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RF TO DC CONVERTER

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Table of Contents

Abstract

RF to DC Converter is a component of a wireless power transfer system. This component will harvest Radio Frequency (RF) energy and convert that energy to Direct Current (DC). The wireless power transfer system is being designed to operate at a frequency of 5.8 GHz. The RF to DC converter is a passive device that utilizes diodes. The only outside energy that this system will receive is the RF energy that is harvested by its receiving antenna.

Acknowledgements

A special thanks to Dr. Prasad Shastry for all of the help and guidance he has provided throughout this project.

Chapter 1. Introduction

Wireless power transfer systems are the next big innovation in mobile devices. This technology will allow for users of mobile devices to be free from the wires that are currently being used to charge these devices. The RF to DC converter will allow for a wireless power transfer system to convert the captured RF energy to a usable DC output.

The first aspect of the project is the literature review. Through research, several changes had to be made to the preliminary design of the converter.

The design process is the next phase of the RF to DC converter project. Each component of the project has to be designed in Advanced Design System (ADS), a high frequency computer-aided design and simulation software. Using ADS, each component is designed and redesigned independently even though all components are actually co-dependent upon one another and must be designed accordingly.

Once all components have been designed, simulations determine whether or not the component is working. ADS has a very good simulation program, allowing the RF to DC converter project to be accurately simulated before manufacturing the printed circuit board. The manufactured board can then be used for circuit assembly and testing. Each component that is not a microstrip has to be soldered onto the printed circuit board. When the circuit has been assembled, it is ready for testing.

The RF to DC converter is tested on its own and in a wireless power transfer system. This system consists of all components present in the block diagram (Chapter 3) and models a real world scenario of how this system may be used.

The possible real world applications for this project are endless. While focus has been placed on near-field wireless power transfer systems, such as pads that have the capability of

charging a cellular phone when the phone is placed on it, this project's applications are more contained within the idea of far-field wireless power transfer systems. This, for example, could be a charger that wirelessly charges a cellular phone from a given distance. However, very little focus has been placed on these applications in industry. This project, though, is moving forward in this direction, showing its significance in a narrow but growing field.

Chapter 2. Literature Review

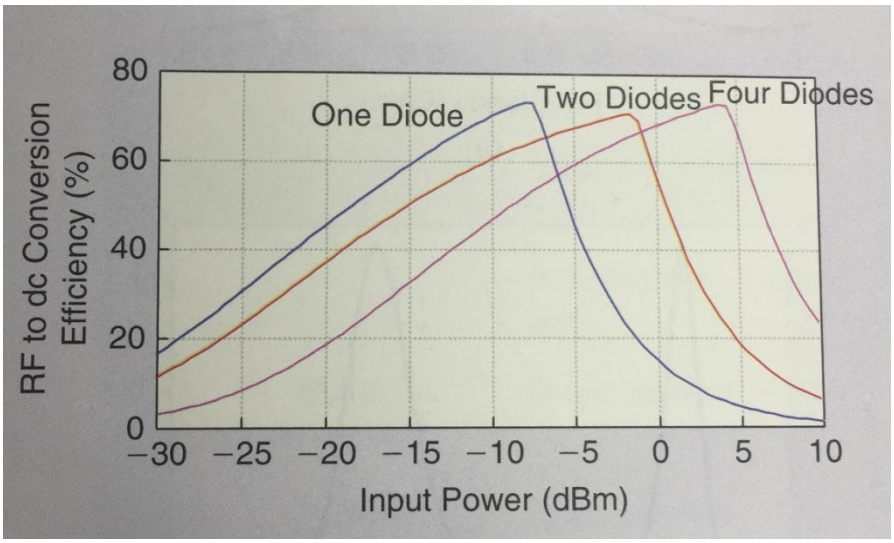


Fig. 1 Efficiency of Full Wave Rectifiers vs Input Power [1]

Fig. 1 from [1] shows that there are numerous options for rectifying RF signals. In theory, it is expected that, the higher the number of diodes, the more efficient the system is. Therefore, it would be expected that the four diode system would be more efficient than the two diode system. For lower power level received, though, this appears to not be the case. Fig. 2 gives a description of the four diode full-wave bridge rectifier. Fig. 3 shows the two diode full-wave rectifier.

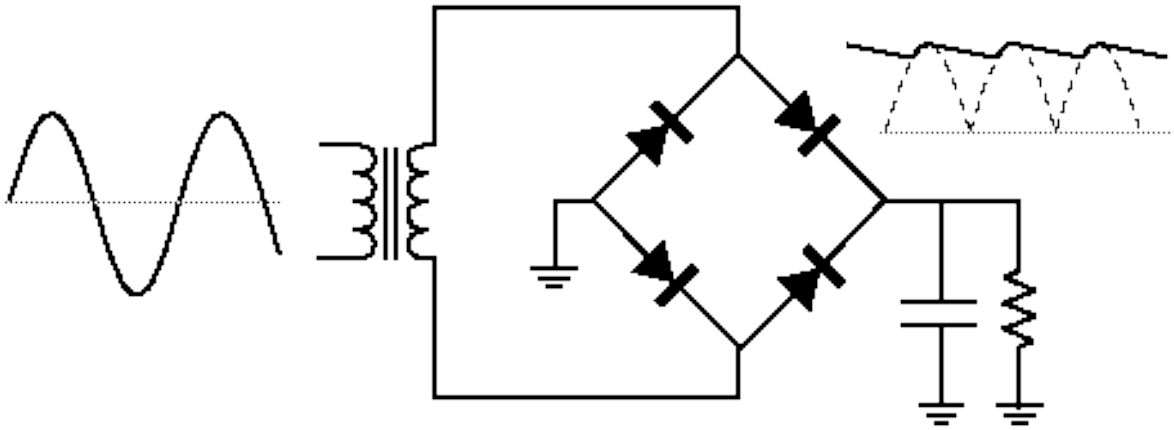


Fig. 2 Four Diode Full-Wave Bridge Rectifier

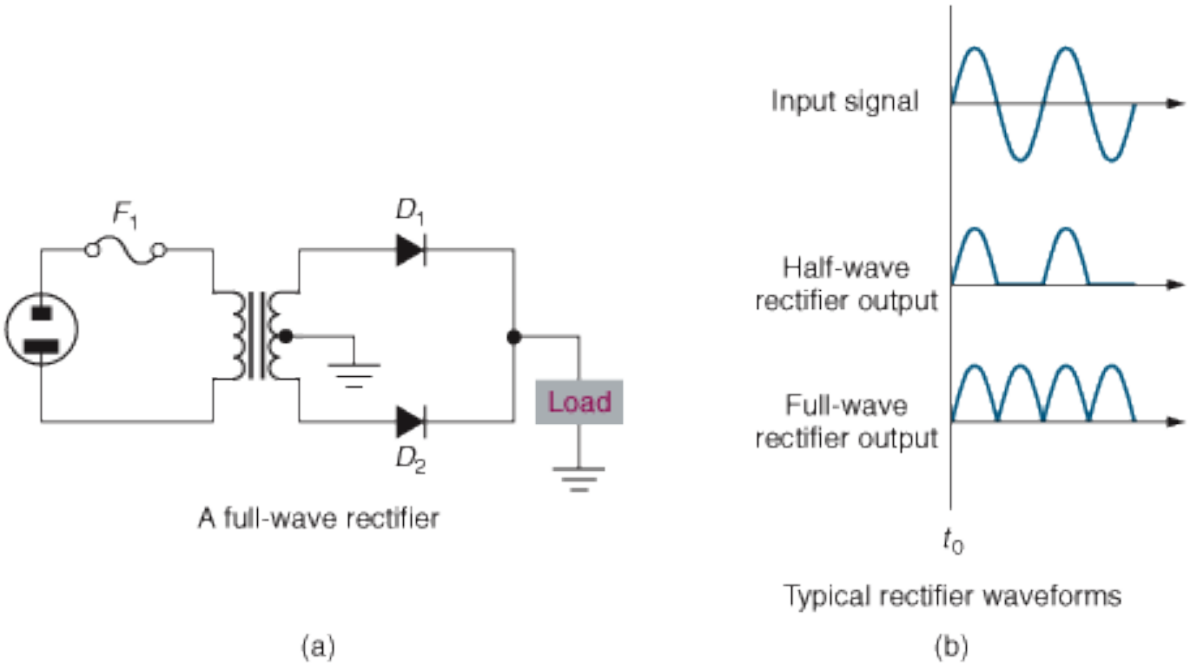


Fig. 3 Two Diode Full-Wave Rectifier

Wireless power transfer systems are not a new idea. Engineers have been trying to harness this technology for years, but there are many challenges that need to be overcome [2].

The first issue is efficient power reception. In order to receive the power efficiently the impedance of the rectifier must be matched to a receiving antenna over a wide range of frequencies. The power that is expected to be received by the antenna is also going to be extremely low, so a high gain antenna is most likely necessary in order to have enough input power in the system.

The issue with wireless power transfer systems is in fact the efficiency at which they operate [3]. The design in [3] was designed to operate at 2.45 GHz, which is in a different ISM band than the one being used in this project, but it gave a good baseline for efficiency expectations. The design in [3] was able to transmit power of 20dBm over a distance of 1 meter at an efficiency of 56%. Once the signal was rectified, the total system efficiency from transmitter to DC output was 19%. These results were also found in [4]. This gave consistency for what is expected of a RF to DC converter system.

This project has to implement a balun in order for the diodes to function out of phase from one another. The balun for this project was designed based off of the information found in [5]. With a little trial and error to maximize efficiency, the balun has been implemented into the system and functions well.

The project in [6] is perhaps the most closely related project to this one, consisting of two portions. The first was the design of a wireless power transfer system operating at a frequency of 915 MHz and being built out of commercially available parts. The second was the design of a rectenna system functioning at a frequency of 5.8 GHz, integrating a rectifier and antenna together. This rectifier system is exceptionally important when referring to this project due to the fact that this is the main focus of the project, making it a continuation of the original project described in [6].

Chapter 3. Functional Description

3.1 Introduction

This section will discuss the overall function of the RF to DC converter.

3.2 Block Diagram

This project focuses on converting RF energy to DC energy as efficiently as possible. The converter that this project uses will be in the receiving block of a wireless power transfer system. While design work has been done mainly for the converter, a full transmitting system and the rest of the receiving system is designed as well. This will allow for the converter to be tested in a wireless power system.

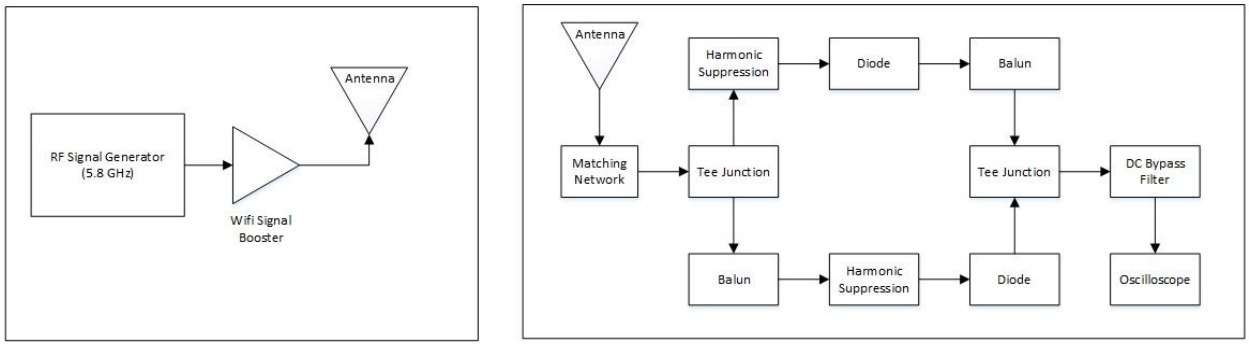


Fig. 4 Block Diagram of Wireless Power Transfer System. Transmitting Block on left and Receiving Block with RF to DC Converter on right

Fig. 4 shows both the transmitting block and the receiving block of a wireless power transfer system with RF to DC conversion, on the left and right of the diagram, respectively. Together, this system is designed specifically to function at 5.8 GHz and can function at variable distances between the transmitting and receiving antennas.

The transmitting block is composed of three components. The first is a Hewlett Packard 8260C sweep oscillator, labeled as RF Signal Generator in Fig. 4. This device can be used to

generate the 5.8GHz signal that will be transmitted. The sweep oscillator has a variable amplitude for the generated signal. The output amplitude of the sweep oscillator ranges from -1 decibel-milliwatts (dBm) to 16.25 dBm, which can be measured using a spectrum analyzer. The next component in the transmitting block is a Sunhans WiFi signal booster, labeled as the WiFi Signal Booster in Fig. 4. This product is designed to amplify WiFi signals between 5 and 5.8GHz from their standard amplitude (0-20 dBm) to 33 dBm. This is important due to the fact that, for this project, the transmitted power must be as high as possible. This product will amplify the signal from the sweep oscillator from 16 dBm to 33 dBm. The next component of the transmitting block is a L-com 19 decibel relevant to isotropic gain (dBi), narrow beam antenna. This antenna is a necessity at the transmitting end of the system due to the losses encountered in free space. With such a high fundamental frequency (5.8 GHz) the transmission losses through free space are going to be extremely large. In order to reduce these losses, high gain transmitting and receiving antennas are a necessity.

The receiving block of Fig. 4 is composed of two components. The first is a receiving antenna. There are two choices that can be used for the receiving antenna. If the received power is considered to be too low, the same L-com 19 dBi gain, narrow beam antenna can be used to harvest additional RF energy. If the received power is adequate, a Sunhans 6 dBi gain omnidirectional antenna can be used. This antenna will not be able to harvest as much RF energy, but it is much more compact and practical for commercial applications. The second component of the receiving block is the RF to DC converter that is being designed in this project. Each component of the RF to DC converter will be discussed in more detail in the following chapter.

3.3 Conclusion

The block diagram for the RF to DC converter project is a good starting point for understanding how the RF to DC converter works within a wireless power transfer system. Chapter 4 will discuss the design of the RF to DC converter system.

Chapter 4. RF to DC Converter Design

4.1: Introduction

This section will cover the individual components that make up the RF to DC converter and provide detailed descriptions of each. Each component is designed individually, but each system is codependent on the others. When a change is made to one component, changes have to be made to all additional components to compensate.

4.2: Diode Configuration

The first aspect of design that had to be considered in this project was how the diodes would be configured. There are multiple ways to design a full-wave rectifier. In this project there were two options to choose from; a two diode design and a four diode design, seen in Fig. 3 and Fig. 2, respectively. In this project a two diodes are used due to the fact that it was found to be more efficient. The two diode design ultimately dictates the overall size of the circuit as well. Each diode has its own branch in the design, which has a component of all other design components that are implemented in this project.

4.3: Matching Network

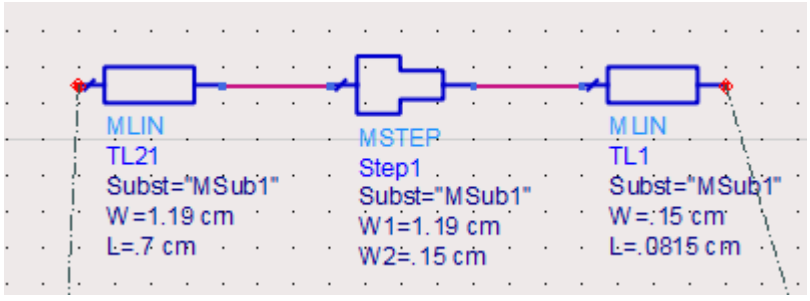


Fig. 5 ADS Schematic Design for Impedance Matching Network

A matching network is designed to match the impedance of the rectifier to standard impedance of a connector. In this project, the matching network is designed to match the

impedance of the converter to 50 ohms. 50 ohms is a standard impedance used in radio frequency engineering practice and will be the impedance of the coaxial cable adapter that will be connected to the input of this component. This will help to maximize the efficiency of the system.

The matching network has to be the last component designed, because the impedance of the system changes as other components are changed. In order to accurately match the impedance of the system, the matching network has to be the last component to be designed. This matching network takes on a couple forms in this project. The first of these forms is a quarter wave transform to match the impedance of the system to 50 ohms. The results obtained from this will be discussed in chapter 5.

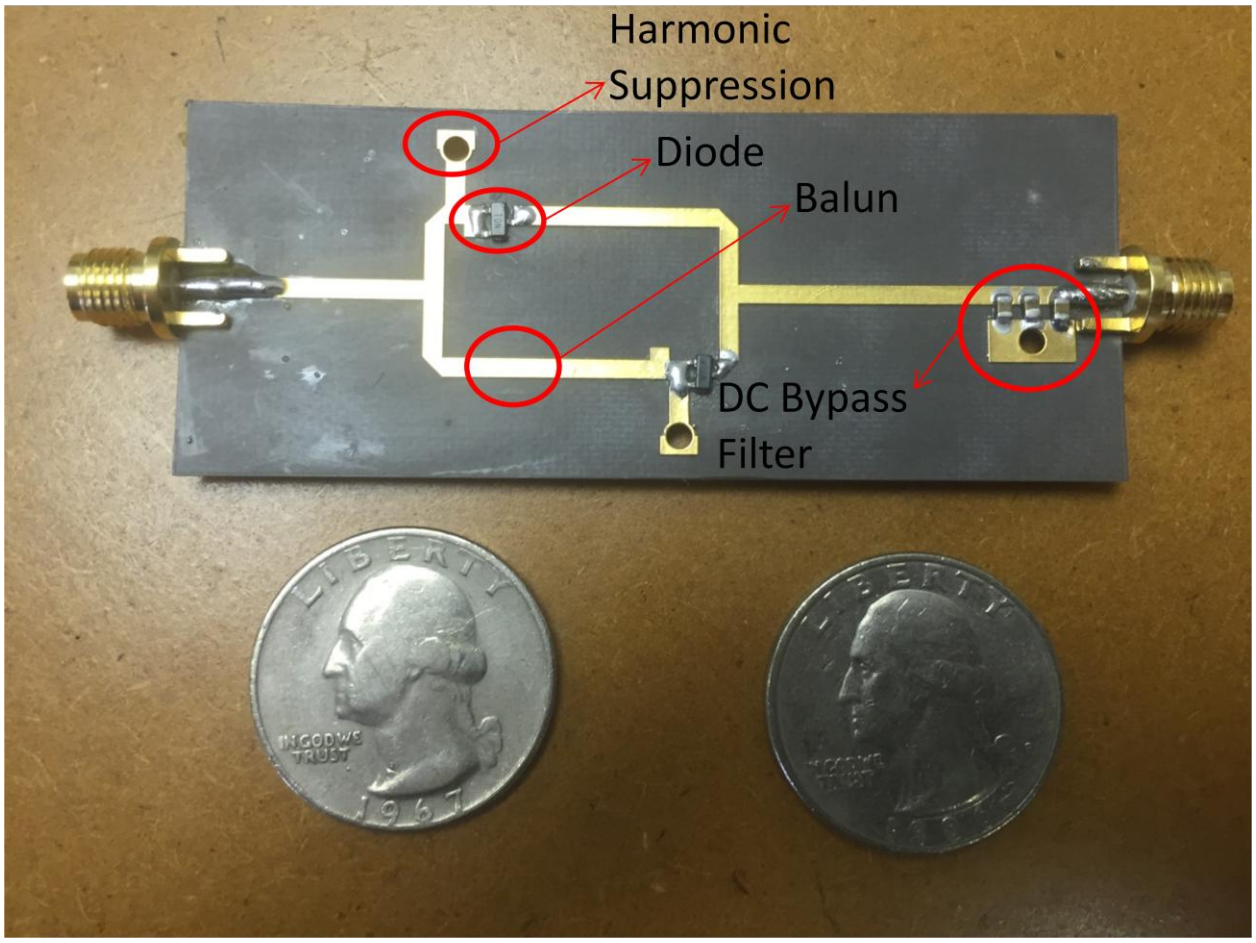
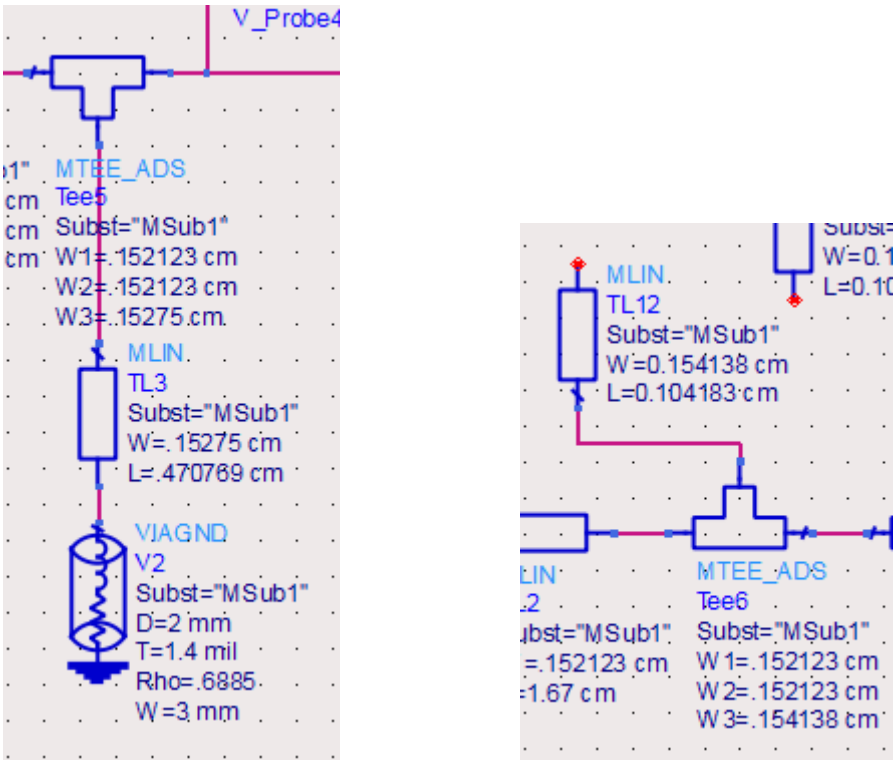


Fig. 6 RF to DC Converter (unmatched)

The second form that is applied and tested in this project is having no matching network at all. For a majority of this component design there was simply a 50 ohm 180 degree phase shift line being used as a placeholder as seen in Fig. 6. The far left microstrip connected to the SMA adapter is the placeholder line. The quarters in Fig. 6 are used as a reference to show the size of the physical component, coming out to about 3 inches long by 1 inch tall. Each of the individual components labeled in Fig. 6 will be discussed in detail later in this report.

The simulation results for the system using only the placeholder line are extremely promising. For this reason, the system using the placeholder line is manufactured along with the system using the matching network. The simulation results will be discussed later in the report.

4.4: Harmonic Suppression



(a) (b)

Fig. 7 (a) ADS Schematic of Second Order Harmonic Suppression; (b) ADS Schematic of Third Order Harmonic Suppression

In this project, harmonic suppression stubs are used as the input filter. The diodes will generate harmonics when they are active. Harmonic frequencies are unwanted signals generated by the diodes. These harmonics are generated and transmitted in both directions from the diodes. If these harmonic signals reach the receiving antenna of the system they will be radiated in space. To prevent these signals from reaching the transmitting antenna, the converter was designed with harmonic suppression stubs. These stubs, as seen in Fig. 7, are designed to suppress the second and third harmonic frequencies. These are the only harmonics that had high enough power levels to warrant a suppression. The harmonics will be at frequencies of twice the

fundamental frequency, three times the fundamental frequency, etc. These harmonics have low power levels.

4.5: Diode

The diode selected in this project is the HSMS-2860 Schottky detector diode from Digikey. This diode is used in several of the projects that were used as research tools in this project. This was also the diode that was used in previous projects of similar type done at Bradley University [6]. This diode was also perfect for use in this project because it had a pSpice file readily available, allowing for quick and accurate simulation results. Once this diode was applied to simulation the results were promising; therefore, there was no further discussion on whether another diode would be used.

4.6: Balun

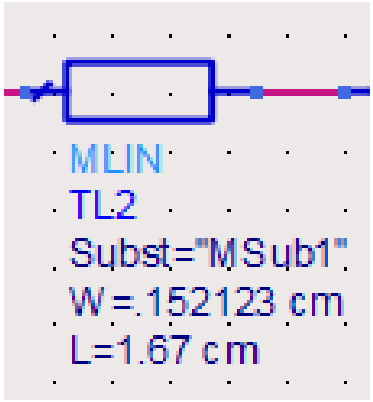


Fig. 8 ADS Schematic Design of Balun

The balun is one of the key components of the RF to DC converter project due to the fact that it allows the diodes in the system to function out of phase from one another. In order for a full-wave rectifier to function properly, one diode must be "on" while another is "off". In this system, the diodes will only be active when the incoming signal is high, or a positive voltage. In order for the system to have at least one diode on at all times, one diode would have to receive a

positive voltage while the other receives a negative voltage. This would imply that the diodes are receiving signals that are 180 degrees out of phase of one another. In order to do this, a balun is placed before one of the diodes to shift the signal being received by that diode by 180 degrees.

4.7: DC Bypass Filter

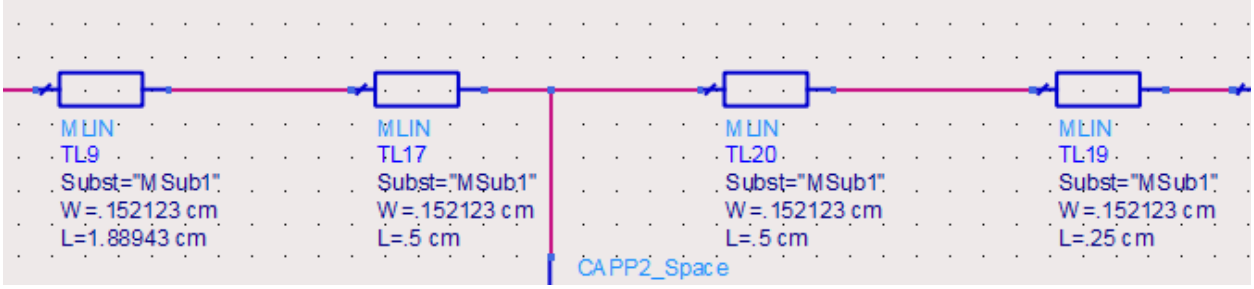
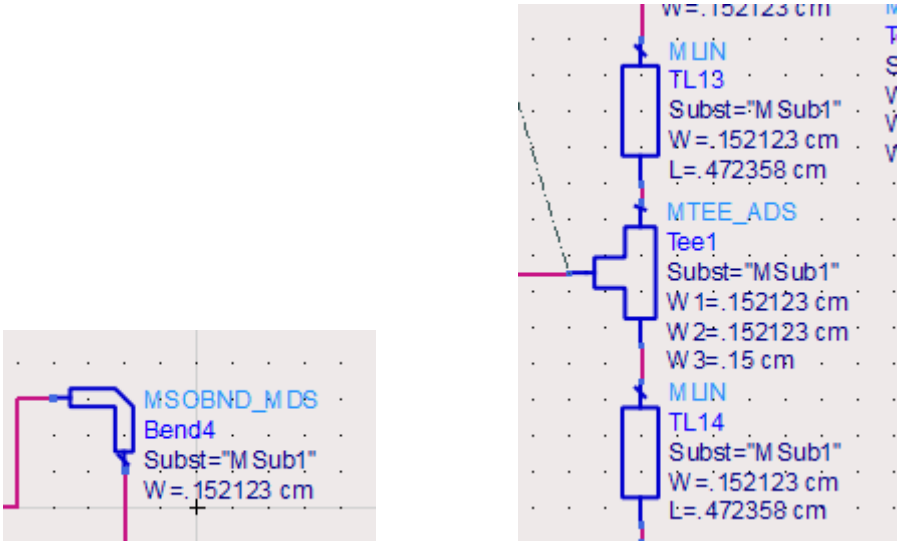


Fig. 9 ADS Design of Output Microstrip Spacing

The output of this system has to be filtered. The goal of this filter, though, is different than the input filters. While the input filter only suppresses the signals that are generated at the harmonic frequencies, the output filtering is designed to suppress all signals that are not DC. The most efficient output filtering technique found through simulations was a DC bypass filter. Fig. 9 shows several microstrips placed one after the other. At each of those intervals a capacitor will be soldered to ground. These capacitors will then run the higher frequency signals to ground and will allow the DC component of the signal to pass through. With several capacitors running the higher frequency signals to ground, this will allow for a smooth DC output from the system.

4.8: Discontinuities



(a) (b)

Fig. 10 ADS Schematic of Discontinuities Present in RF to DC Converter Project (a) Schematic Bend (b) Schematic Tee-Junction

Discontinuities in layout are inevitable in this project. In order to provide the most accurate simulation results possible, it was necessary to implement discontinuities in the schematics in order to accurately simulate the converter schematic as a whole. Discontinuities are inevitable in design of printed circuit board, so they must be accounted for in simulation as well. Discontinuities will give inefficiencies and alter the design of other components, such as the balun and matching network. These discontinuities also allow for accurate generation of necessary layouts. Without these discontinuities to connect the microstrip lines, the layouts would not be a continuous circuit.

4.9: Conclusion

All of the design components of this system come together to make the entire layout of the system. Chapter 5 will now discuss the simulation results of the layout.

Chapter 5. Simulation Results

5.1: Introduction

This section discusses the simulation results of two different designs that were produced in attempts to maximize efficiency. The first was designed by putting a placeholder line at the input of the system. The second was designed with a quarter-wave matching network at the input.

5.2: Unmatched Converter

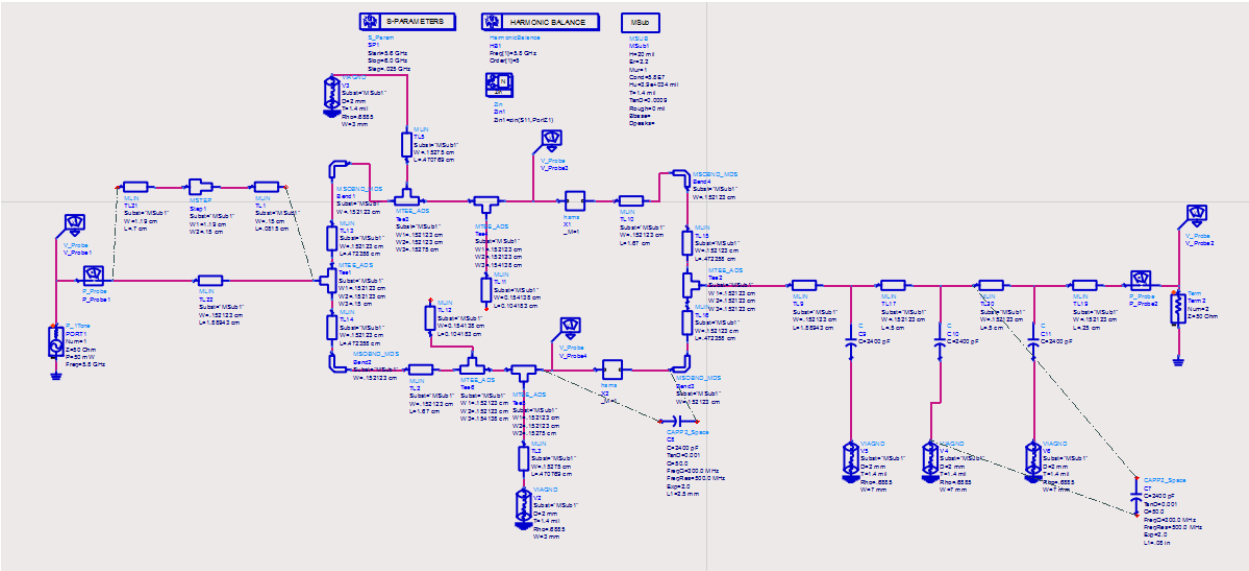
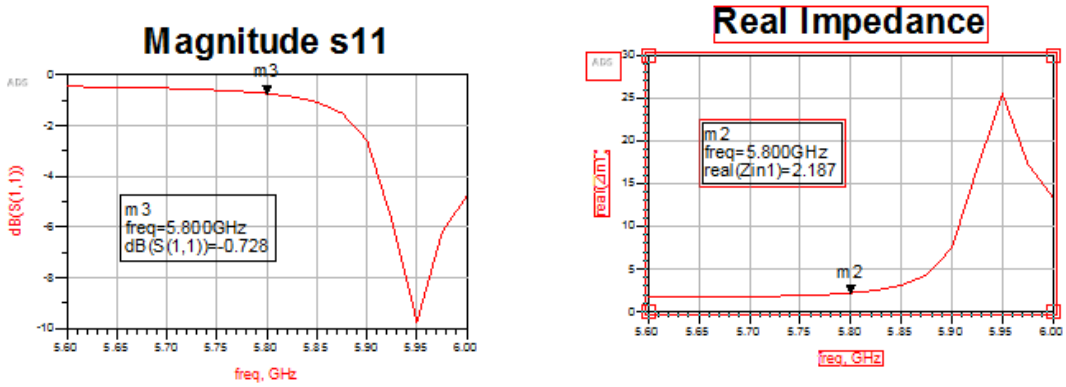


Fig. 11 ADS Schematic Design for Simulation of Unmatched Converter

Fig. 11 shows the ADS schematic designed to simulate the unmatched input design for the RF to DC converter. This schematic has all parts included in the design portion of this report (chapter 4) along with a few simulation parameters necessary to test the schematic. This schematic was tested with no input matching network connected at the input. With no matching network, this system gives a good baseline test for the project. The input, in theory, should

always be matched to what it is being connected to. In this case, the input should be matched to 50 ohms. Refer to the appendix for printed circuit board information.



(a) (b)

Fig. 12 ADS Simulation Results for Unmatched Converter. (a) Magnitude of Reflection Coefficient seen at input. (b) Real Impedance seen at input

From simulation results seen in Fig. 12, there is by no means a match to 50 ohms. The impedance of the system seen at the input of the unmatched network is 2.187-j10 ohms. Theory states that if a system is not matched to the impedance of the source it is receiving signal from, it will reflect a great deal of the signal it is supposed to receive and ultimately have poor efficiency. Fig. 12(a) shows that the reflection coefficient is also very high. The ideal reflection coefficient should be in the -30 and lower dB range.

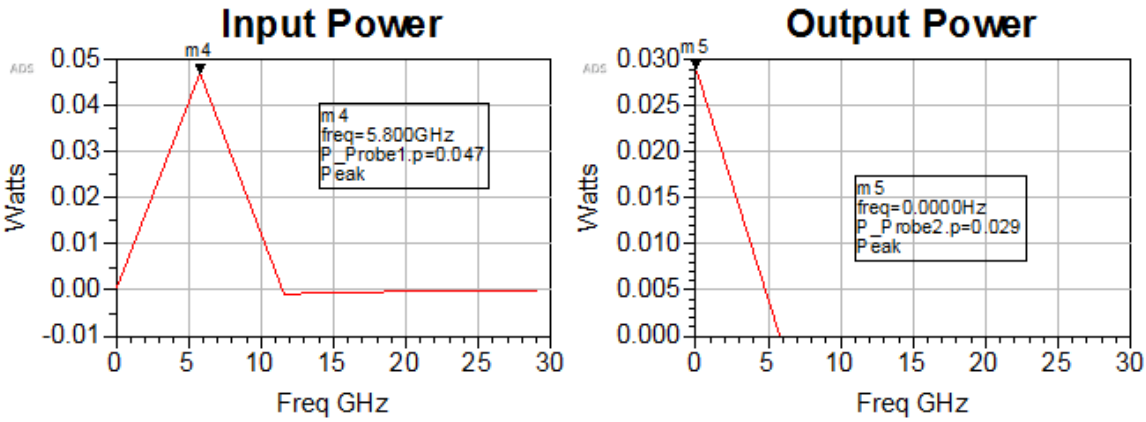


Fig. 13 Input Power vs. Output Power of unmatched converter ADS Schematic Simulations

The power input to the system for simulation purpose was 50 milliwatts (mW) at 5.8GHz from a generator that has a reference impedance of 50 ohms. The simulation results from Fig. 13(a) show that the system is receiving 47 mW, which would mean that only 6% of the power that is at the input of the system is reflected and the rest is taken into the system. This does not coincide with theory, but the results are phenomenal. The output power of the system seen in Fig. 13(b) shows that the output DC power of the system is 29 mW. These simulation results then show that the system receives almost all of the power that is available and operates at 61.7% efficiency. From literature review, the system goal was to eclipse 50%, so a system operating at 60% or more well exceeds project goals.

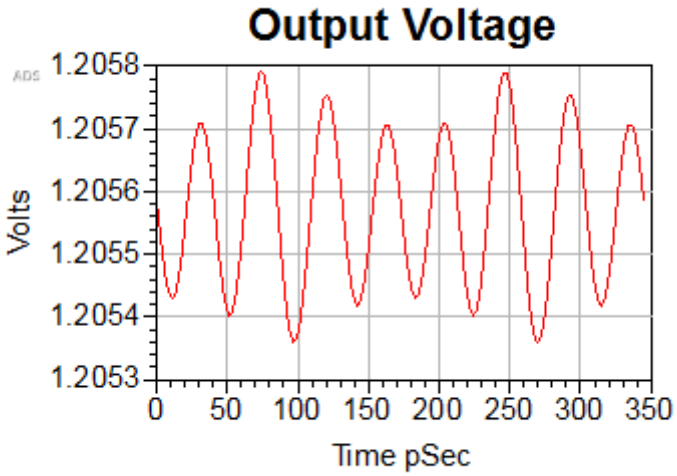


Fig. 14 Output Wave Form for ADS Schematic Simulation of unmatched converter

The output voltage of the unmatched converter is almost completely flat. For this project, ripple in the output waveform must be kept at a minimum in order for devices to be able to harness its output as DC. The ripple in this output is far less than the desired 1% that was originally stated as a specification of the project, as can be seen in Fig. 14. To calculate this, the peak-to-peak difference is calculated to be .0005 volts (V). This value is divided by the average voltage of the signal. This was 1.20555 V. In practice, if there is a lot of ripple at the output, there can be more DC bypass capacitors added to the output to reduce ripple. If the DC output has too much ripple it could damage the device that it is charging. The output here, though, is calculated to be hundredths of a percent.

5.3: Matched Converter

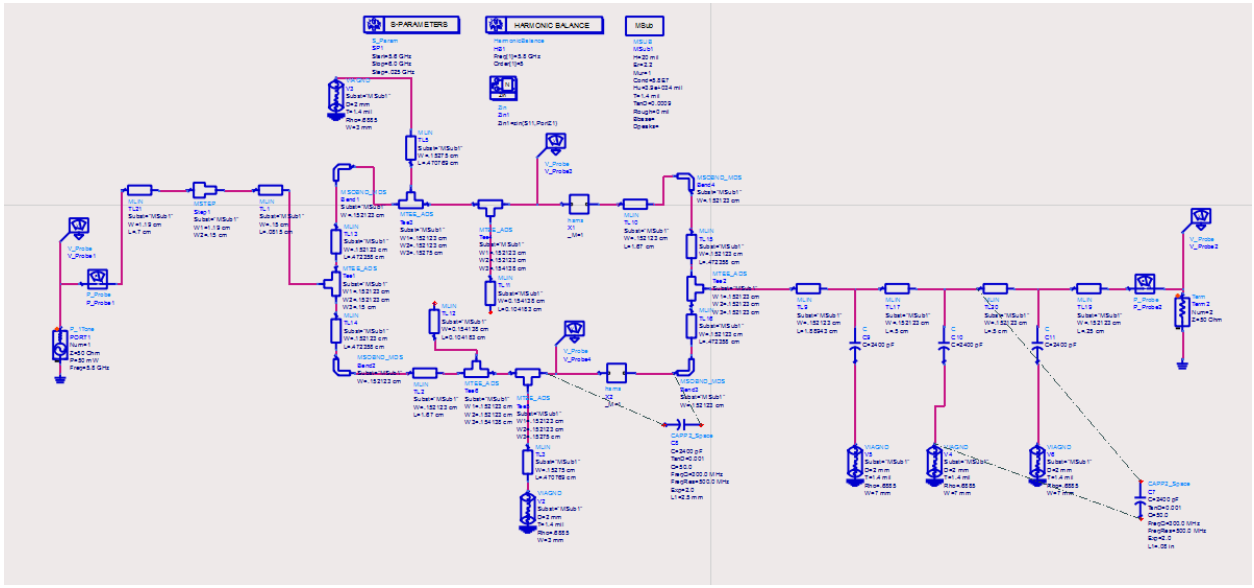
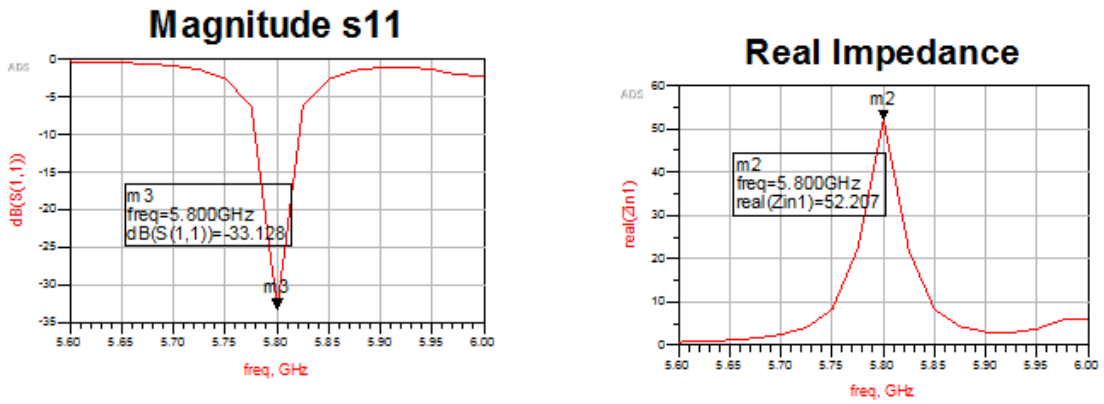


Fig. 15 ADS Schematic Design for Simulation of Matched Converter

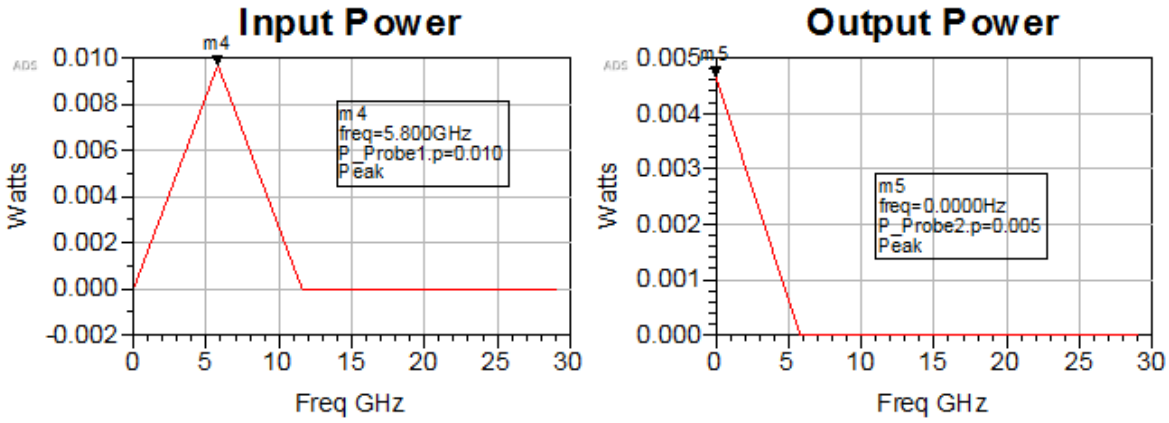
Fig. 15 shows the ADS schematic used to simulate the matched converter design for the RF to DC converter project. The matched converter has the matching network implemented as opposed to simply having the microstrip line placeholder. This design is what theoretically should give the best results possible for the RF to DC converter. Since the input is matched very closely to 50 ohms, the system should receive the maximum power possible.



(a) (b)

Fig. 16 ADS Simulation Results for Matched Network. (a) Magnitude of Reflection Coefficient Seen at Input. (b) Real Impedance Seen at Input

The simulation results seen in Fig. 16 show that the impedance matching network is working extremely well for what it was designed for. The input impedance is matched now to 52 ohms while the magnitude of the reflection coefficient is extremely low at the input. This, in theory, will give the best test results and allow for the system to operate at its full potential.



(a) (b)

Fig. 17 Input Power and Output Power of Matched Converter ADS Schematic Simulation

Fig. 17 shows the simulation results for power input and output of the design with the matching network implemented. These results are not nearly as good as the results obtained with the unmatched input. The input seems to only be receiving 20% of the power available from the generator, which means that it is reflecting 80% of the power back. This gives high inefficiency and does not allow for the system to operate well. Since the input power is so low, the system is operating less efficiently than in the unmatched case. The unmatched case has an efficiency of 61.7% while the matched case has an efficiency of 50%. These results are not necessarily promising, but they are founded in sound logic and good engineering practice. For these reasons, this design was also pursued.

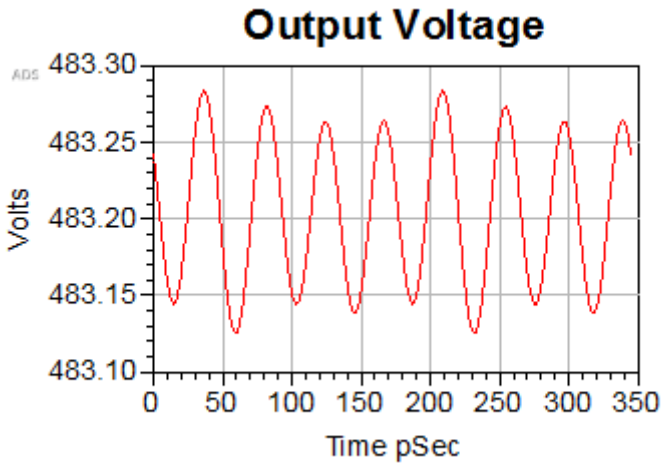


Fig. 18 Output Wave Form for ADS Schematic Simulation of Unmatched Converter (Voltage in mV)

The output voltage of the matched converter is almost completely flat, similar to the output voltage of the unmatched converter. For this project, ripple in the output waveform must be kept minimal in order for devices to be able to harness its output as DC. The ripple in this output is also far less than the desired 1%. To calculate this, the peak-to-peak difference is calculated to be .0002 V. This value is then divided by the average voltage of the signal, which is .4832 V. In practice, if there is a lot of ripple at the output, there can be more DC bypass

capacitors added to the output. This will reduce ripple. Again, if the DC output has too much ripple, it could damage the device that it is charging.

5.4: Conclusions

The simulation results of the two converters give very different results. Chapter 6 will discuss the design implementation and testing results of these two converters.

Chapter 6. Design Implementation & Test Results

6.1: Layout Implementation

Only one circuit is designed and completely fabricated. This is the unmatched converter. Fig. 6 shows the circuit board that was manufactured for the RF to DC Converter project. This component is small in size, less than 3 square inches. Microcircuits Inc. manufactured the circuit boards and each component is soldered onto the board in order to create a finished product. The soldered components consist of the diodes, capacitors, and SMA adapters at the input and output. Major design components are highlighted in red in Fig. 6.

6.2: Test Results

The testing done for this project is minimal due to time constraints. Currently, the best test results obtained include the overall power transferred at a frequency of 5.8 GHz and a verified DC output from the RF to DC converter.

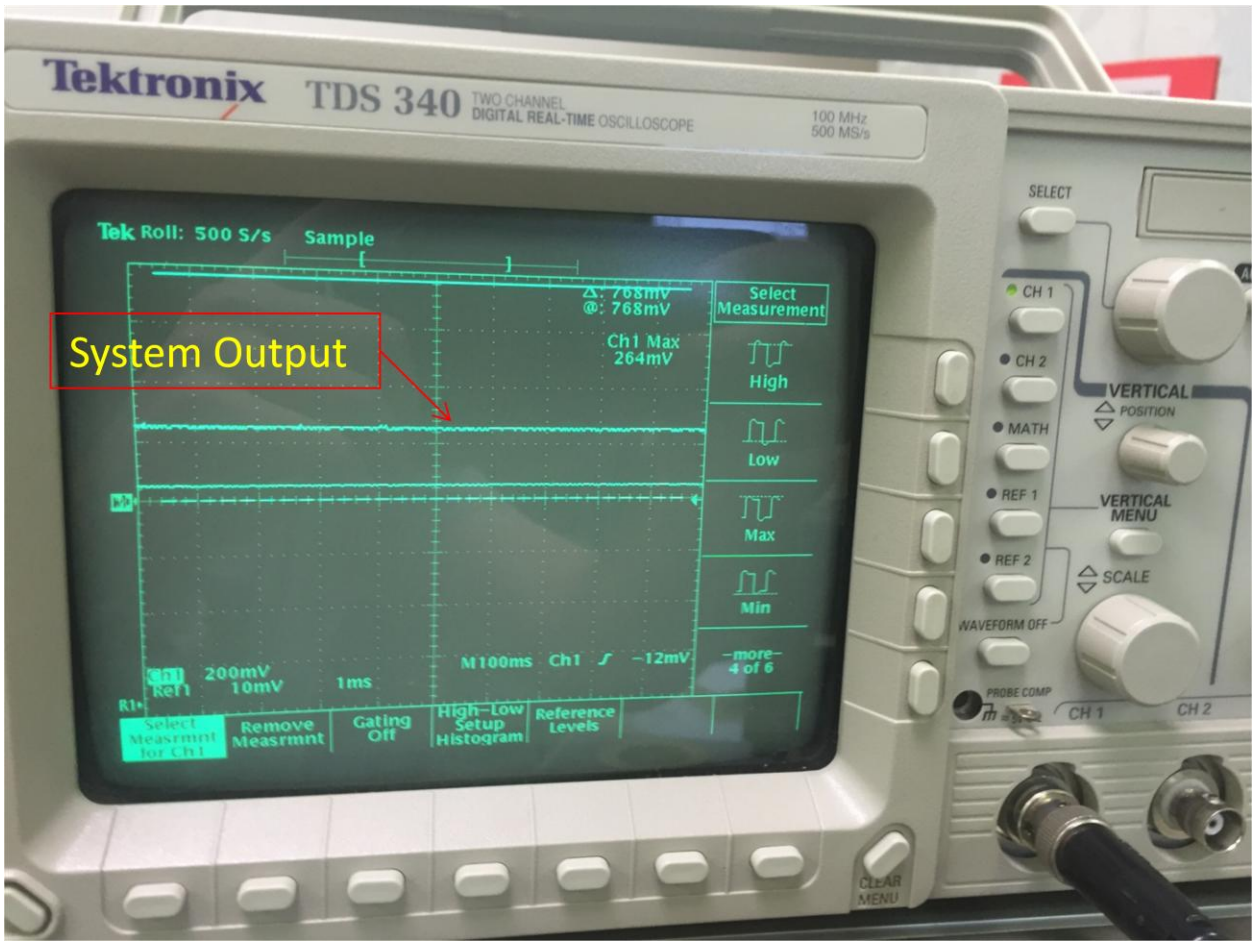


Fig. 19 Time Domain DC output of the RF to DC Converter Project

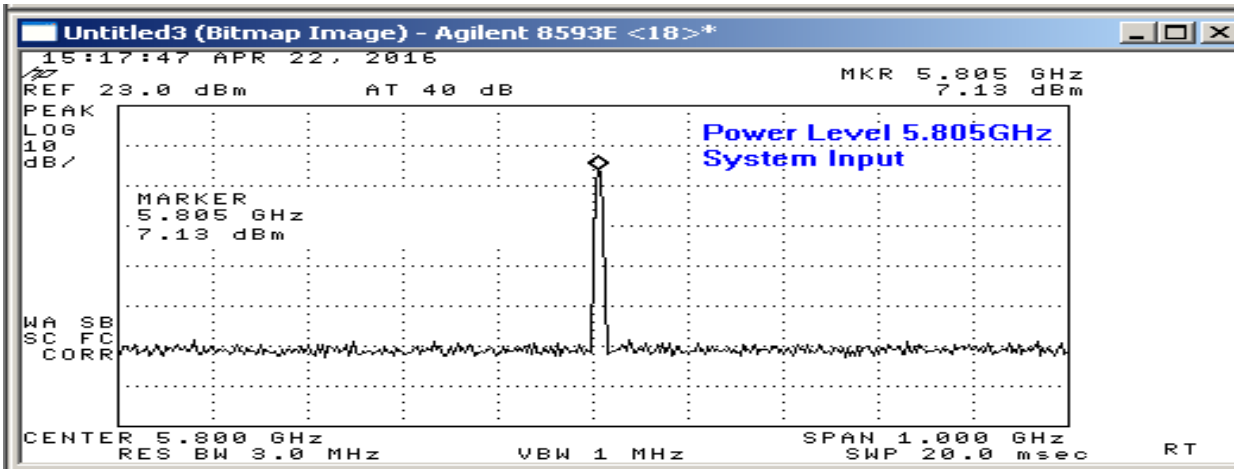


Fig. 20 Input Signal to RF to DC Converter

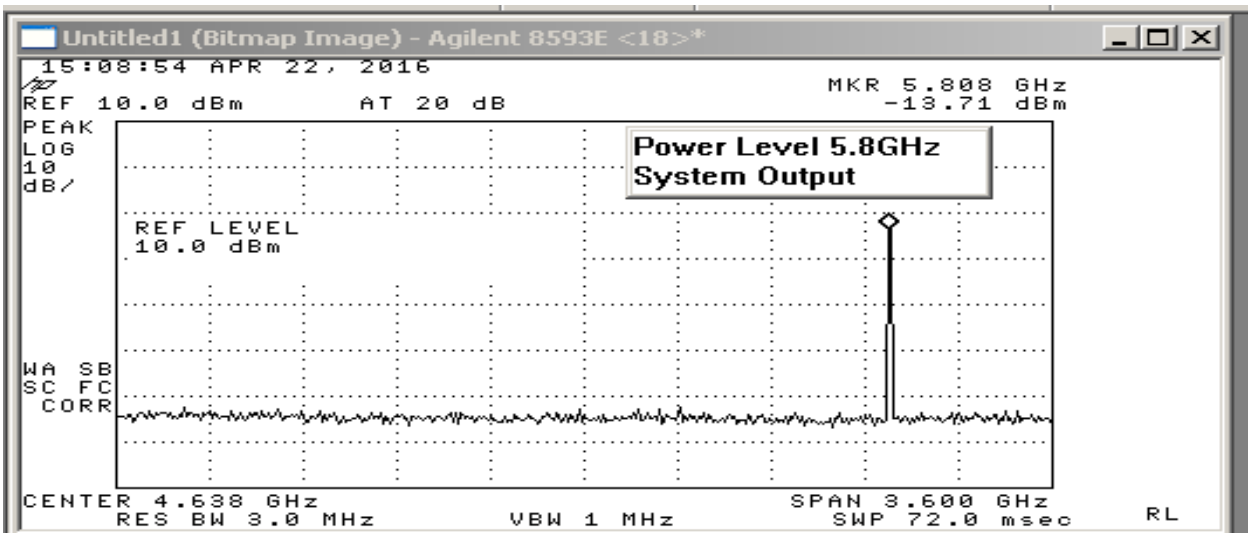


Fig. 21 Output Signal of RF to DC Converter

From Fig. 19, 20, and 21, it can be seen that the system is functioning well and is giving a proper DC output. The goal of the project was to have a DC output with less that 1% ripple. From Fig.19, it can be seen that the ripple of the system reflects that of the simulation results, which was less that .05% ripple. The following figures, Fig. 20 and 21, give a frequency domain representation of the time domain signal seen in Fig. 19. The main signal that makes it through the filtering is the fundamental frequency (5.8 GHz), which will give whatever ripple is seen at the output. This signal is dropped by 20 dB of power from input to output. This shows that the DC bypass filter designed for this project is working very well. The only other signal coming through is the second harmonic, but its power level is so low that it does not affect the signal.

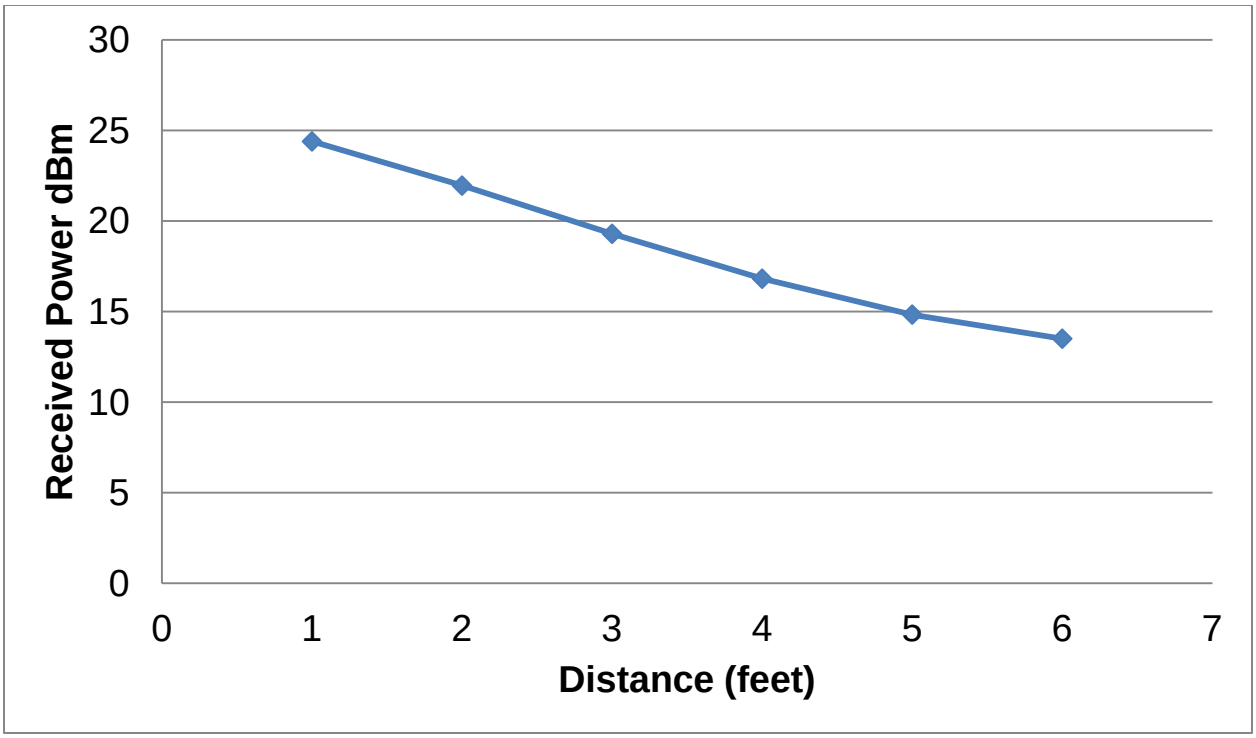


Fig. 22 Power Received at Varying Distances

The maximum power output of the amplifier for this project is 33 dBm. This power is sent to the transmitting antenna and then transmitted to the receiving antenna. Tests were run to see how much of that 33 dBm power is taken in by the receiving antenna. The main result that is focused on for this project was the 6 feet distance. This is the transmitting distance goal that was proposed at the beginning of this project. At a distance of 6 feet, the receiving antenna receives 14 dBm of power at a frequency of 5.8 GHz. This is the amount of power that would be received by the RF to DC converter if it were implemented in a wireless power transfer system, which for this project is more than enough. The received RF power vs. distance is shown in Fig. 22.

There were issues with final testing, but preliminary results show that with a 50 ohm resistance, the RF to DC converter is able to convert a 5.8 GHz signal to DC at around 40% efficiency using the unmatched network. The matched network is yet to be tested.

Chapter 7. Conclusions

The RF to DC converter project is successful on many fronts. The goals of the project are a) function at a frequency of 5.8 GHz, b) have a DC output with less that 1% ripple, c) maximize efficiency and d) minimize size.

The project does function well at a frequency of 5.8 GHz. The filtering and rectifying is able to function at this frequency and handle all of the harmonics generated. The output of the system is a very low ripple DC. Only the fundamental frequency is able to pass through the filter, but the output power level is extremely low compared to the input power, so the filtering functions well. The system efficiency is yet to be correctly determined. From research, the system efficiency goal is to be over 50%. Preliminary results show an efficiency of about 40%, so the efficiency does not quite meet the goal. The overall size of the converter is small. The converter board is 3 inch by 1 inch, which makes it very feasible to be implemented inside mobile devices.

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Appendix

HSMS-2860 Schottky Detector Diode

C08BL242X-5UN-X0T 2400 pF Surface Mount Capacitor

RT Duroid 5880 Circuit Board