Senior Capstone Project Report

By:

Mitchell Pericak

Advisors:
Dr. Prasad Shastry
Dr. Brian Huggins

Bradley University
Peoria, IL

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BRADLEY University
Department of Electrical and Computer Engineering

Abstract

Companies and research groups have investigated the design and implementation of systems that extract energy from wireless signals to power remote sensors. This report describes the design and implementation of such a system operating at 5.8 GHz. The system consists of a basic charge-pump circuit to convert the 5.8 GHz signal to low level DC. This circuit was designed and simulated using SPICE® and ADS®. The output of this stage is applied to a commercial DC to DC converter (LTC1502) to increase the output voltage of the system to 1.2V. The microstrip circuit boards were fabricated by Micro Circuits Inc. based on ADS® designs and components inserted in the Bradley microwave lab. The report compares simulated results to experimental results.

Acknowledgements

I am extremely grateful for the mentorship and advising from Dr. Prasad Shastry and Dr. Brian Huggins for guiding me through this project and the valuable lessons they have taught me.

I would like to express my gratitude to Microcircuits Inc. in helping me with the board designs and manufacturing of the circuit boards.

I would like to express my gratitude to Mr. Mattus and Mr. Schmidt for helping me order all of the components I needed as well as teaching me how to solder surface mount components.

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Chapter 1: Introduction

This report presents the project on the design, simulations, fabrication, and testing of a radio frequency (RF) energy harvester at 5.8GHz. This project has been completed as part of the BSEE program of study at Bradley University. Previous projects have investigated RF to DC systems in the 900MHz, 2.4GHz, and 5.8GHz ranges. Because of the increase in products emitting 5.8GHz, this project's rectifier will be designed to rectify at 5.8GHz.

Chapter 2: Literature Review

2.1 Past Projects

This project is based on the senior projects of Brandon White ’16 [1] and Elie Baliss ’14, Tyler Hoge ’14, and Sergio Sanchez ’14 [2]. These senior projects investigated various wireless power transfer systems at 900MHz and at 5.8GHz. In both projects rectifiers were designed and tested in a wireless power transfer system.

One of these projects utilized a commercial wireless power transfer system made by Powercast®. The Powercast® device was tested at 915MHz to demonstrate the concepts of a wireless power transfer system and determine the amount of power received over the distance of the transmitter and receiver.

2.2 Publications

There are various patents and research publications on wireless energy harvesters. Ford Motor Company, MIT, and even Apple Inc. all have some sort of patents on wireless energy harvesting and charging devices. Most recently, Apple Inc. has filed for a patent for charging one of its devices at a distance of 3 feet.

Other papers such as “A Batteryless Embedded Sensor-Platform Wirelessly Powered From Ambient Digital TV-Signals” [3] has explained a lot when it has come to these sorts of systems. This paper discusses how different bands in different areas all affect the RF harvesting of the systems. The paper also discusses the use of a charge pump which later on will affect this project in particular when the circuit does not initially meet the voltage requirements of the project. The charge pumps act as a boost of voltage for these systems so that burst of energy can power up the system to charge a sensor or load.

Chapter 3: Preliminary Designs

3.1 Block Diagram

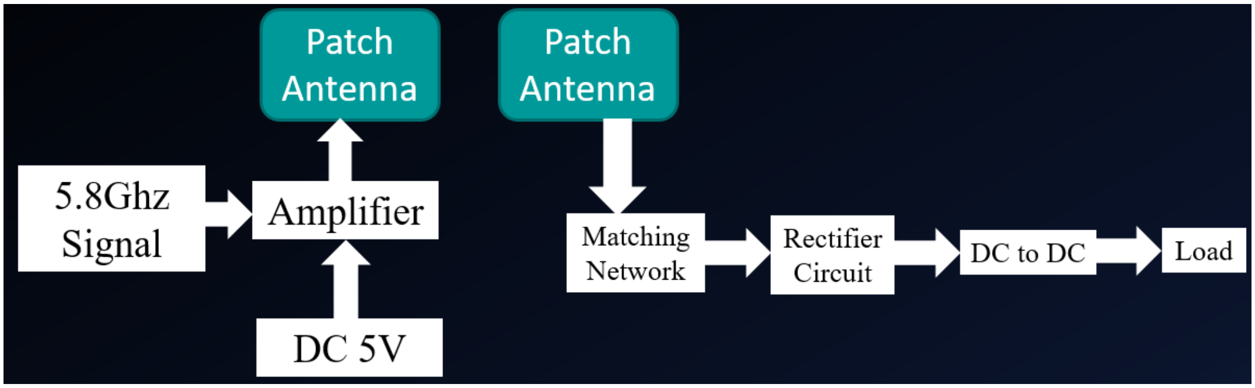

Fig 3.1. Block Diagram of Rectifier Circuit

3.2 Rectifier Circuit Design

A rectifier utilizing one diode will be designed to harvest the DC energy out of the 5.8GHz signal. This system will require a diode and capacitor selection based on the output requirements.

The first part of the design was to select a diode and DC-DC converter that could meet the specifications of the project. It was decided that a Linear Technologies LTC1502-3.3 DC-DC converter would be used as it requires a 10uA input and .9V to 1.8V input to get a voltage of 3.3V at its ouput which would be enough to power a small sensor. For this circuit, the Skyworks SMS7860 diode was selected.

A half wave rectifier circuit in ADS® is shown n Fig 3.2. After simulations, it was concluded that a one-diode circuit could not produce the .9V minimum input for the DC-DC converter no matter how much power was pumped into the system. After research into charge pumps, a one-stage charge pump was created by adding another diode. The results of simulations of this curciut are shown in Figs 3.3 and 3.4.

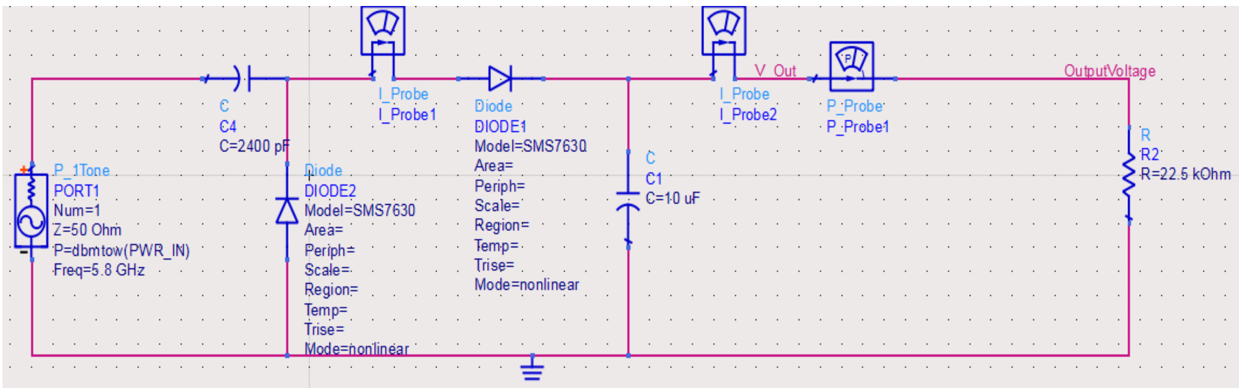

Fig 3.2. ADS® Schematic of a Rectifier Circuit. The capacitors selected were based on various trial sets of values to see which value best optimized the circuit.

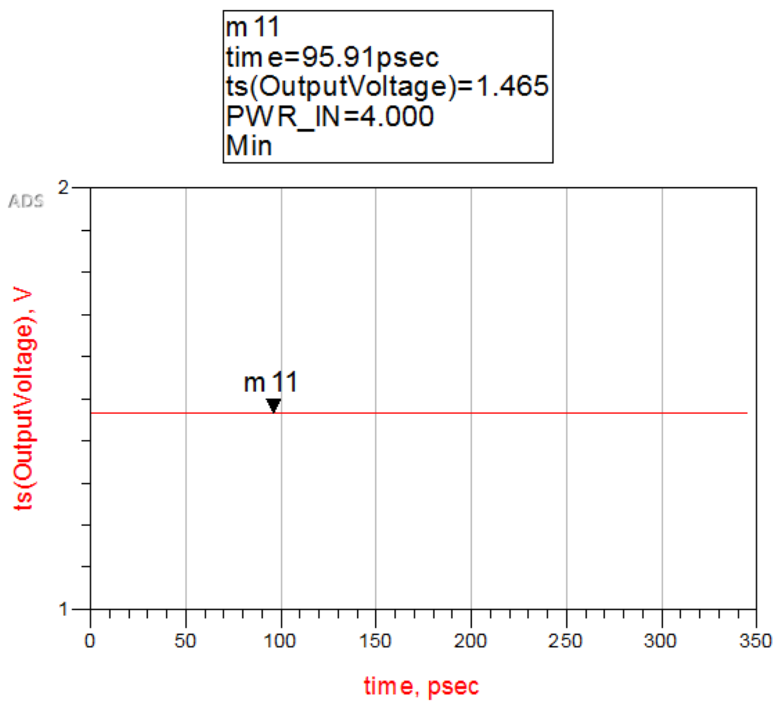

Fig 3.3. Output voltage of the rectifier circuit with an input power of +8dBm

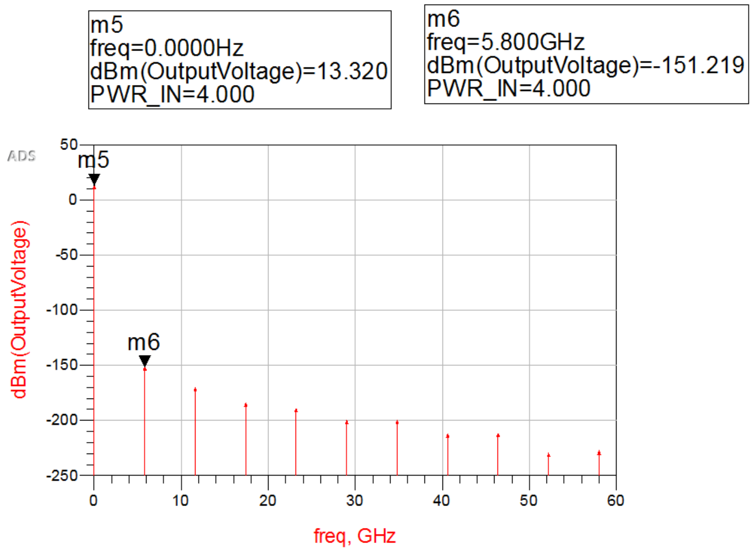

Fig 3.4. Output spectrum of the rectifier circuit

3.3 Matching Network

After simulations using the ADS® software, MATCH was used to design a matching network for the rectifier circuit. The matching circuit is a lumped element circuit with a capacitor and an inductor. The MATCH program provided the values of the components to use in the matching network. After implementing the matching network, the circuit's S11 was determined in ADS. The goal for the S11 of a circuit such as this rectifier is around -10dB. Before adding the matching network, the S11 of the circuit was -2dB. After adding the matching network the S11 was -1dB. This decrease in the S11 is believed to be due to the fact that the matching circuit algorithm does not take into account for the non-linearity of the diodes.

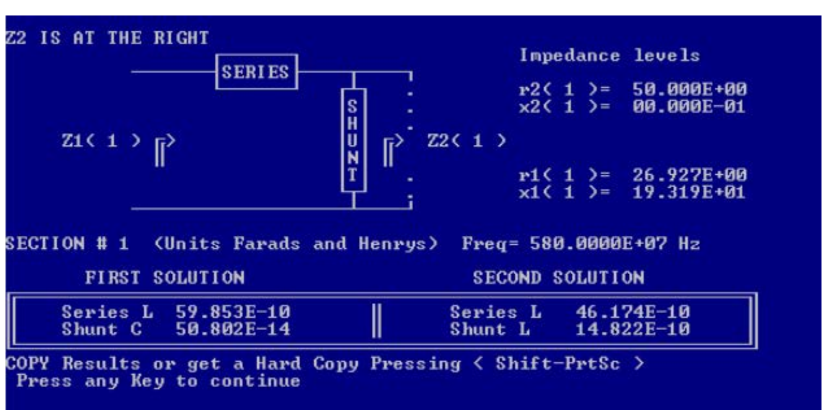

Fig 3.5 MATCH Program Results

Chapter 4: Microstrip Circuit Design

After the rectifier circuit was designed, ADS® was used to design the same rectifier with microstrip lines to allow a realistic simulation of the physical printed circuit.

4.1 Microstrip Data Selection

To design the microstrips, the MSTRIP program was used.

For a 50 ohm microstrip line, the following data was concluded.

Z_0 = 50

Er = 3.9

h(cm) = .059” = .14986cm

W/h = 2.091272

W = .313398cm

Eff = 3.00860

The above data was based off the circuit board type selection. Because of the affordability of the board and recommendation of Microcircuits Inc. it was decided to use the NP140TL FR4 board.

The width of the microstrip had to be evaluated to make sure the SMA connector’s and component’s pin pitch were thin enough to fit onto the .14cm thickness of the microstrip. After evaluating the data sheets and using a caliper to measure the SMA pin, the .14cm thick microstrip board was found to be suitable.

After evaluating the boards and matching networks, it was decided to design three boards. The pin pitch on the DC-DC converter is narrow to where there was a concern that soldering on the physical LTC1502-3.3 chip would not be possible with the available equipment and time in the Microwave Lab. Therefore two of the designs have an SMA connector on the output to which the DC-DC converter connects. The other has the layout for the DC-DC converter on the board. These three boards are: one board with a matching network, one board without a matching network, and one board with a matching network with the DC-DC on board.

4.2 Fabrication Company

It was decided that the company for manufacturing the circuits will be Microcircuits Inc. based out of Addison, IL. This company was chosen for their reputation in high quality RF circuit manufacturing as well as their relationship with Bradley University.

4.3 Board Layouts

Layout 1:

Layout 1 (Board 1) consisted of the matching network on the board. All of the widths of the microstrips are .14cm except the board with the DC-DC converter, it is then brought down to the width of the pins on the chip after rectification.

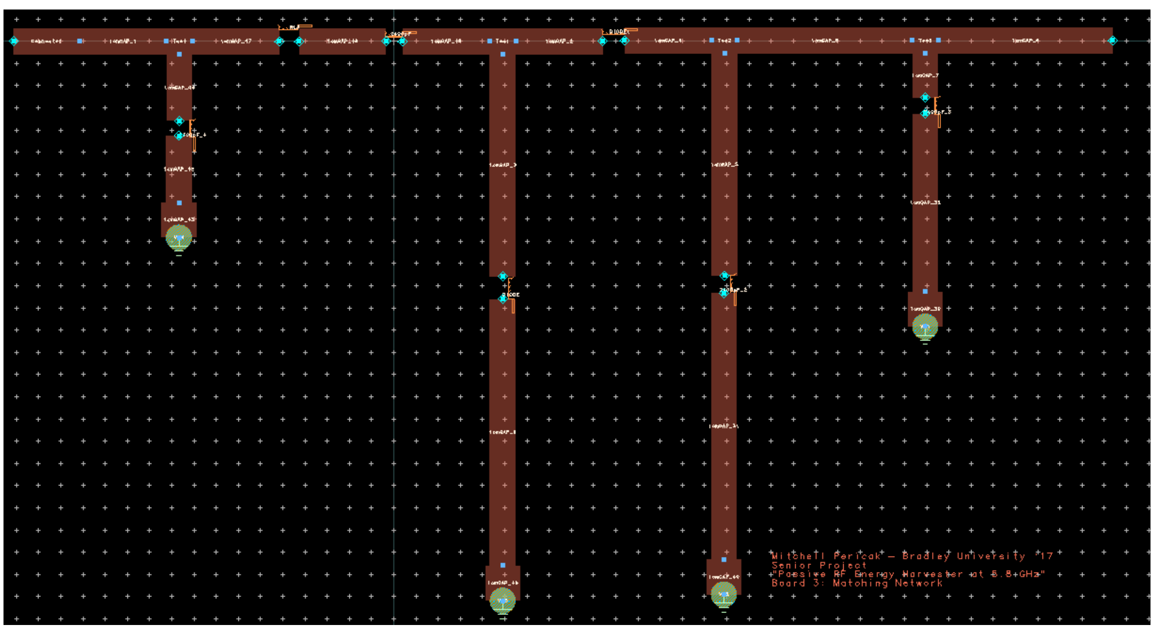

Fig. 4.1. ADS® Layout of Board 1

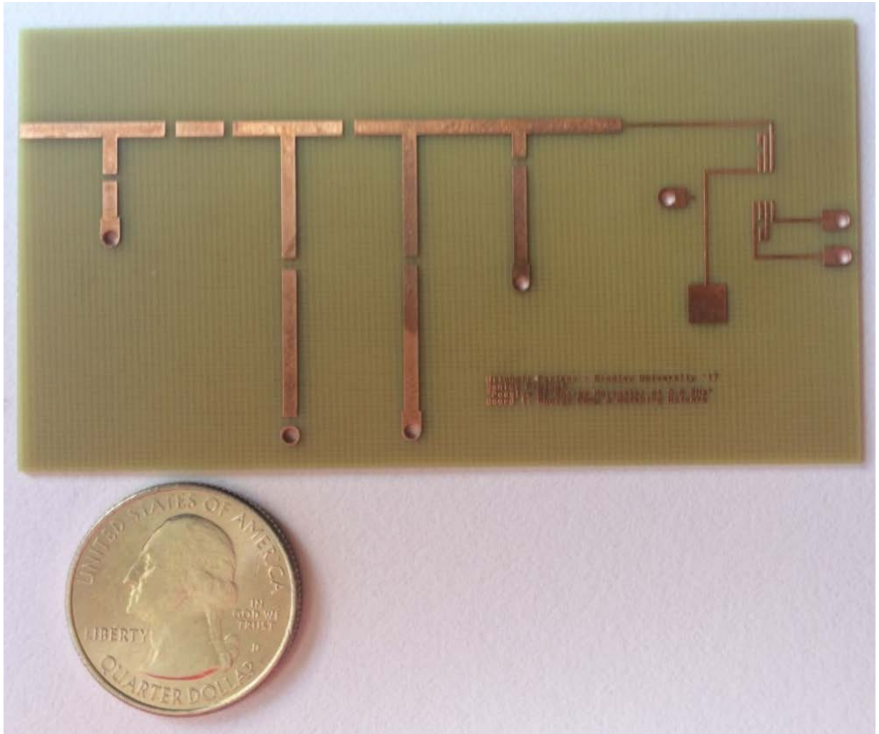

Fig. 4.2. Printed Layout of Board 1

Layout 2: (Board 2)

Board 2 consisted of the circuit without a matching network.

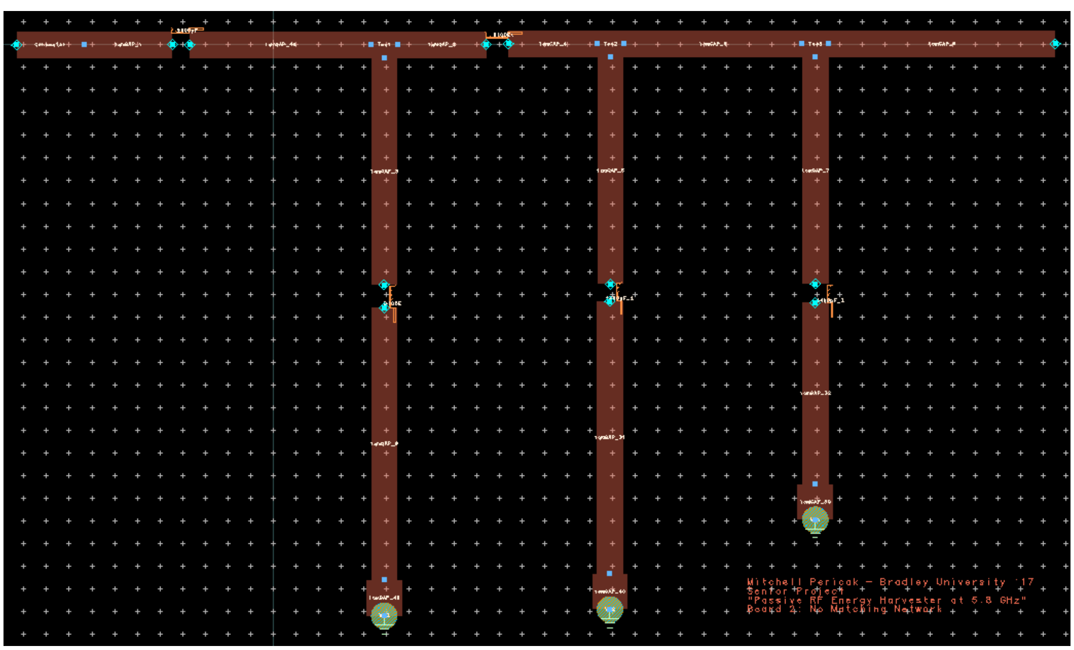

Fig 4.3. ADS® Layout of Board 2

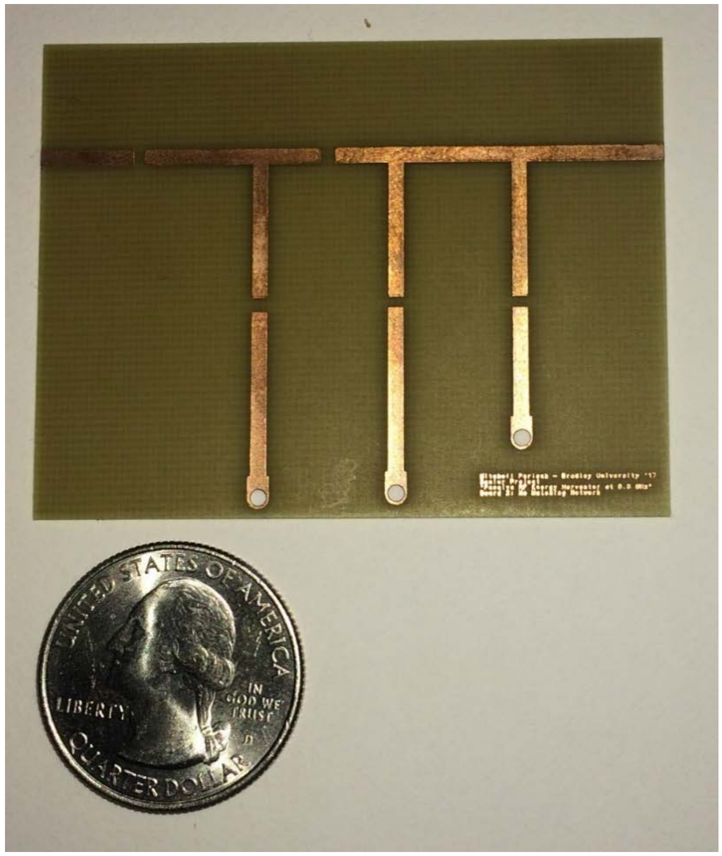

Fig 4.4. Printed Layout of Board 2

Layout 3 (Board 3):

Board 3 consisted of the circuit with a matching network on board.

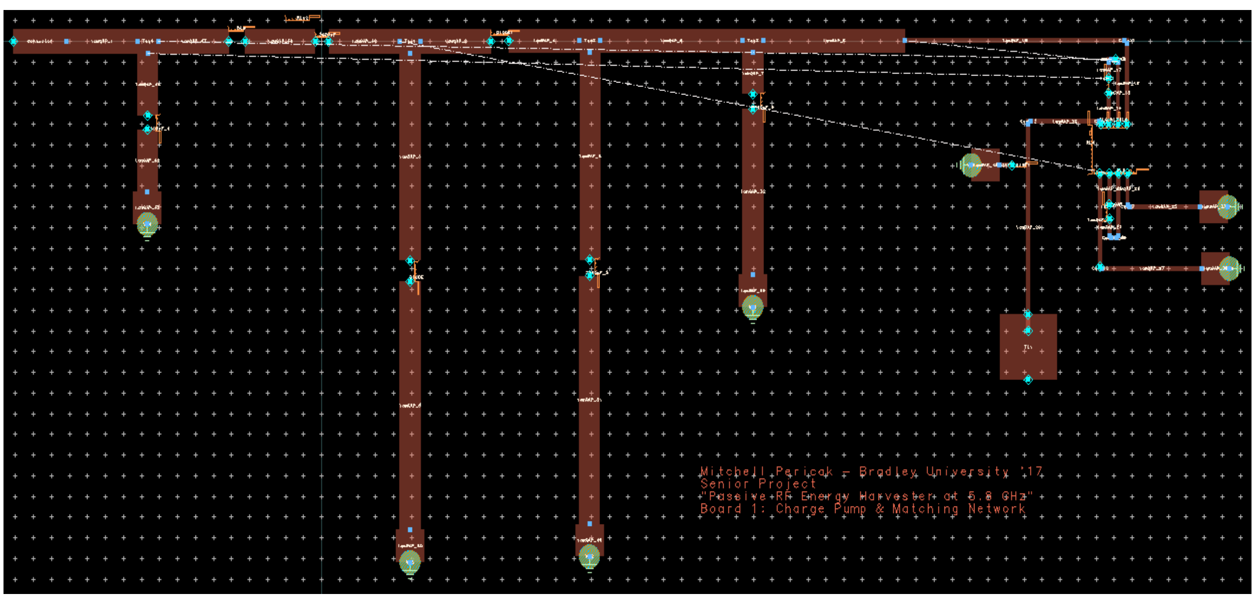

Fig 4.5. ADS® Layout of Board 3

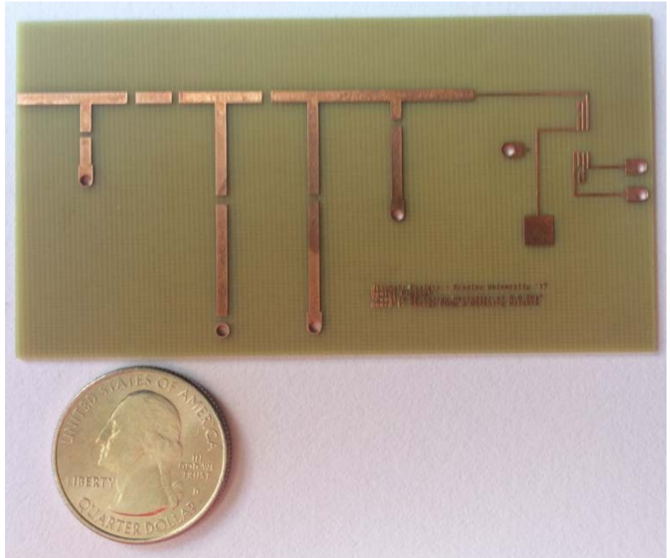

Fig 4.6. Printed Layout of Board 3

Finally, while editing the microstrips to test for optimization of the voltage output, Board 2 had the first vertical microstrip shortened which yielded a higher output voltage with an input power of -3dBm, 11 dBm lower than the other simulations. It was decided then that a fourth board would be developed.

Layout 4 (Board 4):

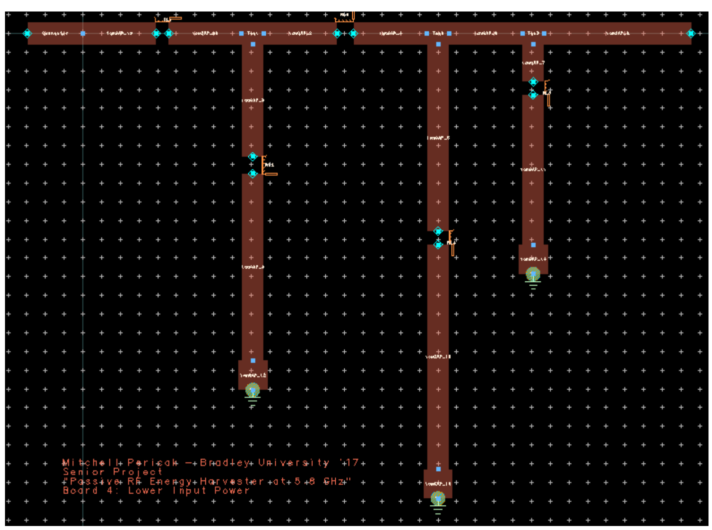

Fig 4.7. ADS® Layout of Board 4

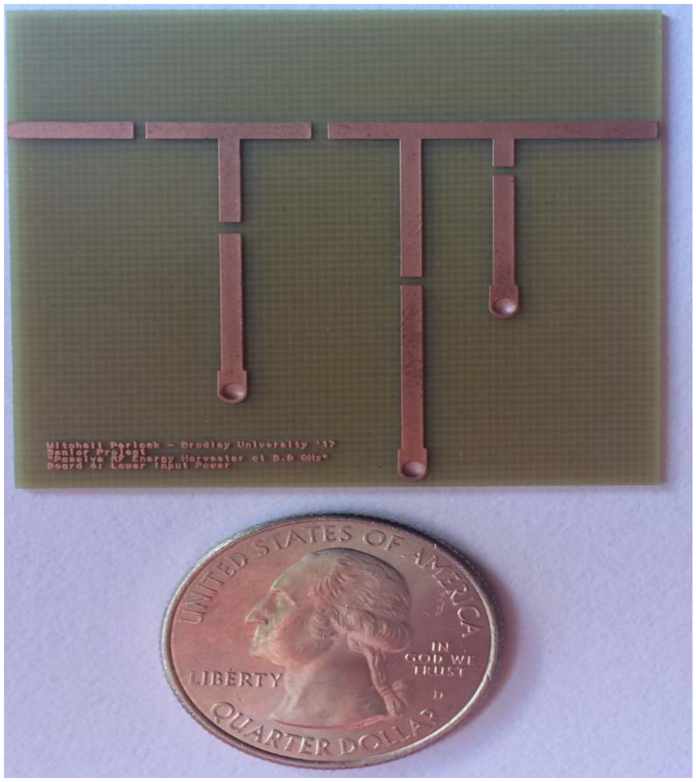

Fig 4.8. Printed Layout of Board 4

4.4 Simulated Results

The following data is the ADS® simulation results of the voltage output of the boards:

Table 4.1

ADS® Simulated Output Results of Each Board

Board	Input Power	Voltage Output
1	+8dBm	1.2V
2	+8dBm	1.1V
3	+8dBm	1.2V
4	+8dBm	3.1V
4	-3dBm	1.17V

The goal was to keep the DC output voltage between .9V and 1.8V to meet the input specifications of the DC-DC converter. After simulating all board designs, layout 4 was expected to perform the best with its low input power requirement and low ripple voltage output.

Chapter 5: Testing and Measurements

After the boards were fabricated, the components were soldered on. It was quickly decided that the pin pitch on the DC-DC converter was too small for our resources to be reliably soldered. Therefore, for tests and measurements, only Boards 2 to 4 were implemented.

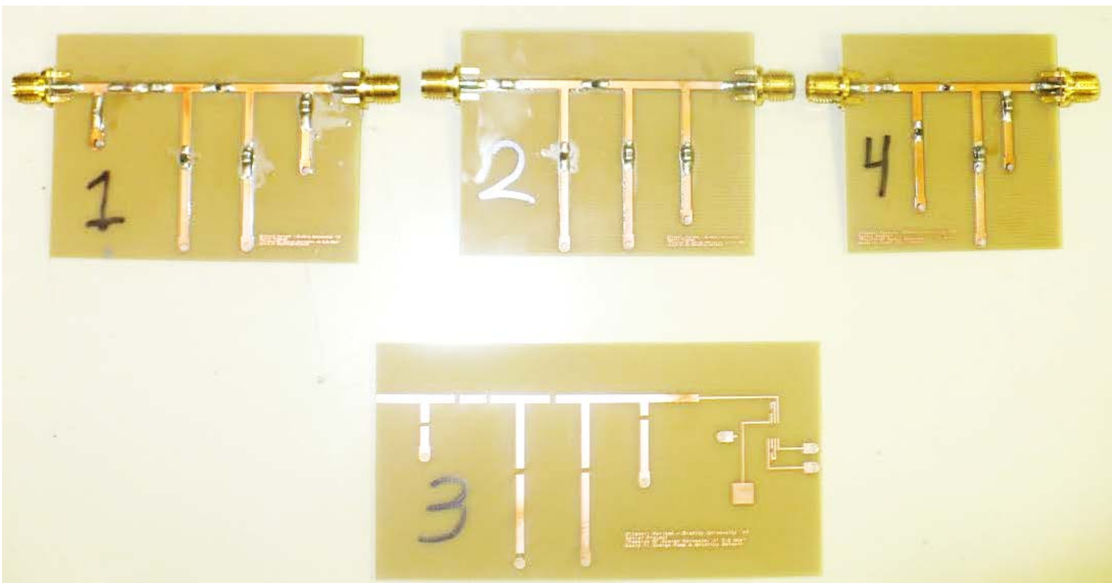

Fig 5.1. Boards with Soldered Components

Once all components were mounted, the S11 for each board was measured from 4GHz to 7GHz with the Network Analyzer. Each frequency point with a low S11 as well as the 5.8GHz point was marked.

Board 2:

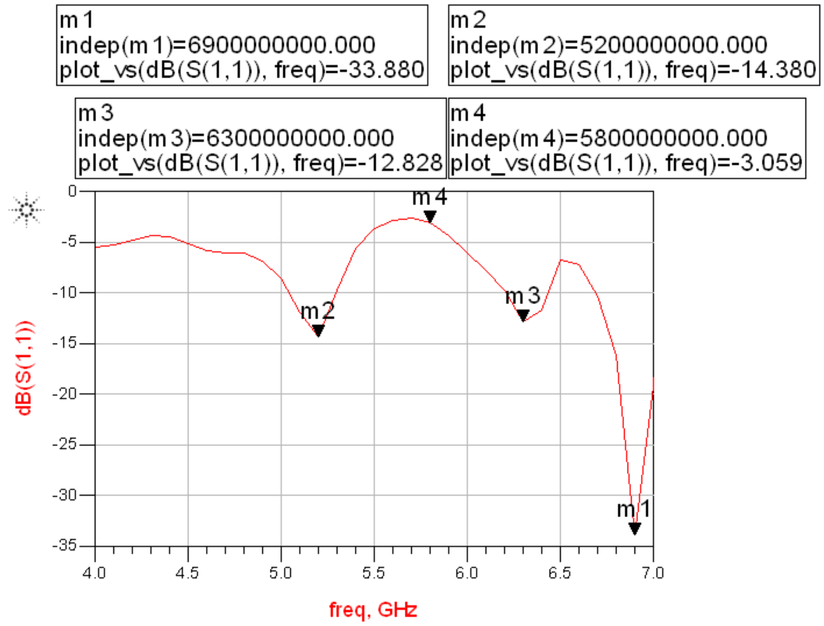

Fig 5.2. S11 of Board 2

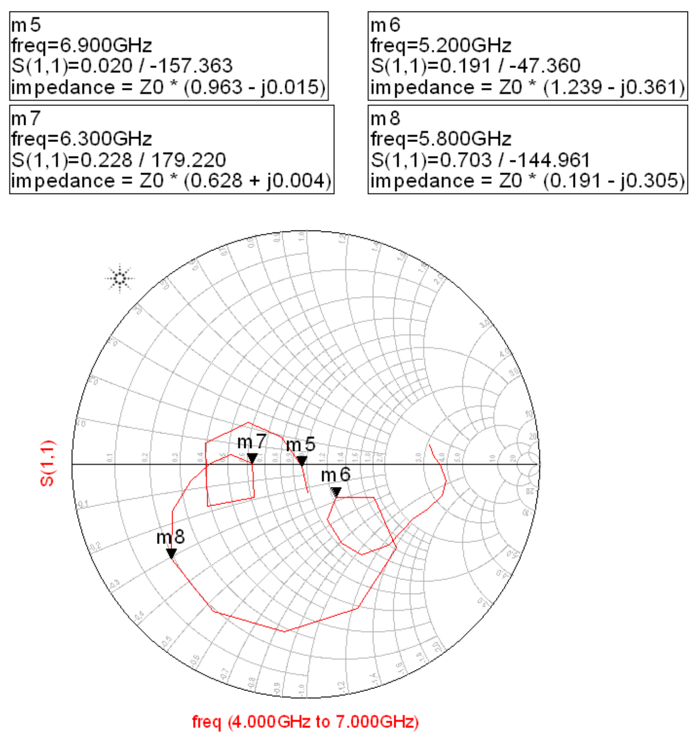

Fig 5.3. S11 of Board 2

Board 3:

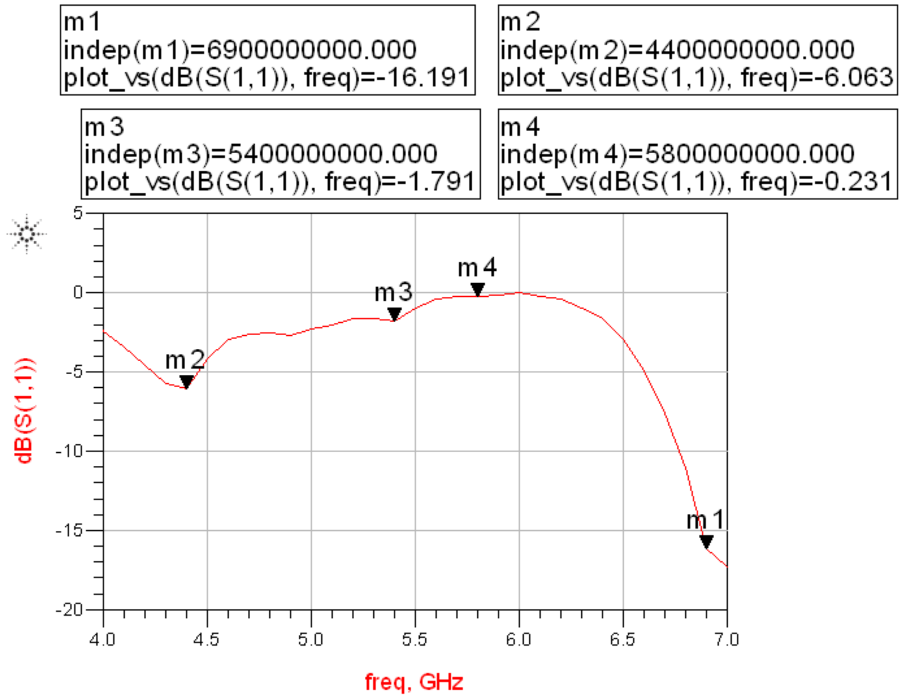

Fig 5.4. S11 of Board 3

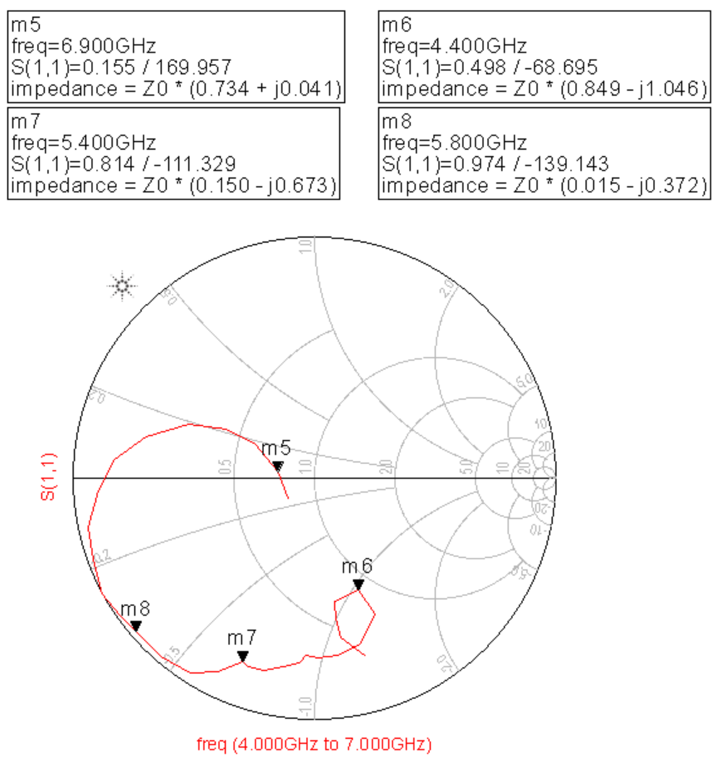

Fig 5.4. S11 of Board 3

Board 4:

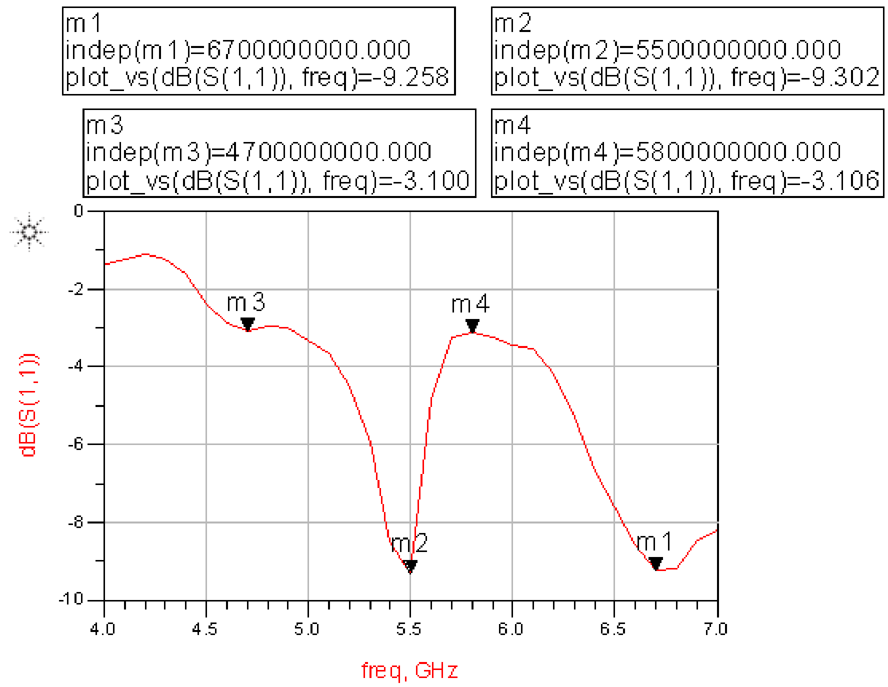

Fig 5.5. S11 of Board 4

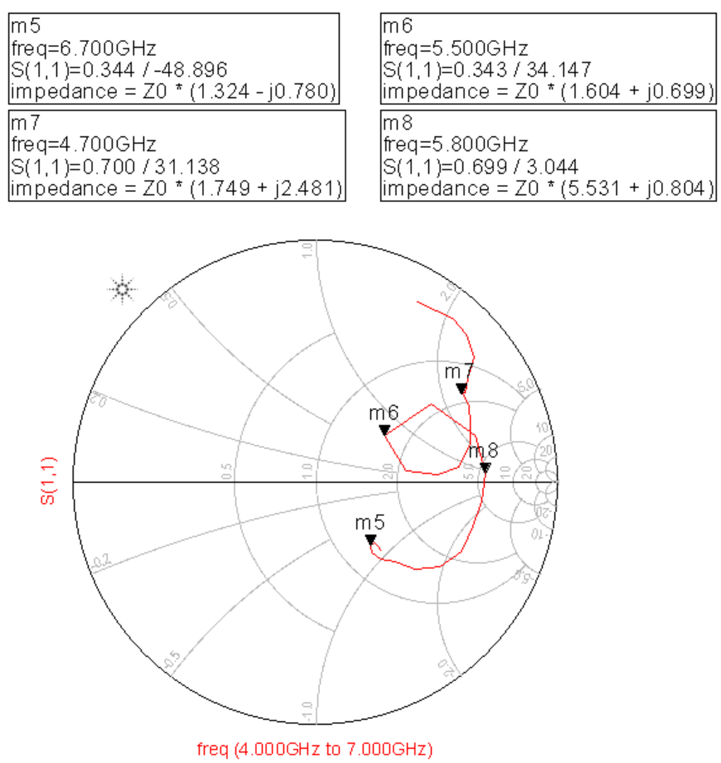

Fig 5.6. S11 of Board 4

The low S11 frequencies were then selected and tested. There were also some measurements taken at other power levels and frequencies just to test the data.

To test this data the system was fed from a HP 8620C Sweep Oscillator. This system fed a coupler where coupler 2 fed the circuit and coupler 3 fed the HP 2593E Spectrum Analyzer to verify power input and frequency. The voltage output was measured with a Tektronix TDS3012B Oscilloscope. The setup is shown in Fig. 5.7

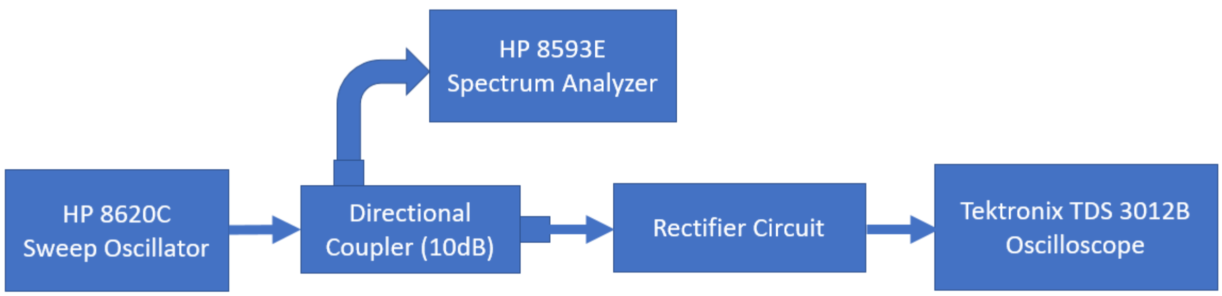

Fig 5.7. Setup of rectifier circuit testing and measurements

Table 5.1

Board 2 Measurements

Frequency (GHz)	Power Input (dBm)	Voltage Output (V)
5.20	.15	1.0
5.20	8	2.5
5.80	.04	.400
5.80	8	1.3
6.303	.08	1.1
6.303	8	3.48
6.903	.10	.060
6.903	8	.400
4.4	-20	.071
4.4	-17	.115
4.4	-11	.264
4.4	-5	.610
4.4	-1	1.09

Table 5.2

Board 3 Measurements

Frequency (GHz)	Power Input (dBm)	Voltage Output (V)
4.405	.81	1.15
4.405	8	3
5.403	.81	.38
5.403	8	.900
5.80	.25	.150
5.80	8	.460
6.903	0	.05
6.903	8	.13
4.405	-20	.03
4.405	-17	.05
4.405	-11	.14
4.405	-5	.36
4.405	-1	.60

Board 4 had errored results during testing and simulations. This is most likely due to a bad diode or incomplete connection somewhere in the circuit. Because of time restraints, Board 4 was not tested.

After measuring this data, the circuits were then wired to the DC-DC converter to see if the rectifier circuit could power it. Unfortunately, none of the circuits were able to power up the DC-DC converter. This may be because the DC-DC converter needs more current than what the rectifier circuits are capable of supplying.

Chapter 6: Conclusion

Overall the project can be considered a success. The requirements were met of designing a system that could harvest the energy and produce a DC voltage. Though the requirements were met, there is still many issues to be considered. Feeding the DC-DC converter was crucial to this project; therefore the insufficient supplied power became an issue. In addition, the microstrips could be designed to function at a lower input power if the time is taken to simulate various microstrips and study why each length matters on each part of the circuit.

Since Board 4 was not able to be developed, only Boards 2 and 3 could be compared. For that reason, it can only be concluded that the matching network circuit Board 3 had better results and needed less input power to function properly. However, the circuits seemed to work around 4.4GHz and not 5.8GHz which does not complete the project's expected results.

For future work, I would recommend that the matching network and microstrip characteristics be studied further. The circuits have already been designed and this project has shown that the two-diode circuit is what will be needed rather than a one diode circuit. The future project would look at optimizing this circuit so that the system can require a lower input power to function at the same voltage output. Further, the matching networks could also be researched to see why the matching network increased the S11 in simulations.

This project's results show a true proof of concept that the circuit does work. It is now time for the circuit to be optimized to function with a high enough output to power small sensors and charge small batteries.

References:

[1] White, Brandon. *RF TO DC CONVERTER*. Senior Project. Peoria: Bradley University, 2016. Report.

[2] Sanchez, Sergio, Tyler Hoge, Tyler, and Elie Baliss. *Wireless Power Transfer System*. Senior Project. Peoria: Bradley University, 2014. Report.

[3] Vyas, Rushi, et al. "E-WEHP: A Batteryless Embedded Sensor-Platform Wirelessly Powered From Ambient Digital-TV Signals." *IEEE Transactions On Microwave Theory and Technique* (2013): 2491-2505. IEE Article.

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