Point to Point Digital Radio Antennas

RT/duroid'5870 and 5880 glass microfiber reinforced PTFE composites are designed for exacting stripline and microstrip circuit applications.

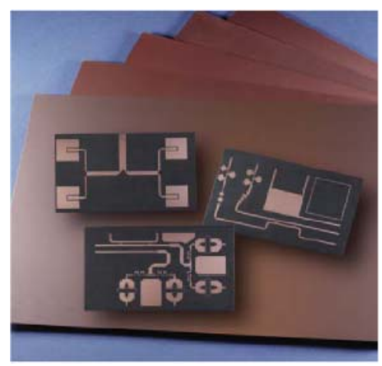
Glass reinforcing microfibers are randomly oriented to maximize benefits of fiber reinforcement in the directions most valuable to circuit producers and in the final circuit application.

The dielectric constant of RT/duroid 5870 and 5880 laminates is uniform from panel to panel and is constant over a wide frequency range.

Its low dissipation factor extends the usefulness of RT/duroid 5870 and 5880 laminates to Ku-band and above.

RT/duroid 5870 and 5880 laminates are easily cut, sheared and machined to shape. They are resistant to all solvents and reagents, hot or cold, normally used in etching printed circuits or in plating edges and holes.

Normally supplied as a laminate with electrodeposited copper of V. to 2 ounces/ft.' (8 to 70f m) on both sides, RT/duroid 5870 and 5880 composites can also be clad with rolled copper foil for more critical electrical applications. Cladding with aluminum, copper or brass plate may also be specified.



When ordering RT/duroid 5870 and 5880 laminates, it is important to specify dielectric thickness, tolerance, rolled or electrodeposited copper foil, and weight of copper foil required.

PROPERTY	TYPICAL VALUE [2] RTrduroid 5670		RT/duroid 5880		DIRECTION	UNITS[3]	CONDITION	TEST METHOD
Dielectric Constant. er ṛ	2.32 233±0.72 spec.		2.22 2,20±0,02 spec,		a		C24i23/50 C24/23/50	1 MHu PC-TM-650 2,5.5.3 IOCHu IF'C-TM 2.5.5.5
Dissipation Factor_ Ian G	0.0005 0.0012		O.CD04 0.0009				024/23/50 024/23/50	1 MHz IPC-TM-550, 25,5,3 1 D GHz PC-TM-2.5.5.5
Thermal Coefficient of sr	-115		-125			ppmr°C	-50- 150°C	IPC-TM-650, 25.5.5
Volume Resistivity	2X 10		2 X 10'		a	M^ph , cm	096/25/90	ASTM D257
Surface Resistivity	2X IC'		3810'		7	hlohm	0/96/25/90	ASTM D257
Tensile Modulus	Test at 23°C	Test at 100°C	Test at 23°C	Test at 100°C				
	1 300 (189!	490 {711	1070 (156)	450 (651	X	MPs (kpsi(	A	ASTM 0638
	1280 1185	430 {63)	860 (125)	380 (551				
ultimate s h e .	50 (7.3;1	34 14.81	29 {4.2;1	20 12.91	X			
	42 (6.11	34 14.81	27 {3.9i	18 12.6J	Y			
ultimate chain	9.8	8.7	6.0	7 2	X	%		
	9.8	8.6	4.9	5.8				
Compressive Modulus	1210 (176!	680 {99)	710 (103)	500 (731	X	MPo (kpsi)	A	ASTM D695
	1360 (198!	860 (125,1	710 (103)	500 (731	Y			
	803 (120)	520 {761	940 (136)	570 (971	7			
ultimate s h e .	20 (4.41	23 13.4)	27 {39,1	22 13.21	X			
	27 (5.3,1	25 [3.7)	29 {5.3!	21 13.1)	Y			
	54 (7.8,1	37 [5.3)	52 {7.5,1	43 16.31				
ultimate shah	4.0	4.3	8.5	8,4	X	%		
	3.3	3.3	,..	7.8	Y			
	8.7	8.5	12.5	17.6				
Deformation Under Load, Test at **150`0**			1 0		Z	q	- 4hr,/ 14 MPa 12 Kpsl1	ASTM 0621
Heat Distortion Temperature	>260 (>500)		>260 {>500)		X,Y	°C (°P)	1 .B2 Iv1Pa (264 psi)	ASTM D648
Specific Heat	0,96 (0723)		0.96 10.23)			c^q'l^g'C)		Calculated
Moisture Absorption	1 3 (0.015)		13 i0 x3151			my i`%°I	X052 { 1 .6mm) 0724/	ASTM t D570
Thermal Conductivity	0_^2 2		0.22		2	00/m,sK	80°C	SSTPvi C518
Coefficient of Thermal Expansion	22 28 173		31 48 237		X Y	ppml°C	0-100°C	ASTM D3286
Td	500		500			°C 408		ASTM 03850
Density	2.2		2.2					7 D792
Copper Peel	20.8 (2.7,ı		2^2_.814.01			pli IN/mm)	alter solder float	IPC-TPa-65024.8
Flammability	V-0		V-0					3L94
Lead-Free Process Compatible	Yes		Yes					

[II Specification va ues are measured per IPC- M-250. method 2.5.5.5 -ICGHz. 23°C. Testing mused or. 1 or, e ectrode posited copper fol. s values and tolerance reported by PC-TM-400 method 2.5.5.5 are the boss for quality acceptance. out for some products these vanes may be incorrect for design purposes` especla ly microstbp designs. We end that prototype boards for a nevi 1 - n s be yerfied for desired e ectrical performance.

[21 Typiica values should not oe used forspecif co-- n ,emits, except where noted.

[31 5I unit given Trot with other frequently used unit: ı ı parentheses.

[41 References:Internal TR's 1430. 2224. 2854. Test were at 23°C un ess otherwce noted.

STANDARD IHICISNESS		STANDARD PANEL SIZE	**STANDARD** COPPER CLADDING
000'5' /O.127mm1, 0.010' (C 254mm), 0.015' (0.381mm). 0.023'~(0.508mmh	G.031' (G.787mm) 0062' (1.575mm) C.125' (3.175mm)	18' X 12"1457 X 305mm) 1 8 ' X 24" {457 X 610mm) 18' X36° [457X 915mm) 18'X48' 1457X 1.224m:	5 pm, z. [S pmt electrodeposited capper toil. cc (I7pm J . 1 or (35pm). 2 oz. (70pm) electrodeposited and ro led cop-perfoi.

APPENDIX A2

HSMS 2860 Data Sheet

HSMS-286x Series
Surface Mount Microwave Schottky Detector Diodes

AvaGo

Data Sheet

Lead [Free
c o p 6 fully
i ~ • 1
compliant

Description

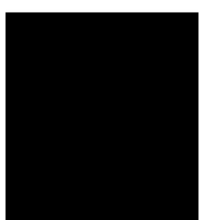
Avago's HSMS-286x family of DC biased detector diodes have been designed and optimized for use from 915 MHz to 5.8GHz.Theyare ideal for RFlIDand RFTag applications as well as large signal detection, modulation, RF to DC conversion or voltage doubling.

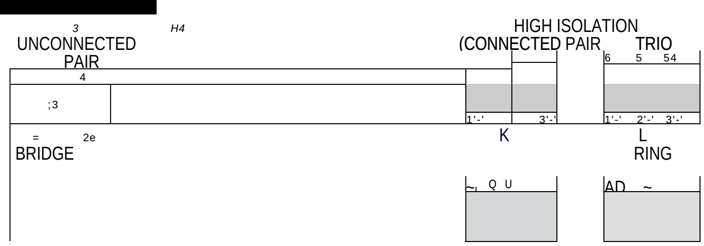
Available in various package configurations, this family of detector diodes provides low cost solutions to a wide variety of design problems. Avago's manufacturing techniques assure that when two or more diodes are mounted into a single surface mount package, they are taken from adjacent sites on the wafer, assuring the highest possible degree of match.

Pin Connections and Package Marking

Notes:
1. Package marking provides orientation and identification.
2. The first two characters are the package marking code. The third character is the date code.

SOT-23 1SOT-143 Package Lead Code Identification (top view)



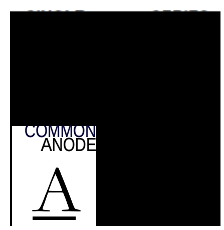


Features

- Surface Mount SOT-23/SOT-143 Packages
- Miniature SOT-323 and SOT-363 Packages
- High Detection Sensitivity: up to
  5D mVIpW at 915 MHz up to
  35 mVIpW at 2.45 GHz up to
  25 mVIpW at 5.80 GHz
- Low FIT (Failure in Time) Rate*
- Tape and Reel Options Available
- Unique Configurations in Surface Mount SOT-363 Package
  - increase flexibility
  – save board space
  – reduce cost
- HSMS-286K Grounded Center Leads Provide up to 10 dB Higher Isolation
- Matched Diodes for Consistent Performance
- Better Thermal Conductivity for Higher Power Dissipation
- Lead-free

For more Information see the Surface Mount Schottky Reliability Data Sheet.

50T-323 Package Lead Code Identification (top view)



50T-363 Package Lead Code Identification (top view)

SOT-23 /SOT-143 DC Electrical Specifications, T_C=+25°C, Single Diode

Part Number HSMS•	Package Marking Code	Lead Code	Configuration	Forward Voltage V_F (nV)		Typical Capacitance C_T(pF)
2860	TO	0	Single	250 Min.	350 Max.	0.30
2862	T2	2	Series Pair[1]			
2863	T3	3	Common Anode[2]			
2864	T4	4	Common Cathode[2]			
2865	T5	5	Unconnected Pair [1,2]			
Test Conditions				I_F=1.0mA		V_R=0V, f=1 MHz

Notes;
1 . ΔVF for diodes in pairs is 15.0 mV maximum at 1.0 mA.
2. ΔCT for diodes in pairs Is 0.05 pF maximum at-0,5V.

SOT-323 /SOT-363 DC Electrical Specifications, T_C = +25°C, Single Diode

Part Number HSMS-	Package Marking Code	Lead Code	Configuration	Forward Voltage V_F (mV)		Typical Capacitance C_T(pF)
286B	TO	B	Single	250 Min.	350 Max.	0.25
286C	T2	C	Series Pair[1,2]			
286E	T3	E	Common Anode[1,2]			
286F	T4	F	Common Cathode[1,2]			
286K	TK	K	High Isolation Unconnected Pair			
286L	TL	L	Unconnected Trio			
286P	TP	P	Bridge Quad			
286R	ZZ	R	Ring Quad			
Test Conditions				I_F=1.0mA		V_R=0V, f=1 MHz

Notes:
1 . ΔVF for diodes in pairs is 15.0 mV maximum at 1.0 mA.
2. ΔCT for diodes in pairs Is 0.05 pF maximum at-0.5V.

RF Electrical Specifications, Tc = +25°C, Single Diode

Part Number HSMS-	Typical Tangential Sensitivi TSS IdBm) ia f = 915MHz	2.45GHz	5.8 GHz	Typical Voltage Sensitivity g (mVI pW) 4 f = 915 MHz	2.45 GHz	5.8 GHz	Typical Video Resistance RV (RD)
2860	-57	-56	-55	50	35	25	5.0
2862							
2863							
2864							
2865							
286B							
286C							
286E							
286E							
286K							
286L							
286P							
286R							
Test Conditions	Video Bandwidth = 2 MHz Ib=5 µA			Power in=-40dBm Rb=100KO, Ib=5 µA			I6=5 µA

Absolute Maximum Ratings, T(=+25°C, Single Diode

Symbol	Parameter	Unit	Absolute Maximum[w] SOT-23114	50T-3231363
Plc	Peak Inverse Voltage	V	4.0	4.0
T	Junction Temperature	°C	150	150
Ts7u	Storage Temperature	°C	-65 to 150	-65 to 150
TOP	Operating Temperature	'C	-65 to 150	-65 to 150
;,	Thermal ResistanceRI	°C/W	500	150

Notes:
1. Operation in excess of any one of these conditions may result in permanent damage to the device.
2. Tc = +25°C, where TL is defined to be the temperature at the package pins where contact is made to the circuit board.

A

Attention:
Observe precautions for handling electrostatic sensitive devices.

E5D Machine Model {Class A)

E5D Human Body Model {Class 0)

Refer to Avago Application Note ADD4R: Electro-static Discharge Damage and Control.

Equivalent Linear Circuit Model, Diode chip

Rt

Rs

CI

Rs = series resistance (see Table of SPICE parameters}

Cj =junction capacitance (see Table of SPICE parameters) R

8.33 X 10^{-5} nT

Ie+I_s

where

I~ = externally applied bias current In amps

IS = saturation current (see table of SPICE parameters) T = temperature, °K

n = ideality factor (see table of SPICE parameters)

Note:

To effectively model the packaged HSMS-286x product, please refer to Application Note AN1124.

SPICE Parameters

Parameter	Units	Value
8v	V	7.0
Rio	pF	0.18
EG	eV	0.69
lay	A	1E-5
Is	A	5 E -S
N		1.08
15	R	6.0
P_6(VJ)	V	0.65
P7 tXTI}		2
M		0.5

High Frequency Laminate Selection Guide

Frecuency r

PRODUCT SELECTOR GUIDE

ROGERS

rc.....- v.`rnr nls

Custom Materials

Eli IFLTP I fi ICL" T M M " YT cr~•r.:. i.-

Piotlucl	6Frer8k Gorcmn4 •r 4r 18 GM (rPm11		M ma WI oY 06dh	T~wW m ~el~thnt or •r ~JOrGM ISErG	401u01a nOH~	ˇf f i f H~ n01	k1r~Yner• D4&!41
	Fioc "	EMilwr'	Iha)		i~ldmil	41M	11 cap
M + PTFE 3as Rhcr	233 t 5.03	233	5.0012	-115	2 1 0 '	3X10`	0.11
R71tlrwl1 STM FFE Sass Rhlr	220 t 5.53	2.10	0.00X.	-125	2% 10'	3X10•	0.03
RTIdurW 68601.2 FIN M E [anpmm	I.9fi t o.Ew	1.96	0.0014	+U	2.1 X10.'	2,6x 10~	03~
fnJtluHld&f~ PTFE Oaamc	241x0.0.1	2.98	0.0012	412	15'	14f	Dill
RTIdraldl 2 PTFECaramE 55S%n Gwsa	•291x4.0♦	2.40	5.0075	c-0^	10°	I &	0.01
RTi d PTFE Caramc W"io5 Crass	MN- 3.OQ x OA1	2.96- 3.00	5.0015	-!.5	10°	I &	5.13
Mf~ PiFE CaraME	1430:0.35	10.4	o.OQ73	ia5	3 8 1 4	5 X 1 '	0.01
TINA+ 9 H}Vrncatan Farank	327=U032	3.34	0.0024	+d7	IX14~	1x10°	"10.06
1 M I I H}4rncatan C ra-l:	450 ~ 4.0.'5	-1.54	5.5024	+15	111 10kff	i m i 0"	"x 0.07
71Y/A 6 HlUrncai ac	6.00 t 5.06	6.O)	o.O@3	-11	1 X 10 '	i R i o"	•s UA)
161116 H~vrncaian Earanlr	4.20 s 823	9.56	0.0022	-	2 %i e	8 x i 0"	"s 5.04
Tli1314 Hldrwa{nn Earank	OM=8.215	9.M	0.[I®8	•-3	nkie	m e	"cu;
OLTRA,L4M`N66 'rl : Hrurr G4	210-2.60 x 041	2.16-1.B4	5.0014	-A00	2%10`	1X15•	0.03
IILTRAILAY 7846 Lqud Erysblrnc 'uymrr	295	3.06	0.5525	421	1110	i x to"	0.01
%TI .1I0 88163 igh TUnpuaLra ·hcrapl~U=·	10.05		0.06»	sP	10•	10'	030

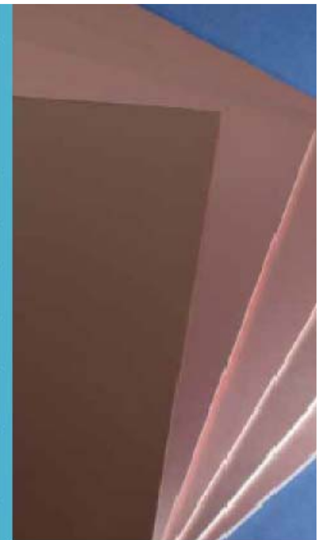
r h ° Oon~LYRp W m"K ;irpld} BU MrM Ala	I:nI I	El~a mlori hckcTl U 1Fenn N	I	N ~ I ne;36₃rm} EL11 Follbh, Iwnwrt {Trylral}	IlelCIGI' CrIₚlrll	RrRnadbL1 BaNg UL wI	Laa& I'rorrc MM	FnJ₃ Lam
B.M	IF	ppmf'L [rml mlf	E	I 17.7 all	21	xo		res
a.74	IF	17	Z4	7.1		Y-0		Yt§
U.{%	ii	11	16	El	2B	xo		
	17	17	24	4-1	21	xo		
0 4e	ii	13		14.2 11 HI	7.1	xo		res
n)E;	1Z	13	34	1~'~ 1121	27	xo		
o s1	ii	13	34	14 iL I	uo	xo		res
1J1	11	11		6B 11$	1.a	IION FR		TP5
	14	IG	36	;5 8+7	1.3	xo		rr$
	17	15		5h	z2	xo Fsnan		Yt§
n £2	14	1E		52 I	9.9	xo		res
a A	18	23		6 2cgl	-E	41Y1 D		YI5

T1~ r1Yar arr a rr~l~~ of >. n~apr ~~ br Cx rl+n a

1'R ~drladwl ■We amh~ I b p R ~ .

Iti rrwnrrrtbn ran har Pnel I' br Orls Y. mrd In -you n ~rpr Sr. lr~r IoM rr.rn.~ Il a MYrtirbabatl mrrrcl sr~1. Nrvanv n4 1 var~r4 Yslrbrp ~rwrraflrt nw,ira~6Y1b' a 116~~ b a w-rarlrr ea•~ra Iti urw rlwid S rnha a. .JIb ty a IIRr[cE nftirt_br rrrir Wa

M1slmp tl c~rr• Si ar crlrMr~ arfln n~1 trap b a,. ~Yrhlr paprlYr A h L ~tl rrvYrthO. lla ra4 a tla~ rsr~a rt Ir~ar Y rp~fln. autl a h1~rFr tlgar S ri rrr vı cfuk ~r¢r Mhu¢~ Fsgaa' 1 h haws} raYrYY hrn• bwn rcd araa ~rl~ n I.. zn.n4lr lr I~e'Y elaM I~IItl4b ~pm4~a rr ehal~k, II, BAR H R H 1ti n~~r wWrW rik ~Wartl~~m~l:db flrTr I'Xrsa owr .ru t Mrrt as pn~L



Metal Claddings

1~'n0 t a T~1o,•c

m rtara Hn nec. P4 I ml I!add

A ~ i d

9R~0d1pr111Y~	1 p5l FT1	0.4	CZ	8]3603. HLta 0G, RD 0I I . R630C3 F 3 8732114 00310
	14 ux 0 A n i l	n.3	C3	RTitluold 597.3, ,60x262!62. 505,601 d1A LLSMLAAI ` 20 0 m IIr !
	1 Q5l FT1	2'.1	OS	8]3603, 64J3006.F 301q 000036. RP '03 0(020fi. 873210
		1A	DA M m	I4GTIU9Id39FO S ~ h M 2 , 5203.60P5,BP1D.M
	15 of 19Wm1	OA	t19u m 0.4	LLTR4L.0J4 3600 TIYY• 74.610, 101 I.nlr11
		os	0.4	LLTTYLL.AAI 3000, STR Y- 7DDO.%T71ur91a-8000 ~ I ~ Ds

91k~c1d~pwlr4
Lary. Pra4Yr
0o•v'r 1FMt~tl

		os	0.4	
		os		
2n[170um1		3.7	0.4	
1 m. [35um1		3.4	OS	874601 0474.30
1&ux(I		2A		
m. (36um1		OA	1.1	A7o10
tl	ml	os	CS	lb345

LoPra~Fdl

TAY Thh R h Fa5lstr Fdl !a {16uni1 olln*¢~ly'	2A	0.4	
OaWtI . R I Pasdstr-CmWCGr Y6tlcrtY	74	OS	073603, 7433066. Fn3010 0000£. 04-103. FC~rR06.
25 ahnc'3 ax 119ym~			873210. Rr1fu 4970.5906 BCU2. 6-202.6006 6I2!O.. a-ImM
Ohmcgd F. t - -CarWCbr h6tlcr~Y	1.0	0.3	04346036. F 4}171# LIn 874603[14mhabz

FroPer'LY

14	33	00	40		2.2
					27 1.74
2		3	3	9	3
	1A6	1 .62		1.30	1.74

L I x O ' n i ~ J Y b I a•ea t HLb1

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TnnlYF 7S4(I .kpd

Ytl Rrilaihlq' AIEHn a Nn

TF/cl411U In Imoµ	000417 .UC1 Ta	00014 C 0356.	O 0033 Y} C71	0 0861 1a01a7.	00067 .C 2114	00023 6302

Meuhnx~hYN	IIerclt7	rhennd Cu LL11Nty	0DIMOent 6 r h 7nd

.ʸ,rrrlnri	**BC61**	Poor	2.7	1y7	24
~071YF	?W lgo	Ertl	# S	1W	20
01046w	1 70	**Fdrb50o4**	**09**	396	17r

High Frequency Laminate

Standard Thickness, Tolerance & Panel Size in (mn-)

	UrMUGliJ J I M : I HIE LHC PilE {WII FJUi I IIE;LAUUIMGI	;iLAlILI4HD L' L=UUIHGS	SIAHU U ME L EI1L'S
RTJdurell• SR'N RTJdwc11 5686	O M ' 27In . : OBBB3' OB1B' C25am rOI -09F' OB15' C~91mm rOI -01' O BM' C309m rO1FR1• OB31' CT97mm rOI -01' OB53' 1 37Bm = O W 0125' 3.175m x O 1 F 6 i '	!4, !r. 1 2w EM 193. 7Bum ELCI T&I 2o2 RdNtll (19 35 79 FWIW Eu) ThIrll meml AL Eu. BR	16'X12- i3 mm X305mm1 18'X21- 137mm Xfiidnml 18'X35- 137mm X 915inm1 18'X%9- I137mm X1 21On1
I· TTJI . &1 56b7LF	OB1B' IC25Emm1 x ODBi O BM' C x OIFB1 0 B25' o625m rOIFB13 0830' C7F2m rOI -02 OB10' 1OOfim rOh42 O M ' 12T9mm z8hf3 OA M' 3.31Bm x OIFBS	A 1 uz FOI II um 35um WG)	12'X18 I2 P2% +i 7 m 21'X5 IFIO% 1 i2m1
RT· .~drdl e&12: III! c119282 '1IT!durdtl 92fi2FR	•aDBS' - - - x a[IBo-~' 'aI J1B' a[IB07 'a n n 1x11' 'aa39' z x1991' 0 D50' 1.321mm x OIFB2' 0120' 3M9mm r O f W '	3i A 1. 2w EC4 IB.3. 1# 7Bum EM I o2 RdNtll F J!19 35 7B FdIW Eu) •• I 1B ro a1MMa NI ThdM memIAL Eu. BR	18'X12- 137mm X3BSinm1 18'X21- 137mm XfilBmml 18'X35- 137mm X 915mm1 18'X19' +~FmmX1.21'7 II
R· TJdwc119666 RTJdwc119810L.M	O M ' C.127mm rOJFBB' OB1B' C25Amm x01FBB7' 0 B25' CF35m rOI -01' 8959' i2romm r a f l a r OB75' 19B5m rO11 O IBB' 3 31Bm xOMFBS'	M. !a. 1 2w ECG {B.5 19, 35, 7Bym I o2 RdNtll E J {17. 35. TB Fo1o-i Cu) ThIrlL meml AL Eu. BR	18'X12- X rid aial inn 085'IB.12 mml and M M p2S4nml I S ' I I e I F N 610m antl aBIC' 54nm 14'X10'1 mx ng 20'X28- I9CE nm X509nm1
	OBIS' Alm = O M P OL2B' C 309m rOfl-013' 0830' i 2mm rOfl-013' QM' 1,~2lni m4L=91i' 0125' I3.175mml x ODBi3'	A1.2asWCCiS.36.79nmfDL] ThtltmembAL BR	1 8 ' X 1 2 ' X 306inml I9Fmm
– 1MM6 W M 16 1MM I d 7MM 1'11	OB15' C:Almm rODBi3' O M ' D95 m = 0 : ' OBSB' 127Bmm rOfl-013' OB75' 1 m rOfl-013' 4109' ~3,349m'n~ =4JF913'	A1.2 wWC (19.35. 7Bw EDL) ThtltmembAL BR	18'X12- 4 mmX3O5inm1 1 8 ' X 2 1 ' FmmX61dfml
	o m' to mml x OL-0C4 OBioi 259^ xaD004 09117' 8 7 3 n x a M I OoI H %92nm1 = a m oo3B' C7E2mm =Of-0i 4980' 1 33Inim =4L42	1& 1.2 w W E 1EL.1 B 35 Town WL] 3&I 2 o7 RdNtll w B 35 TB m I -1 Eu)	18'X12- 137% 15m 18'X21- 137% Flam 18'X35' 1sJ% 9 1 5 m 18'X%9- 1219
UWIIAI..dM ST6F	ODBI• CA¢Smm x1253L OD62' CA51mm =125'I OM' ILitilmm =125%	A 1 o7 I1F nO FBC m g Io>•nIO11W nr~vw tcm WI 1d1	18'X12- 57mm X 31 n 18'X21- 4 mm XfilBm
TCT.~durall°6608	0L62' ~ILc5l mml x 12 91L	!r I18wrt1 vEq Iol tarawr~11mt EBG 101	18'X12-I4 mmX3O5inm1 1o'X21' 137mm XEI Wm'

{{i ~'i~6 C79-m'		; I m x 1E2 1m;
110'1' p A05mml IIQF P A51 mm		12' % 19' [30~4nm x J6Jmml
nos , . 1 2 7 ,		24' 1B' IUnm X157^+^1 25
Im5• ~0.127n~		X1E'
IIR36'f 'Erm-:		12' 1B' (305m 15 24' 19' 112m X1 m X 5 7 9 7

RBI150F' h gisi L01' 16 C ' m ,

Ordering Information

Rogers' nigh maq.,eney ran11R8ˆ163 can be p d by orntsc4rg a F1ogers' Cuehonler rvx3e Reprehonisti we et (4801961-Y o2 or one01 our Inlerrlet]arffil a>ttleas.

To erleure }eu rec* 1lle rnalensl rc dour sppllcauon, please rncl.1tle artier Intarlne4on ier ea[tI of lire tata[yxles l lsled beew. For more daTaled pr M u d Inkxn ~hcrl, rerer o the ttlsr1a In i n s product 9elecior gr Id

Gd

L'I ul wIls RTR7Jrrrd 'J1S FU,' ,60a'2, +J2t?. 1". lY1PR,tla[& L3}1:;LM.WTRl~LAIA' xya,LLTR,SLAkM lXI,TMM'A,a,F,,❑, errtl ra, 7[TAiJrad~, SYRf7hr", F$1)3[xr~^'. R~x~rrJ!~'", ROreaJS~, F$IX4lD!i' , F9-Jf3d11 ROrau 1 u^' Rac121U ~~

RCUa'J.+eC^' . F tSJ.1;u^' end RLtTi ~ hKjfr Irequon_~ Iemirr ! . 6mtlrrg Frm 7lU J1 Propop R17xaxi, ROrlJL16,

ROC~c11 o, F7Dts:K1' , RC~4 ~t . R C W 4 Jfˆ'~ entl RT rod aurJ2.

THICKNESS AND TOLERkNCE
L'1~u'uhr`.IVt..ra!sr.rlarnly!gNStllxfdosll.dA r r Ihckrera; ..rlI Irl ociper ~adtllig- Caelmi iokrarrom e1r 1tva11nhlu m U M Mm upon IoQ~sl.

TYPE **OF FOIL** C **LADDIHG:**
·i %s l c w. Ulultn>]r>cn l l M + t e r lal, 1h, 1, ax. rokd rwppmrlai. TMM entl Po.}ilJ K1 *saioe* lemrr~ *arm rc[* appllu1 wrlh *!A or.* are~rc•]r>pmdlotl *ar* rdled aoppor kill *Sar o* nlalorlel p a i n s rosy to a.~>fplled u,dad. C;er Ro~re CY~amor Sorxoe Fbpr mnhl es forinc lap6orc.

ThtkaFJmInun,e1r>QFerantl61aech~tl1l **a 1 d m a n** *Rogers* R T . i u ld lemrvlee. Thrd+.akrnlrum **andhre_scleddms ora dmlohlo** an n1o~ TMI11 l o m r ~ , Thtx **mold** m t l d r g 1s

rc[a mlmhlo *m R* l e m r e l e . Thtx d r u m , cnppa, arrtl hra~ Gadtlingr ere• aba aaerehh h a range al Lhldrrlo®s attl I F r r r a e Io4aanms Clrxrr Ihki'. rnnW 6edurF~are avalFrih i{an rmgr.esr

9mrl~r' S;fo~asEdaaleRimers'ITEIdmr'~10GVh!11e16.

C C f 1 U leoal~rlhnluorloomavdmhk,

Al D *,or* r' u l r *r o o m s* rnreA he klarlrllod al l *he* lrnrr the *area !s* pmood. *M* s p o i l ioslIrq *a* dad *w a* vnikin *e~* regrJretl, *o* I1c nel nrey M Flamed

A904JT ADVANCED CIRCUR MATERIALS
Ir DJ 6lNi r] i , r:7JC Milk~nal'i U 4n A1~ 1mn.J cILm Fr~'l

Iraquarcrr Wnr~lus ord prmpr4 ; lar opplKahcc h IAe wlreleee Wm sle[Im, eeroepam antl d i l a r n , w1anndh~o, h/gh oed d u a l acrd atlverrnd a,p podrogrlg ntluslries Nl a our protlucd *are* menurecLLraJin *an* I J- Jl21J MJ ccrtF 1 l o d l r w[lh 'areed el the c urrd prr-.xas nc4.og .

O U R G U S T O M E R S

C r c .111 7; rK)lij!! l7rFarvl Equ~nnnf r nr.famama ([}CM) andprlri 1Kr1_1.11l>t%lrd luhrK~ors{Tram grrd'.-lum pmlcl,pe shraps lu high v l>tI.m xupura llom} tar atlverroed aredronk appllmlKrrcs.Y mNr aae>brnas arourd the gU **wEh** rrrenakclurg 1oal6oc ar 1 c~mror sappart In M U , E u v p e , and Mmrvr ~4nbi-~.

HOW WE WORK WRH **YOU**
Yn, we r tk,x:l r w' lh pm' r'nAlAl **1 r ~ g o l s** b **ar4~uh: ropily** w N i.M d!; krunc>•gi:;i ;I arrarc, ontl xe rnan~ledua protlrrcL•-c lu }+o.rr arcxl m1alr;l'K1a raqulremmr~ LHlr pravklo all llrm r n o ~ r y 7Nnlrrg aid 4x nrkal suppa'I la irrcsrm IFer ou rrretaiehwak In K i u prcra 4 I ; . 1h aremmlrl .1 la WWN

u nned lrrleroeainpellllon Wh ur~q.e hlgh-palamrarne saY.allora.

SPECIFICATION R E W I EMENTS:

APPENDIX B

Schottky Diode Selection Guide

BIBLIOGRAPHY

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