Wireless Passive Power Transfer Using Wire Antennas

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Acknowledgements

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Abstract

This project tests and analyzes the efficiency of directional and omnidirectional antennas in wireless power transfer for charging. The project demonstrates the steps of construction and properties of dipole, monopole, and Yagi Uda antennas. A low power high frequency DC rectifier circuit converts the received RF power from the antenna and stored it as DC voltage on a capacitor. The receiver circuit also estimates the power received by the antenna. Wireless RF power transmission proves to be inefficient for short distances. The best efficiencies of the antennas were under 50% even at 0.1meter. The near field attenuation starts at around 3db every 0.1 meters and slowly decreases. Although the Yagi Uda array improved received power, the attenuation over distance made wireless power transmission impractical.

I. Introduction

Wireless technology has evolved much over the century, from telegraphs and radio to modern WIFI and cell phones. Battery technology has also rapidly evolved in the early 21th century. Numerous advancements have been made to try and wirelessly charge batteries in preparation for a cleaner future that revolves green battery and super capacitor technology in place of fossil fuels with the first being cars[1]. The new battery and capacitors will require effective charging techniques. While charging with a wire is more efficient at short distances, sometimes they need to be wirelessly recharged, mainly to bypass obstacles. This project explores the practicality of charging batteries and capacitors in short range. The block diagram below shows the setup of the project.

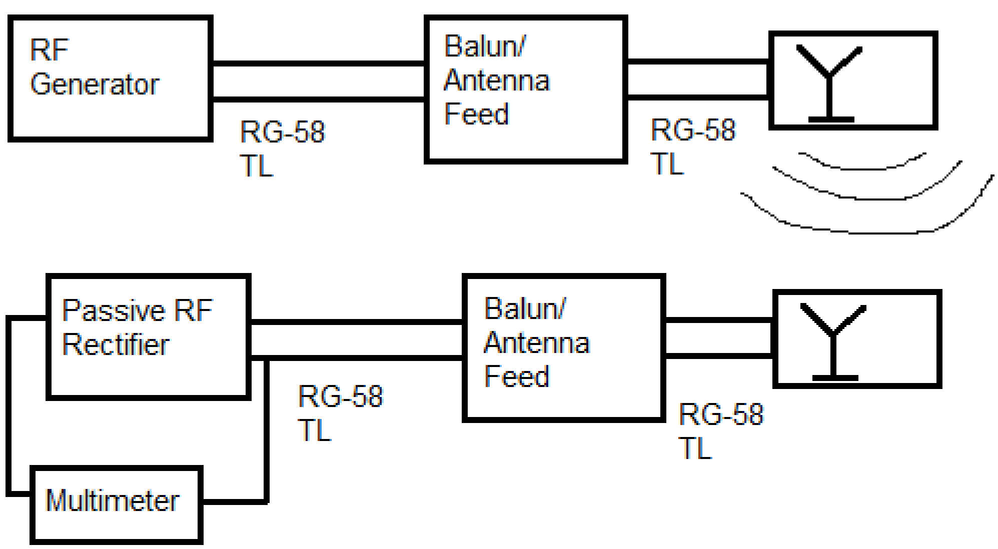

Figure 1: Block Diagram of Intended System

[1] http://medillonthehill.net/2011/02/1892/

II. Background

Antennas transfer signals and, therefore power, through electromagnetic radiation. The transmitting antenna converts electric signals into electromagnetic waves that propagate through the air and the receiving antenna converts received electromagnetic waves into electric current. Antennas that focus most of their power in a single direction are called directional antennas. Because of this focus, directional antennas, in theory, have lower loss from radiation in all other directions. However, if the positions of the antennas are not well aligned, the received power drops drastically. This requires precision control sensors and motors to correct and may prove to be a hindrance when it comes to manual positioning.

The antenna chosen must be able to efficiently transfer and receive power. One deciding factor in efficiency of antennas is frequency. The Friss Transfer Equation (See Appendix) shows that the far field attenuation of a signal through air varies proportional to the square of the wavelength. $f = \frac{v_p}{\lambda}$. Vp is the speed of the wave which is the speed of light in free space, but varies with the medium the wave travels through. This shows that the attenuation is inversely proportional to the square of frequency. Therefore lower frequencies are more efficient at transferring power than higher frequencies. Another limitation to the antenna is its size. Since antennas are built according to wavelength, lower frequency antennas are larger and bulkier. A frequency of 433MHz was chosen as an arbitrary compromise between size and efficiency.

Several directional antennas have been considered including Yagi Uda variants, microstrip patch, and aperture antennas. A dipole Yagi Uda antenna array was chosen for the ease of construction and higher directivity. Although they are less compact than patch antennas, Yagi Uda antennas are cheaper, easier to construct, and more efficient at UHF frequencies (300MHz – 3GHz) and below.

A Fluke 6060B RF generator provides the input power to drive the antennas, so either a BNC or PL-259 connector is required for the coaxial cable to match with the generator's 50ohms. RG-58 50ohm cable was chosen, because of versatility and the ability to match the impedance of the generator. 50ohm cables are lighter and more commonly used and provided with more connector options.

Batteries and capacitor are charged using a set DC voltage and fed slowly with DC current. If AC power is applied, they will simply charge and discharge. The DC voltage also needs to be amplified. Since the RF signal can't be amplified using DC power, the rectifier circuit must be able to passively convert current into voltage. The RF generator can only output 13 dbm max; therefore the circuit must dissipate as little power as possible. A low power RF rectifier circuit is therefore crucial to the application of the project. Various circuits were designed and tested for this application.

III. Project Requirements

Two working dipoles and their corresponding Yagi Uda arrays should be designed and constructed.

Circuit must efficiently convert received RF power into DC voltage.

Student should be able to calculate the efficiency of constructed antennas and compare with store bought antennas.

System should not cause interference other systems in the vicinity.

The DC voltage rectified must be enough to be read by a multimeter.

IV. Design

1. Dipole Design

The half wave dipole is one of the simplest antennas to construct and is used to drive the Yagi Uda antenna array. At 433MHz, the wavelength is .6928 meter or 27.277 inches. A factor of .95 is applied when calculating a dipole. The dipoles would have a length of 13 inches or .33 meter. Because the length of the dielectric wood, 1.5inches, should match the width of the Yagi Uda boom, the legs of the dipoles were shortened slightly to 6.2inches.

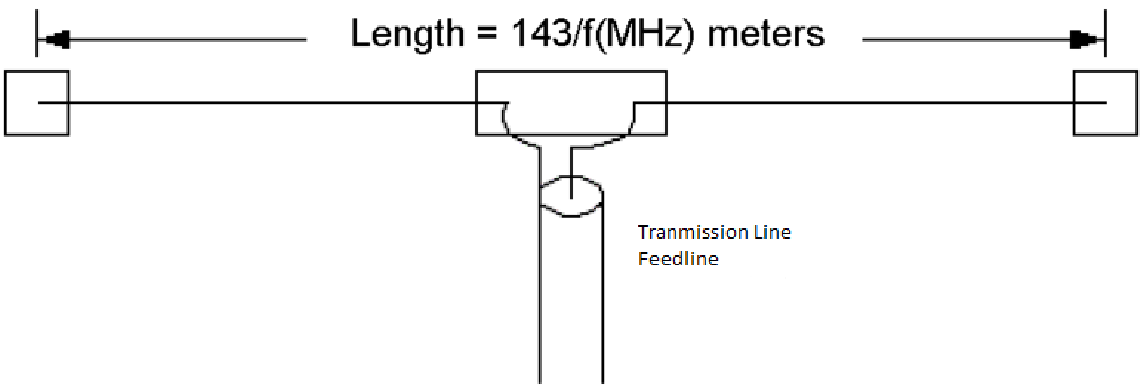

Figure 2: Simple Dipole[2] Design

The dipoles should have a near omnidirectional radiation pattern as shown below. The gain is 1 in all horizontal directions as opposed to isotropic where the gain is 1 in all directions.

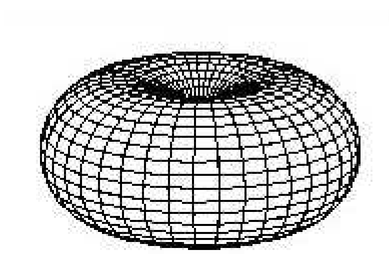

Figure 3: 3D Dipole[1] Radiation

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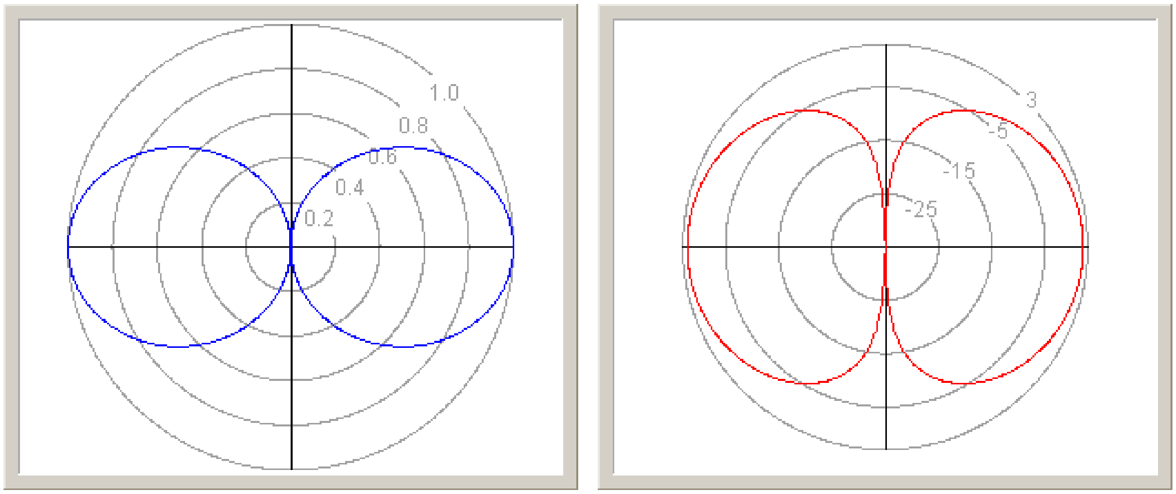
[2] http://en.wikipedia.org/wiki/Dipole_antenna



Linear Scale Radiation Pattern

Logarithmic Radiation Pattern (dB) over isotropic

Figure 4: General Simulated Radiation Pattern of Dipoles[1]

2. Balun

Coaxial cables conduct equal but opposite phase current in the inner copper conductor and outer copper shield. The current on outside of the shield is different from the inside when the outer conducting shield is connected directly to one leg of a dipole. This is due to the skin effect and current flowing back outside of the shield. Whereas the fields from equal but opposite phase currents cancel each other out, imbalanced currents radiate unequal fields turning the coaxial cable into an antenna. If the imbalanced current is significantly large, the coaxial radiation interferes with the antenna and a balun is required to fix or mitigate the problem. Baluns use only the inner conductors of coaxial cables to bypass the problem. The type of balun required is based on the impedance of the antenna. For 50 or 75 ohm dipoles, a 1:1 balun is required. Several types of baluns have been taken into consideration. The balun chosen is the quarter and three quarter wavelengths balun as shown below. Its principles of operation are easy to understand and relatively cheap and simple to construct.

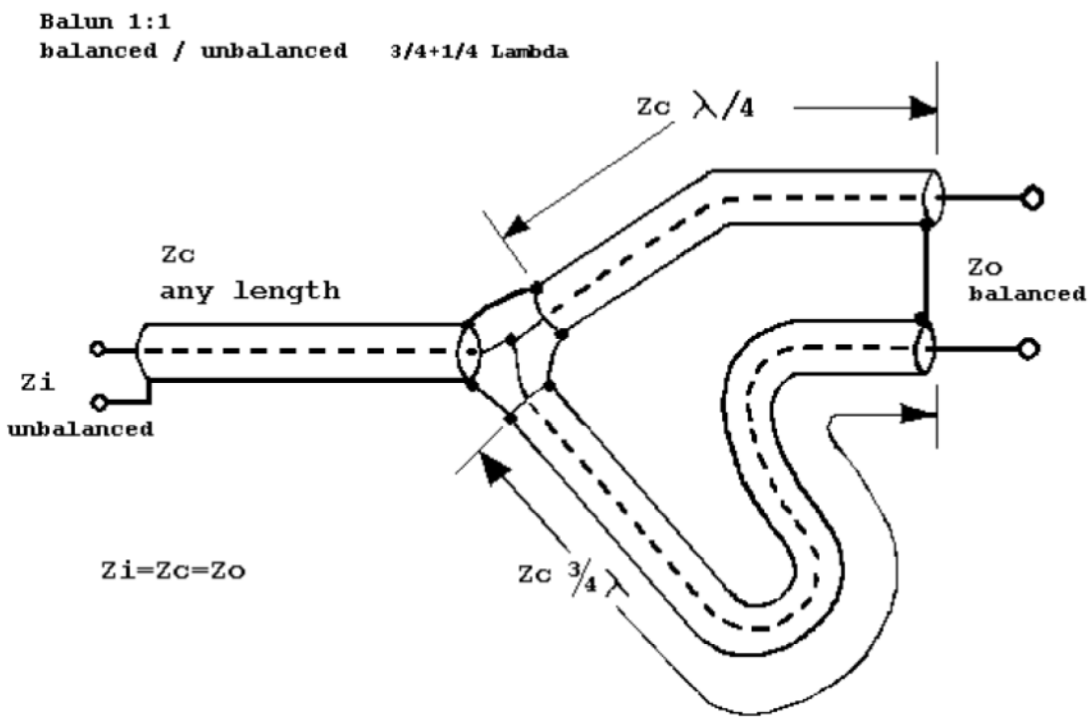


Figure 5: ¾ + ¼ wavelength 1:1 Balun[3]

Because the phase shift variable β= 2π/λ, a difference of λ/2 in length results in opposing phases at the antenna. This type of balun utilizes the inner conductor of the coaxial cable, so a velocity factor is applied when calculating the length required. The velocity factor for RF-58 copper core is 0.66, so the wavelength should be 1/3 shorter than the wavelength in free space. The quarter and three quarters coax lines radiate in opposite phases canceling each other out. The balun however is narrowband and limits the range of frequencies that the antenna can use, but has little drawback in this project since only a single frequency is used.

Another balun constructed is the choke balun. Although it is called, the choke balun does not match a balanced load to an unbalanced transmission line, but rather helps improve VSWR by acting as an inductor and isolating the two coaxial cables. The effect of the choke is reliant on

[3] http://www.iw5edi.com/ham-radio/files/I0QM_BALUN.PDF

the length of coax cable used rather the number of windings. The figure below shows a choke balun.

Figure 6: Choke Balun[4]

3. Yagi Uda Array Design

The Yagi Uda dipole array is an array of parasitic dipole. The reflector blocks the back or "grating lobe" of the antenna while the directors direct the frontal lobe towards the front and reduces the half power beam width. The first figure below shows the effects of adding a slightly longer than half wavelength parasitic reflector element to a driving dipole. The second figure shows the effects of adding a slightly shorter than half wavelength parasitic director to the dipole. The third figure shows the combined effects.

[4] http://www.hamuniverse.com/balun.html

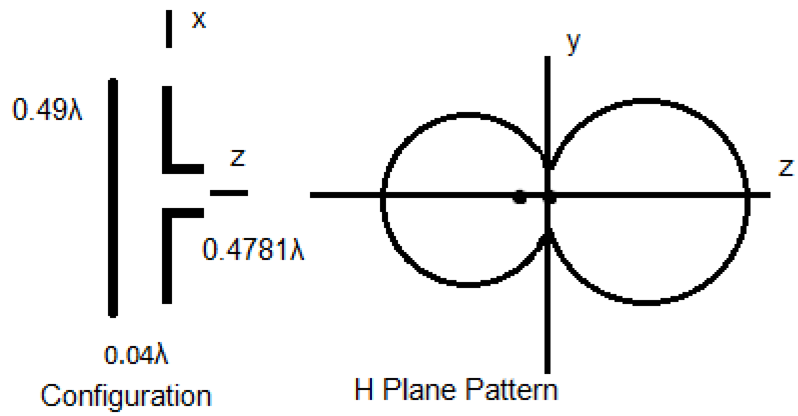


Figure 7: Effect of a Reflector[5] , H Plane Pattern

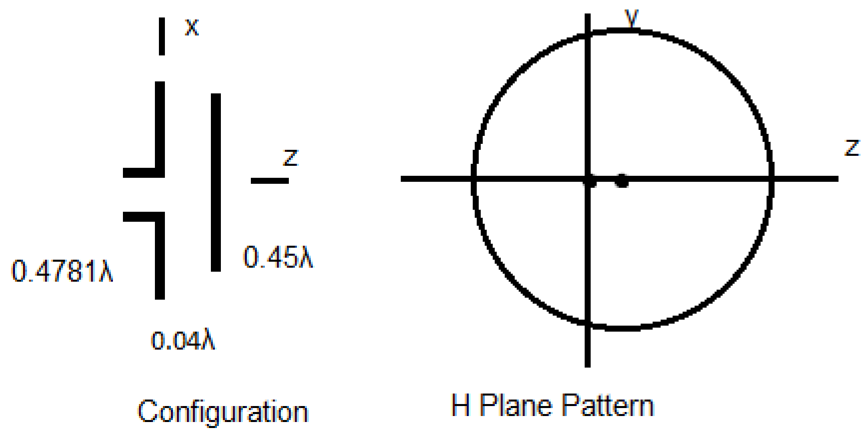


Figure 8: Effect of a single Director[4], H Plane Pattern

[5] Warren L. Stutzman, Gary A. Thiele, ("Antenna Theory and Design" 1998, pg. 188-189)

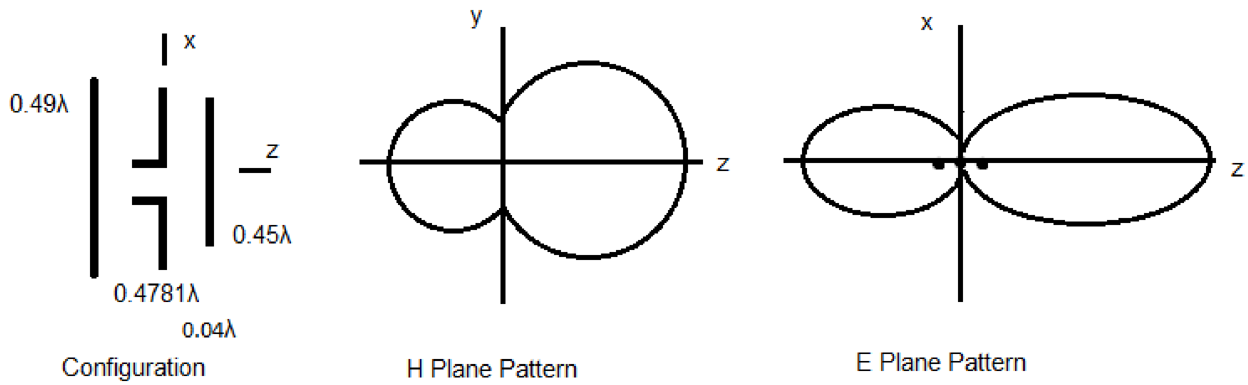


Figure 9: Combined Effect of Reflector and Director[4]

The design of the Yagi Uda uses an optimized predesigned version from "Yagi Antenna Design," NBS Tech. Note 699, National Bureau of Standards, Washington DC found in Antenna Theory and Design by Stutzman and Thiele. Given the limited space, a five element Yagi Uda array was chosen as a compromise between gain and size. The element lengths of the selected Yagi are shown in the table below.

Reflector Spacing = 0.2λ		Length at 433MHz
d/λ = 0.0085	Boom length = 0.8λ	0.554m
Reflector Length	0.482λ	0.334m
D1	0.428 λ	0.2965m
D2	0.424 λ	0.2937m
D3	0.428 λ	0.2965m
Director Spacing	0.2 λ	0.1386m
Gain relative to half-wave dipole	9.2	

Table 1: Optimum Element Lengths and Spacing for a Four Element Yagi Uda at d/λ = 0.0085

Because the 8mm radius of the tubes, d/ λ = 0.024, therefore the optimum length of the parasitic elements also have to be increased by 0.011λ increasing the parasitic element lengths as shown in the table below.

Reflector Spacing = 0.2λ		Length at 433MHz
d/λ = 0.0245	Boom length = 0.8λ	0.554m
Reflector Length	0.493λ	0.342m
D1	0.439 λ	0.304m
D2	0.435 λ	0.301m
D3	0.439 λ	0.304m
Director Spacing	0.2 λ	0.1386m

Table 2: Optimum Element Lengths and Spacing for a Four Element Yagi Uda at d/λ = 0.0245

4. DC Rectifier circuits design

Several types of rectifier circuits were considered. The first circuit considered was a simple bridge rectifier borrowed from power electronics. The standard diodes have been replaced by 1N5711 Schottky diodes which possess faster switching speeds and lower power dissipation and turn on voltage.

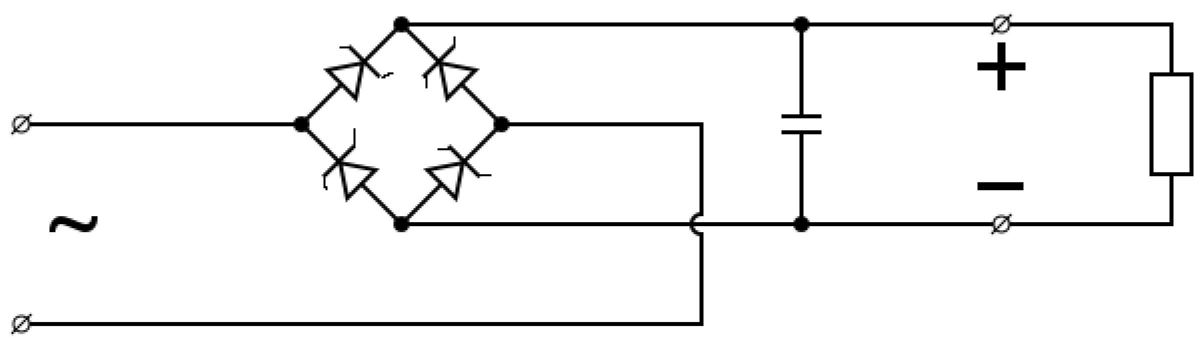


Figure 10: Bridge Rectifier [6]

The circuit could rectify AC voltage, but the DC voltage would be lower than the AC voltage and contain rippling effects depending on the frequency and size of capacitor.

The second circuit, shown below, is a half wave voltage multiplier that utilizes a clamping circuit and a half wave rectifier. In theory, the circuit can double the input voltage, but

[6] http://en.wikipedia.org/wiki/Diode_bridge

it is dependent on the capacitors and diodes chosen, therefore another circuit that can vary the output voltage is needed. In practice, the capacitors drain some of the AC voltage making the DC output much smaller for 100nF capacitors.

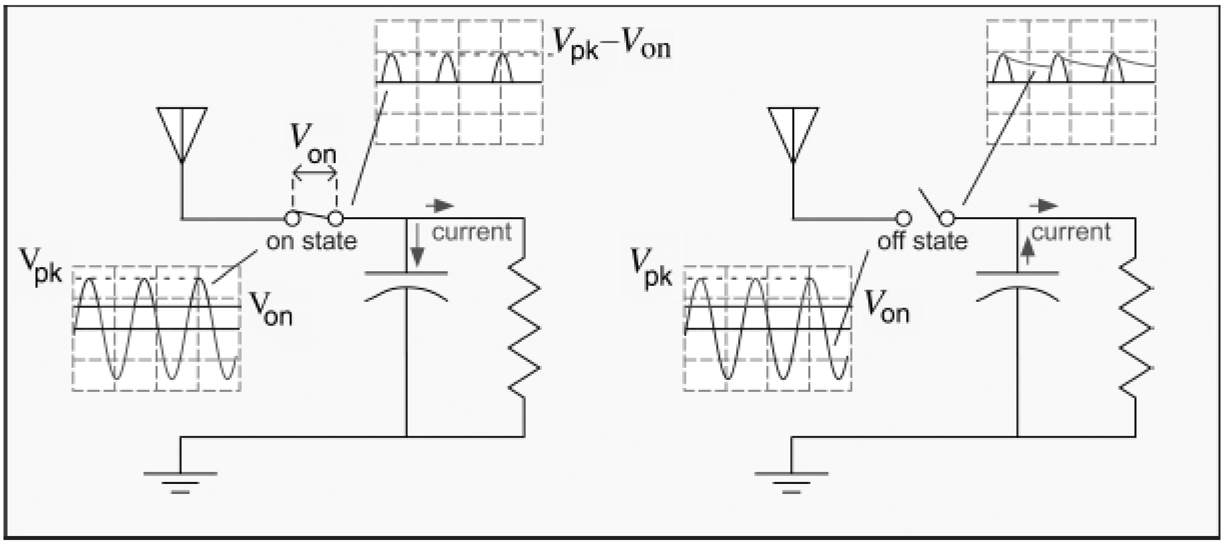


Figure 11: Half Wave Rectifier[7]

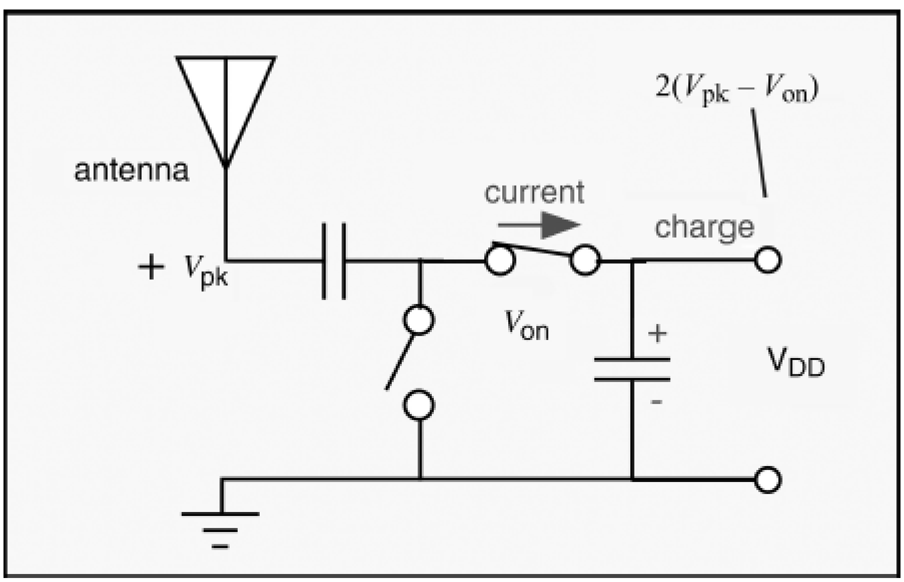


Figure 12: Voltage Multiplier and Rectifier circuit [6]

[7] http://rfid.net/basics/passive/137-uhf-rfid-tags

The final circuit uses a series of charge pumps multiply the output voltage of the previous circuit. When they are fully charged, the earlier stage capacitors charge the later stage capacitors multiplying the initial DC output voltage by the number of stages in the circuit.

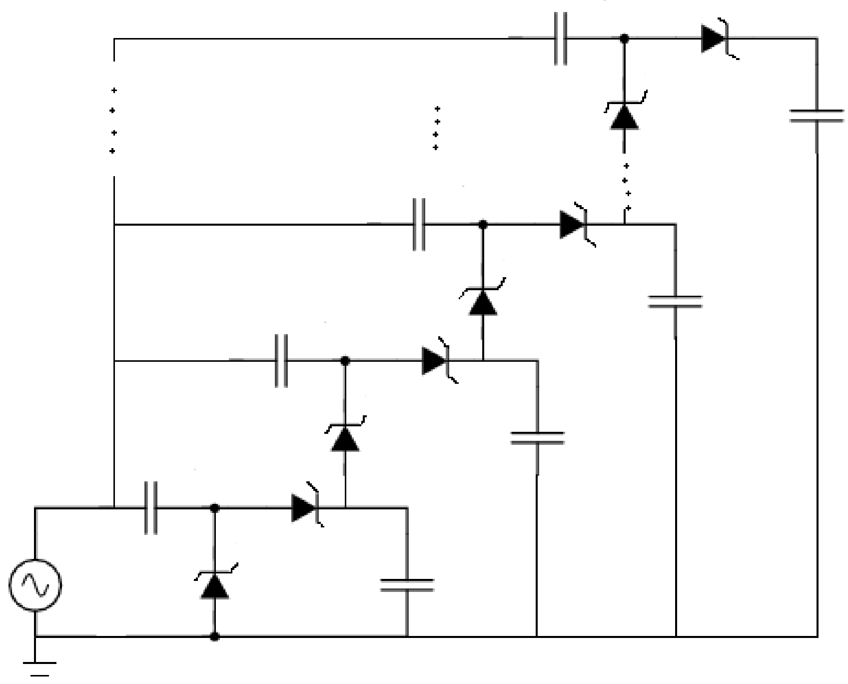


Figure 13: Charge Pump Voltage Multiplier and Rectifier

V. Construction

The construction of the antennas was done manually. The dipoles were made brass 5/16 x.014 (7.94mm x .355mm) brass tubing. Brass, copper, and aluminum are viable materials to construct the dipoles. Brass was chosen over aluminum because of aluminum tubes require unique soldering techniques and alloys. The dipoles are shown in the pictures below.

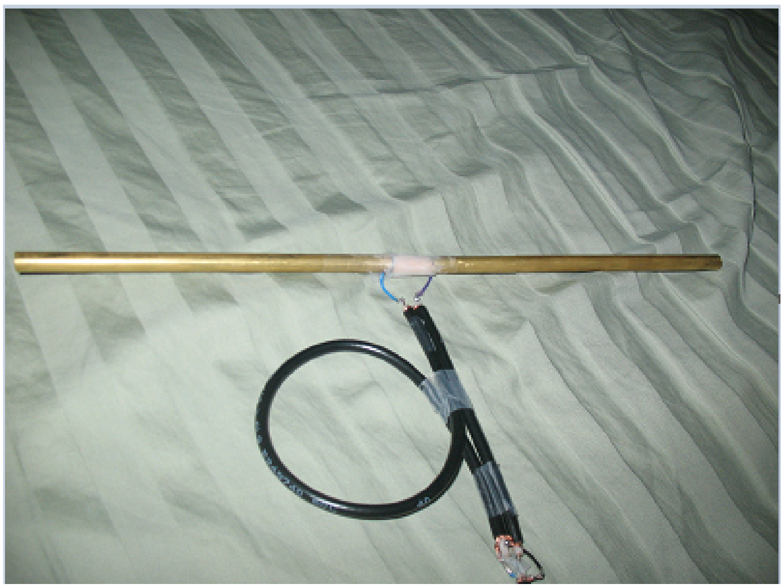


Figure 14: Constructed Dipole

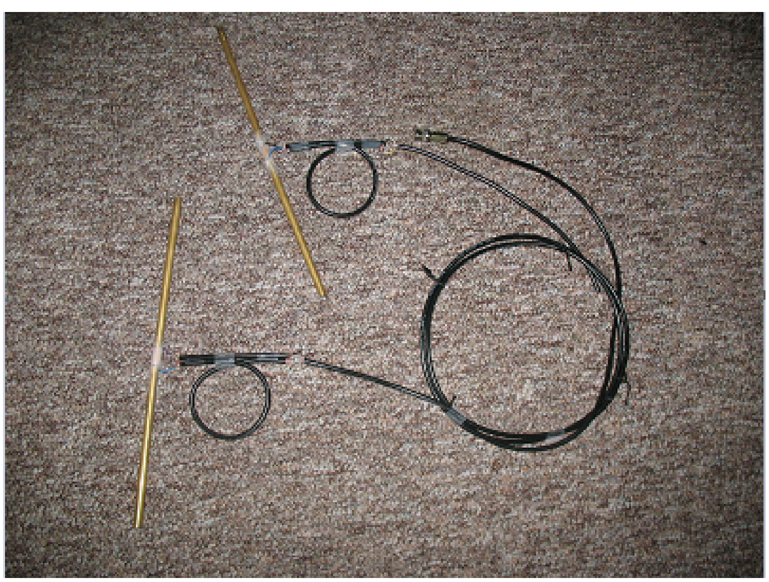


Figure 15: Both Dipoles

Wood was used as the dielectric separator in the dipoles. The dipoles were created with the Yagi Uda Array in mind. The boom of the Yagi Uda antennas were created from 24in. x 1.5in x.5in blocks of wood. 5/16 x .014 aluminum tubes served as the passive dipole elements of the Yagi Uda. (All antenna construction materials were provided by the local Ace/Miner's hardware store.) A position, shown below, was carved out of each Yagi Uda to allow the placement and removal of the dipoles.

Figure 16: Constructed Yagi Uda Arrays without the dipoles inserted

RG-58 coaxial cables were used to feed the antennas and create the baluns. Each balun was made from 4.5 and 13.5 inches of coaxial cable with connections soldered and taped together as shown below. Electronic tools and components were bought from the local Radio Shack.

Figure 17: Constructed Balun

The DC rectifier circuits require Schottky diodes which switch faster and have a lower voltage drop and turn on voltage than conventional diodes. 200 nF capacitors were used as they are the most readily available and aid in matching the impedance of the circuit. As a trade off, they have a lower power tolerance which makes them ideal for RF applications. The baluns were created from RG-58 coaxial cables. A choke balun was created using excess coaxial cable to improve VSWR of the antenna system.

Figure 18: Constructed Multiplier/Rectifier Circuit

VI. Test Plans/Procedures

The antennas and circuits were tested in steps before fully assembled. The test procedures are listed below.

1. *Dipole*
   a. Connection Test
   An initial connection test should be applied to the dipoles. This tests the solder connections of the dipoles to insure that power can flow into the dipoles.
   b. Impedance Test
   The impedance of the dipoles needs to be determined to design the balun as well as calculate any reflection and transfer loss from the antenna. The Vector Network Analyzer will be calibrated for one port reflection only at 430MHz to 440MHz using a BNC to grabber.
2. *Balun*
   a. Impedance Test
   Individual baluns will be subjected to a reflection/impedance test with a terminated load of 50 ohms to test viability of the balun.
   c. Combined Impedance Test
   After the balun is soldered with the dipole and transmission line, a VSWR/Impedance test will be performed to calculate overall VSWR and possible power loss.
3. *DC circuits testing*
   a. Low Frequency Test
   The principles of the single stage circuit will initially be subject to a low frequency (1kHz-20MHz) AC test. This simulates the results of higher frequency tests when not taking mismatch into consideration.
   b. Cascading Stages
   Additional stages will be applied and tested using low frequency as much as resources will allow.
   c. Impedance Tests
   The impedance and VSWR of the circuit will be tested with and without a shunt 50 ohm resistor before the circuit. The resistor helps approximate the amount of current received to determine initial power received by the circuit.
4. *Testing reference Antennas*
   a. Impedance Test
   The telescoping monopoles will be measured for lowest possible VSWR at 433MHz and set to the selected length.

Figure 19: Radioshack Extendable Monopoles

b. Active Transmission Testing

The antennas will be connected to the generator and rectifier/multiplier circuit. Output DC voltage range will be recorded from an input of 10dBm from the RF generator. Voltage/Power received based on distance and input power will be recorded.

5. Dipole/Yagi Uda Active Testing

a. Dipole Testing

The dipoles will be tested similarly to the monopoles based on input power and distance.

b. Yagi Uda Testing

To further analyze the problem with the project. Three types of active testing will be used to test the Yagi Uda. The first will use dipoles for both Yagi Uda. The second will use the Yagi Uda to transmit the power, but uses a dipole to receive. The third will use a dipole to transmit the power and receive using a Yagi Uda. The results will be recorded, analyzed, and compared.

VII. Experimental Results

Impedance/VSWR Tests

Transmission Dipole System

The dipole impedance was measured to be 80.2ohms at433MHz. This results in a reflection coefficient of 0.232 or a VSWR of 1.604 at the point of the feedline. After connected with the quarter/three quarters wavelength balun and a choke balun, the VSWR shifted to 1.669. This could be due to approximation and flaws in the balun construction as well as inaccuracy from the VNA due to sensitive cables. The graph from the VNA shows the best case received by the VNA.

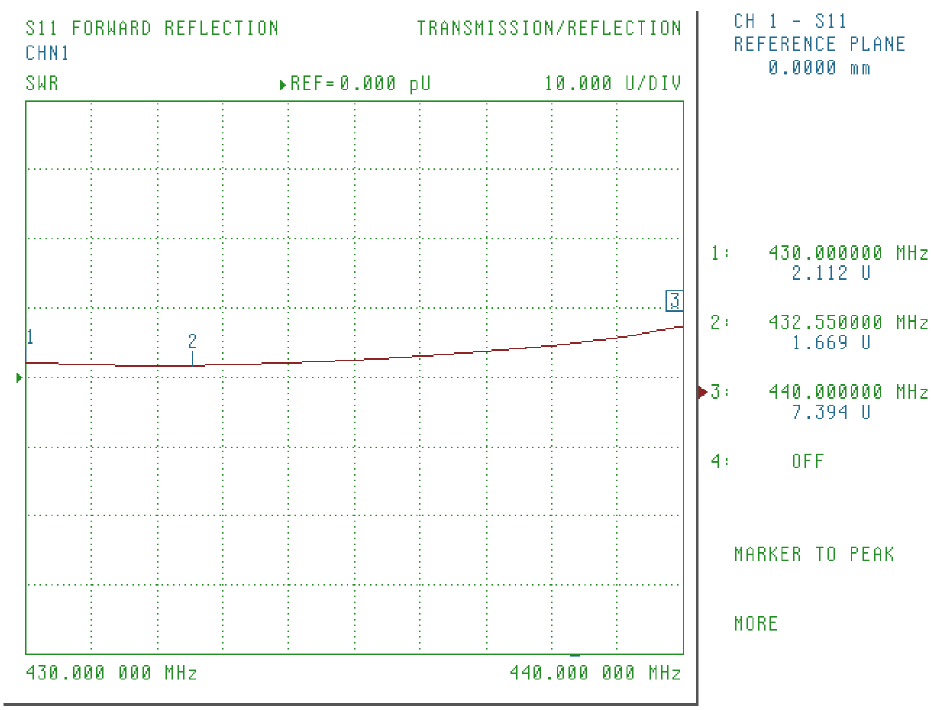


Figure 20: Transmission Dipole VSWR

Receiver Dipole System

The receiver dipole has an impedance of 78 ohms. This results in a reflection coefficient of 0.219 or a VSWR of 1.56. The graph below shows the VSWR after connecting with the quarter/three quarters wavelength balun. This time there is a 0.068 decrease in the VSWR. Both the receiver and transmitting dipoles comes within 10% of the theoretical value of 75ohms.

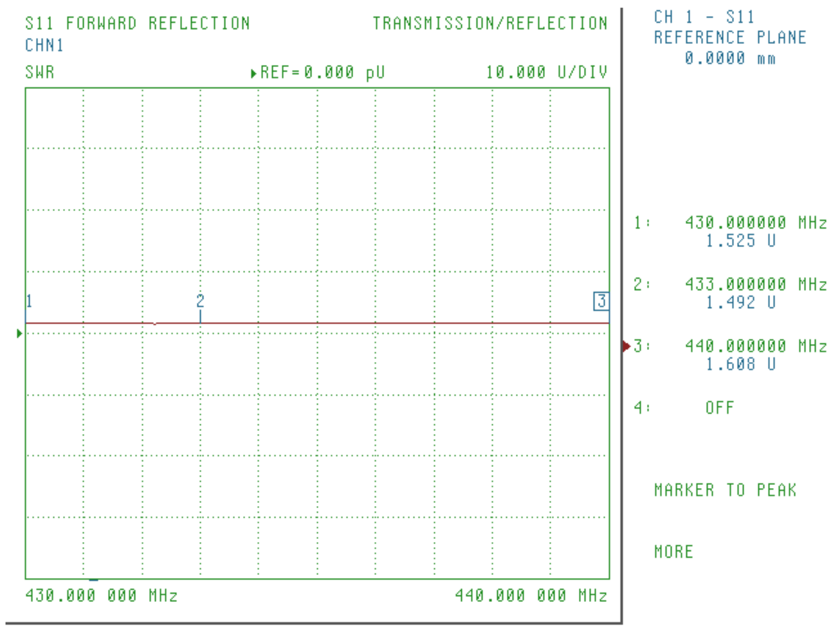


Figure 21: Receiver Dipole VSWR

Telescoping Monopole VSWR

The actual lengths of monopoles are 8.5 inches, instead of the designated 6.5 inches from the instruction manual. This was achieved by adjusting the monopoles for minimum VSWR while connected to the VNA. The antennas are wideband, so they trade off VSWR for a higher range of frequencies.

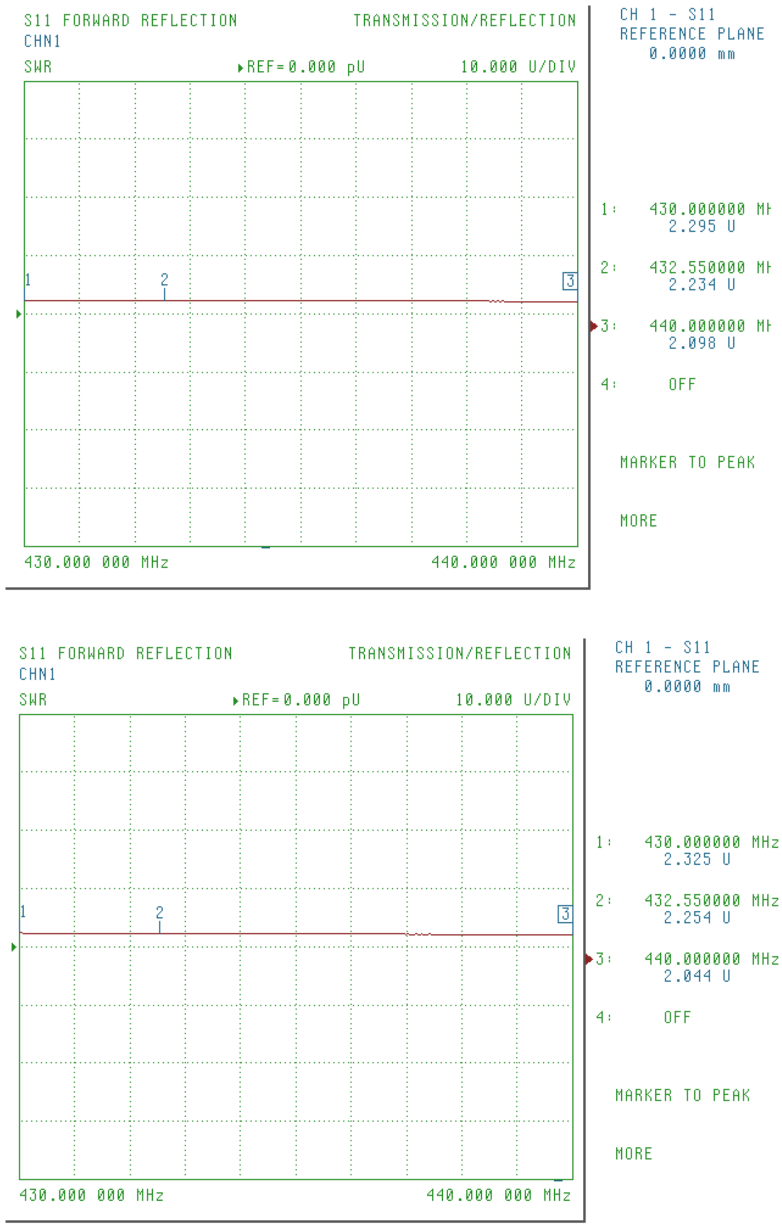


Figure 22: Telescoping Monopole VSWRs (Top - transmitting, Bottom – receiving)

Circuit VSWR

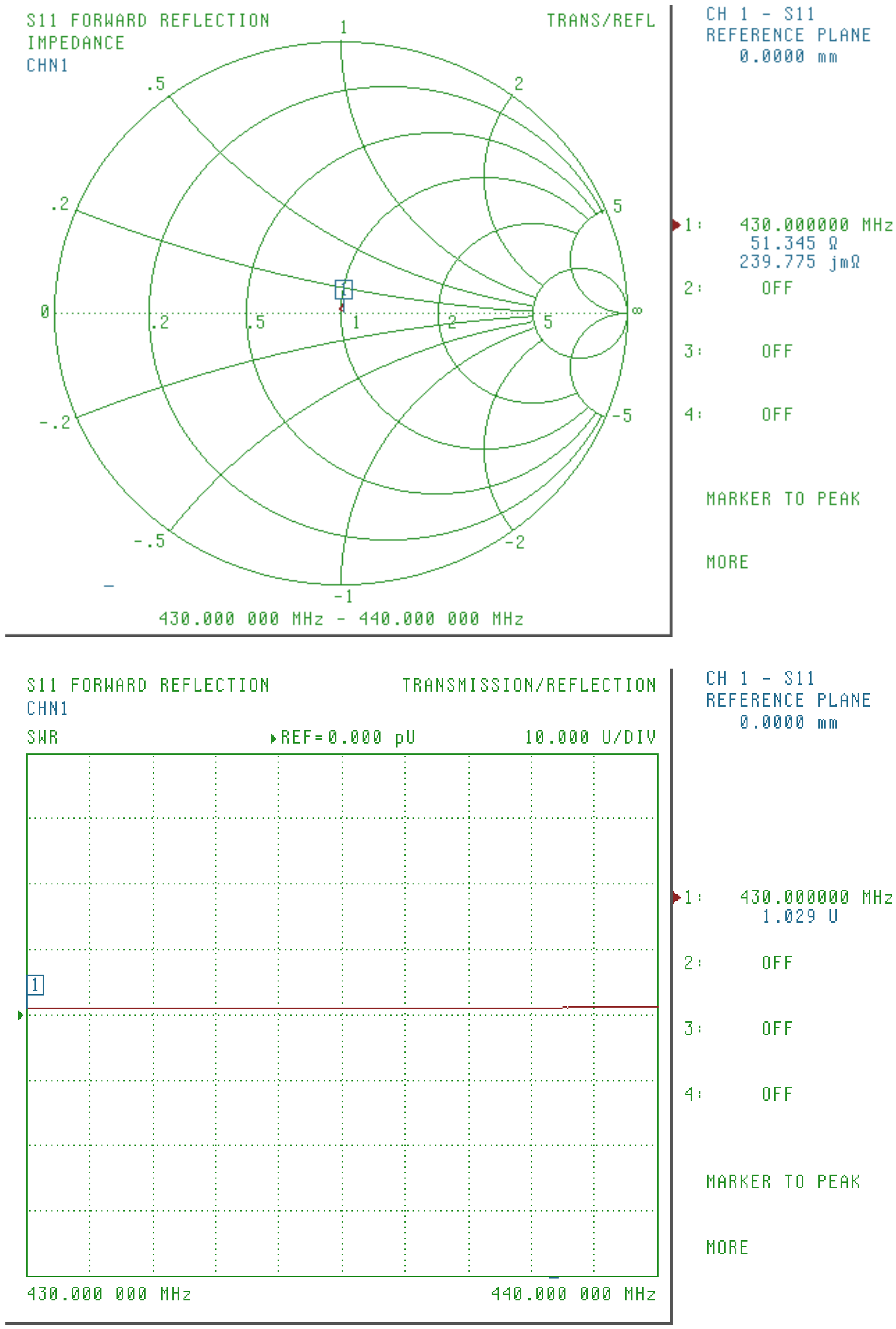


Figure 23: Voltage Multiplier/Rectifier Circuit VSWR

The impedance of the circuit is estimated using V_{in}/I_{in}. Because of the voltage multiplication properties, the current should theoretically be more erratic as the capacitors charge and discharge. The impedance of 51 ohms was therefore unexpected.

Circuit Low Frequency test

Comparison between standard diodes and Schottky diodes

As expected, the Schottky diodes have a lower turn on voltage than regular diodes. The 1N5711 diode particularly has a turn on voltage of 0.2V, 0.4V lower than regular diodes. Schottky diodes also have a faster switching speed which prevents oscillations in the waveform at RF frequencies.

Reg. Diode(VinAC)	VR	Schottky	VR
0.1	0	0.1	0
0.2	0	0.2	0.006
0.3	0	0.3	0.05
0.4	0	0.4	0.124
0.5	0.002	0.5	0.208
0.6	0.016	0.6	0.296
0.7	0.065	0.7	0.386
0.8	0.138	0.8	0.477
0.9	0.222	0.9	0.57
1	0.311	1	0.663

Table 3: Output characteristics of 1N5711 Schottky and a standard Diode

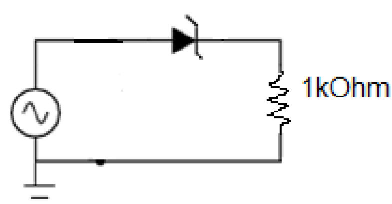


Figure 24: Schematic of Diode characteristics test circuit

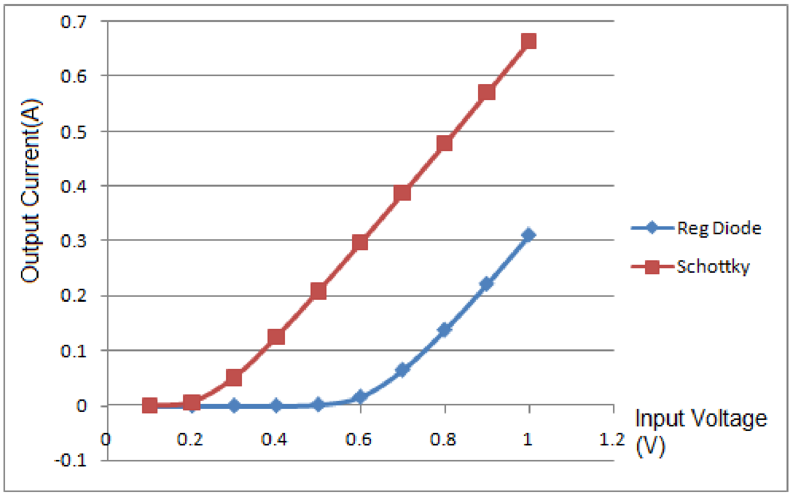


Figure 25: Output characteristics of 1N5711 Schottky and a standard Diode

Multiple stage test of voltage multiplier/rectifier circuit

The voltage multiplier/rectifier circuit fully rectifies the input AC waveform after a voltage drop based on the input voltage and number of stages in the circuit. The output voltage multiplies by the number of stages in the circuit.

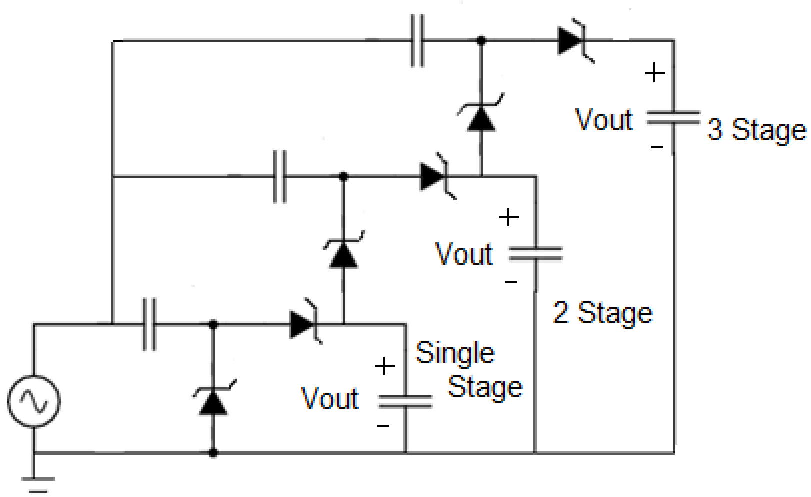


Figure 26: 1 to 3 stage Voltage Multiplier/Rectifier circuit

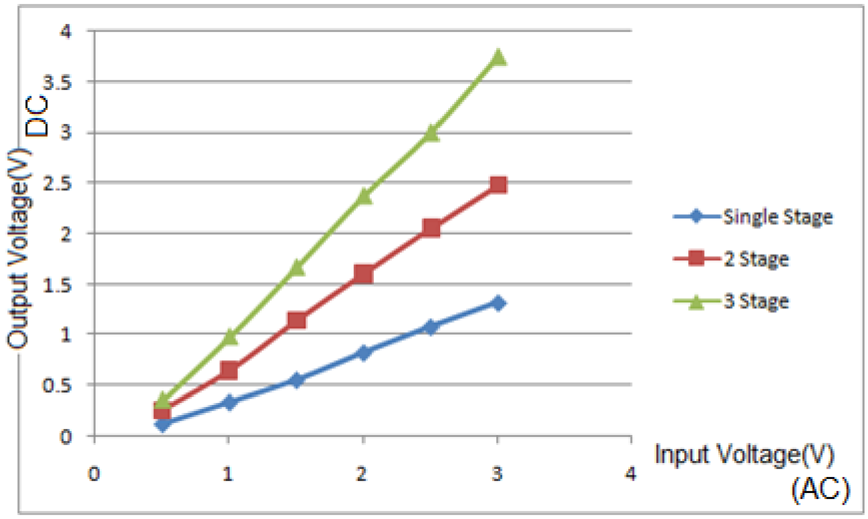


Figure 27: Output characteristics of Multi stage Schottky Diode Multiplier/Rectifier circuit

Effects of increasing frequency

With the input voltage set to 1V, the output voltage of the 3 stage multiplier/rectifier was tested as a function of frequency from 1 kHz to 20MHz in order to approximate its functionality at 433MHz. The voltage increases to 1.2V then starts to saturate towards 1.3V-1.4V.

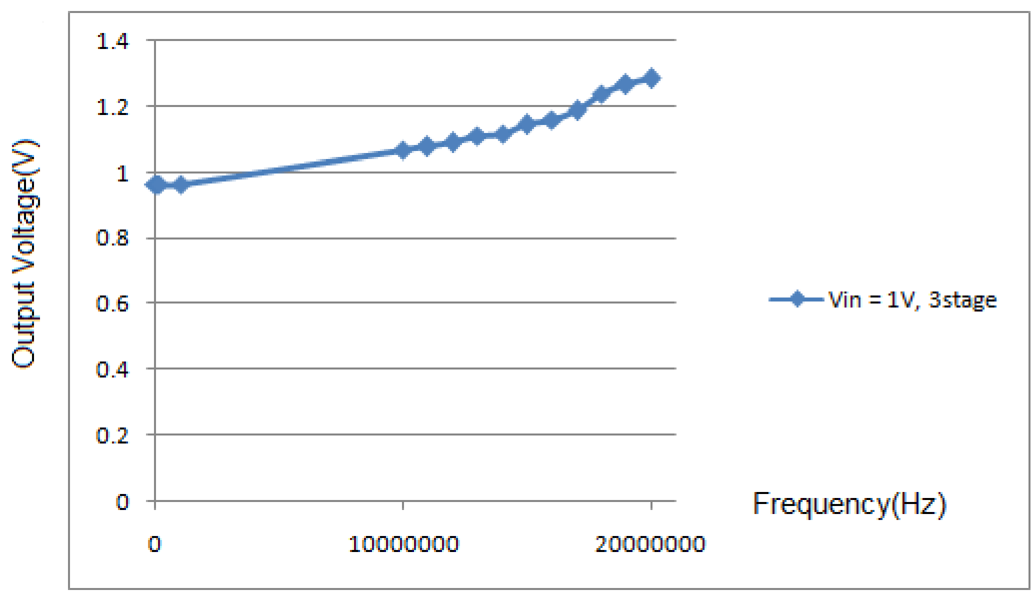


Figure 28: Frequency Characteristics on a 3 stage Multiplier/Rectifier

Transmission Test

Due to the erratic nature of the antennas from movement of the coaxial cables, there are discrepancies in the data. Certain methods, such as taping the cable down, were used to improve consistency.

Monopoles Output Voltage

10dBm Distance	10dBm Voltage	5dBm Distance	5dBm Voltage	0dBm Distance	0dBm Voltage
0.01	0.68	0.001	0.21	0.001	0.06
0.1	0.39	0.1	0.06	0.1	0.022
0.2	0.298	0.2	0.048	0.2	0.013
0.4	0.14	0.4	0.026	0.4	0.002
0.6	0.05	0.6	0.009	0.6	0.001

Table 4: Transmission characteristics of Monopoles

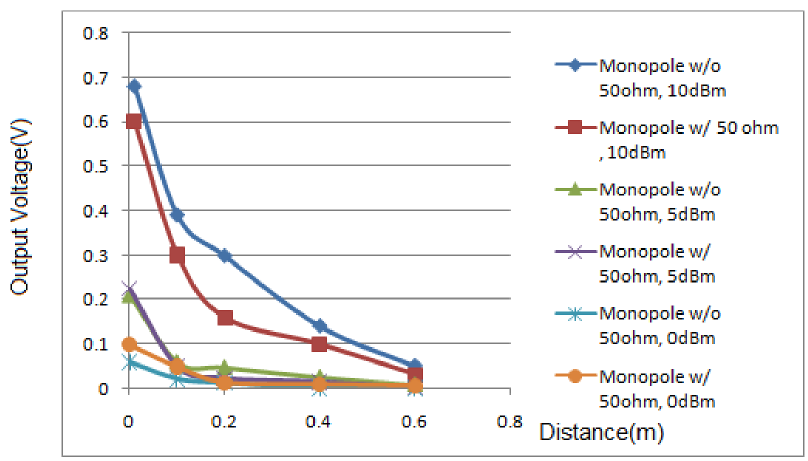


Figure 29: Output Characteristics of Monopole to Monopole Transmission

Dipoles Output Voltage

10dBm Distance	10dBm Voltage	5dBm Distance	5dBm Voltage	0dBm Distance	0dBm Voltage
0.01	0.89	0.001	0.306	0.001	0.172
0.1	0.58	0.1	0.198	0.1	0.152
0.2	0.365	0.2	0.174	0.2	0.098
0.4	0.214	0.4	0.16	0.4	0.045
0.6	0.114	0.6	0.104	0.6	0.022

Table 5: Output Characteristic of Dipole Transmission

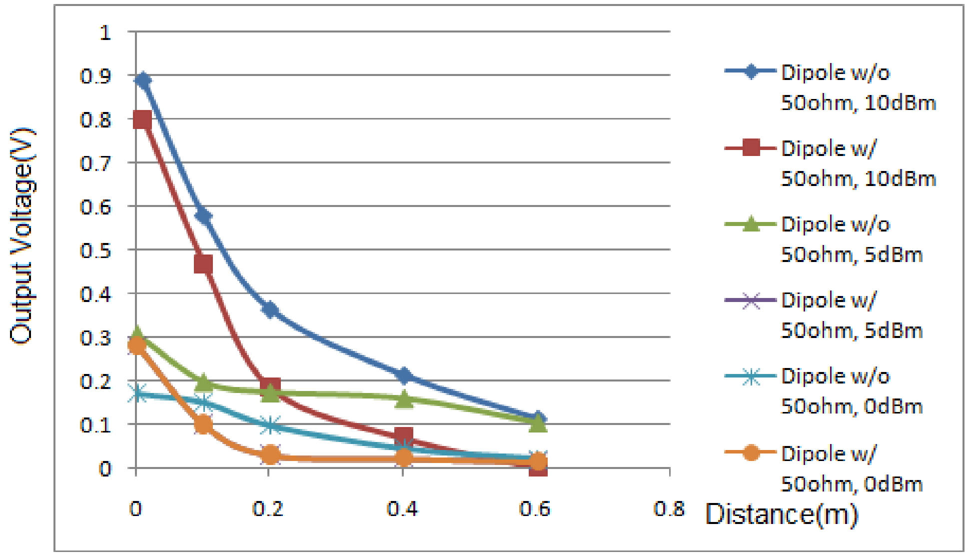


Figure 30: Dipole to Dipole Transmission Output Voltage Characteristics

Yagi Uda Output Voltage

Yagi to Dipole

Distance(m)	Voltage(V), 10dBm	Voltage(V), 5dBm		Angle (degrees)	Voltage (V), 10dBm, 0.6m, Angle based
0.6	0.7	0.25		0	0.42
0.8	0.1	0.028		10	0.22
1	0.015	0.012		20	0.15
1.2	0.012	0.007		30	0.082

Table 6: Yagi to Dipole Transmission Output Voltage Characteristics

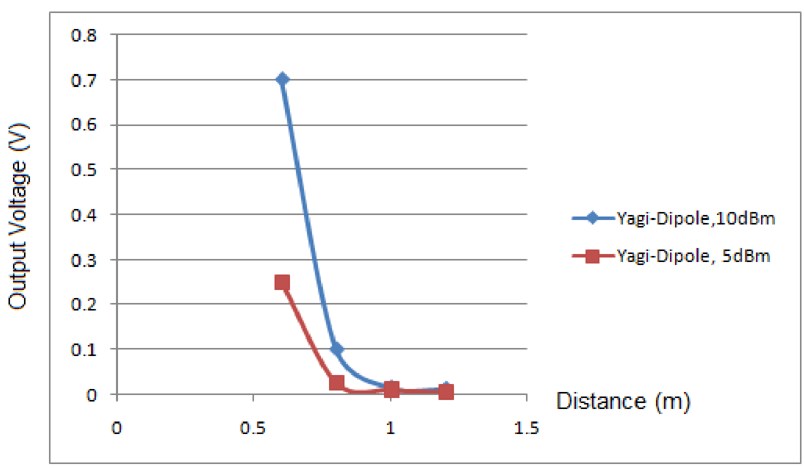


Figure 31: Yagi to Dipole Transmission Output Voltage Characteristics

Dipole to Yagi

Distance(m)	Voltage(V), 10dBm		Angle (degrees)	Voltage (V), 10dBm, 0.6m, Angle based
0.6	0.304		0	0.1
0.8	0.084		10	0.065
1	0.006		20	0.06
1.2	0.004		30	0.03

Table 7: Dipole to Yagi Transmission Output Voltage Characteristics

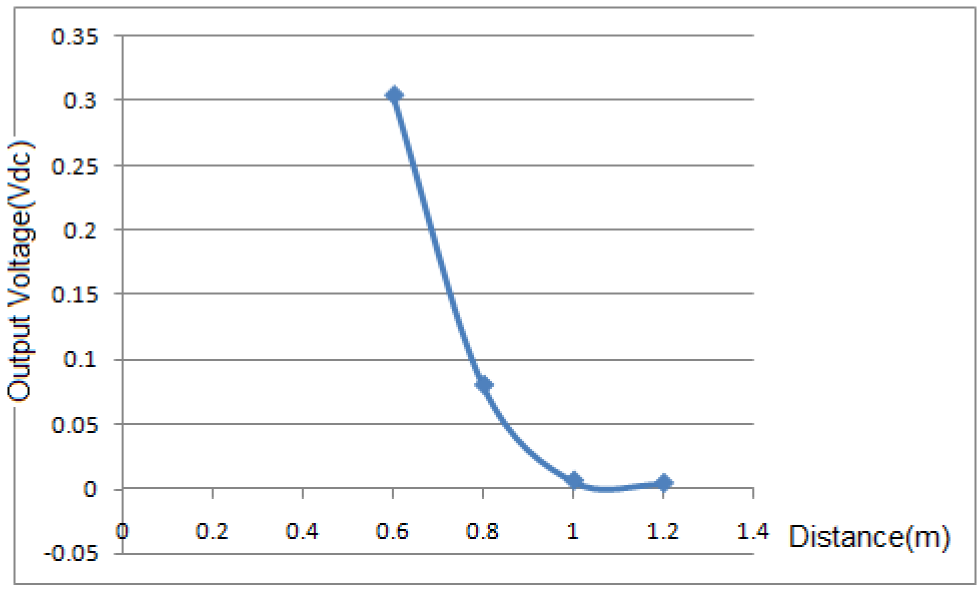


Figure 32: Dipole to Yagi Transmission Output Voltage Characteristics

Yagi to Yagi

Distance(m)	Voltage(V), 10dBm
0.6	0.104
0.8	0.03
1	0.006
1.2	0.004

Table 8: Yagi to Yagi Transmission Output Voltage Characteristics

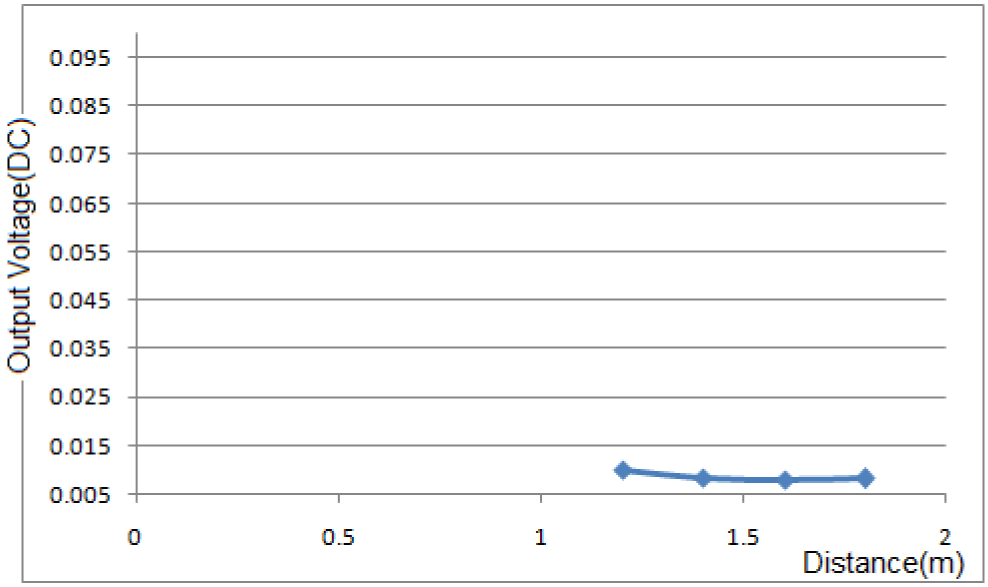


Figure 33: Yagi to Yagi Transmission Output Voltage Characteristics

The data for the Yagi transmission is distorted because the attenuation due to the distance of the drivers reduced the received RF voltage to lower than the turn on voltage of Schottky diodes. A higher power generator is required to test for longer distances. The voltages shown that are lower than 0.2V, can be anywhere from 0.1V to 0.2V.

Output Power

Output power can be approximated using Vout with 51ohms, since $Pout = \frac{1}{R}V^2$. Since the reflection coefficient $\Gamma = \frac{ZL-Z0}{ZL+Z0}$ is 0.01 when Z_L = 51ohms, reflected power can be largely neglected. From the low frequency tests, V_{DCout} is approximately V_{ACin} for V_{ACin} less than 1V. The increased frequency test demonstrates that the voltage might increase by up to 40% as the frequency increases. Therefore, Pout is approximated as $\frac{(V_{DCout}/1.4)^2}{Z_L}$. % Total Efficiency = 100%* Pout/Pin.

10dBm			
Distance(m)	Voltage(V)	Power(mW)	%Eff
0.01	0.68	4.63	46.3
0.1	0.39	1.52	15.2
0.2	0.30	0.89	8.9
0.4	0.14	0.020	2.0

Table 9: Monopole Output Power Characteristics and Efficiency

10dBm			
Distance	Voltage	Power	%Eff
0.01	0.89	7.92	79.24
0.1	0.58	3.37	33.65
0.2	0.365	1.33	13.33
0.4	0.214	0.46	4.58

Table 10: Dipole Output Power Characteristics and Efficiency

10dBm			
Distance	Voltage	Power	%Eff
0.6	0.7	4.90	49.02
0.8	0.1	0.10	1.00
1	0.015	0.00	0.02
1.2	0.012	0.00	0.01

Table 11: Yagi to Dipole Output Power Characteristics and Efficiency

10dBm			
Distance	Voltage	Power	%Eff
0.6	0.304	0.92	9.25
0.8	0.08	0.06	0.64
1	0.006	0.00	0.00
1.2	0.004	0.00	0.00

Table 12: Yagi to Yagi Output Power Characteristics and Efficiency

10dBm			
Distance	Voltage	Power	%Eff
1.2	0.0102	0.001041	0.01041
1.4	0.0085	0.000723	0.00723
1.6	0.008	0.000640	0.00640
1.8	0.0082	0.000673	0.00673

Table 13: Dipole to Yagi Output Power Characteristics and Efficiency

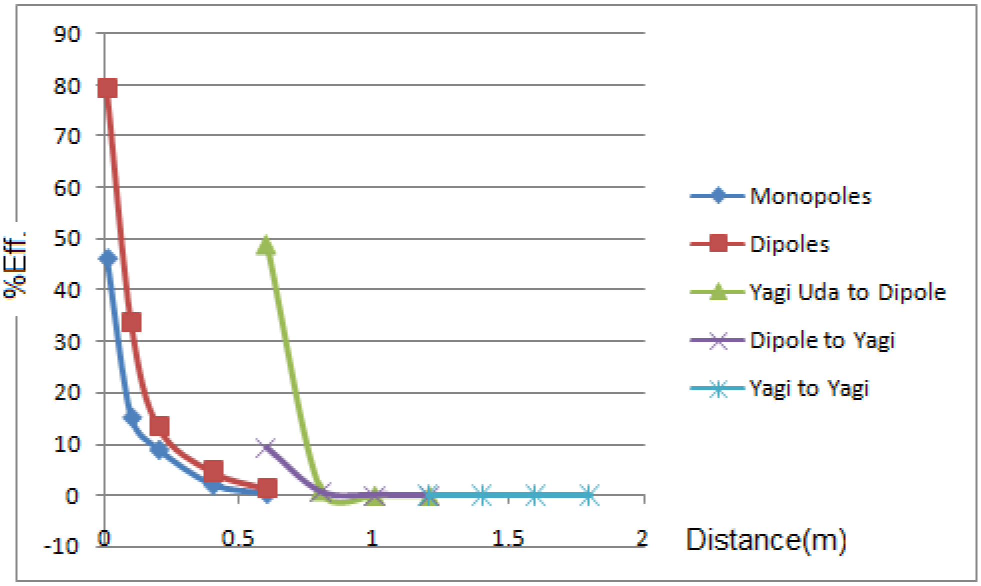


Figure 34: Efficiency of Antenna Transmission Combinations

Although the data is slightly impaired from the incoming RF voltage dropping below V_{DON} of the Schottky diode, the graph demonstrates how the efficiency of wireless power transmission is impaired as distance increase. An interesting result is that the Yagi to Dipole transmission is more efficient than Dipole to Yagi transmission. This is due to the directional properties of the Yagi Uda antenna array. The unidirectional dipole loses power in a specific direction since it propagates in all directions.

VIII. Project Difficulties and Possible Future Improvements

Difficulties: Several difficulties were encountered throughout the project which attributes to large amounts of time wasted and inefficiencies. One of the major difficulties is lack of access to the proper materials and equipment due to lack of nearby radio stores. This led to alternative construction plans and excess manual labor as well as delaying the project. Wire dipole elements were considered for the project, but due to the length and required precision, was replaced with tubes for easier placement. Lack of experience also hindered the project. The initial order of construction was reversed. The dipoles were not tested when built into the Yagi Uda. The first dipoles were constructed from aluminum. Since aluminum cannot be soldered to copper wires using tin solder, the connection had to be made through punching a hole and taping a wire into the hole. The dipoles had VSWR over 12, possibly due to the unconventional connection method and excess impedance from solder, glue, and tape. Certain materials such as Schottky Diodes are only supplied online and require sometimes long shipping time. Triple inner conduction soldering connections in the baluns break after a period of use and had to be constantly resoldered. The HP 856813 Spectrum Analyzer that was initially planned to read and record output power did not work as intended and was unresponsive to controls and input signals. The final dipoles slump and did not match up well with the parasitic elements without external help to prop up the slumping legs of the dipoles. Calibrations for the VNA were done with sensitive coaxial cables which often distort data. The data has to be constantly checked using a 50 ohm resistor and requires recalibration when the data is severely distorted. The amount of attenuation over distance is too high to acquire much usable data below 10dBm. The Yagi Uda antenna arrays were not symmetrical causing loss of power through the propagation.

Future Improvements: If the project is to be improved or replicated, the dipoles must be made and tested first. 50ohm dipoles instead of 75 ohm will improve the VSWR. Alternative higher

quality baluns may be used to improve the frequency characteristics. Other types of antenna arrays can be tested such as higher frequency microstrip Yagi Uda or loop Yagi Uda arrays or aperture antennas. The circuit can be improved by adding additional stages to further increase the output voltage. Radiation patterns can also be acquired beforehand if time allows in order to compare far field propagation to near field power transfer.

IX. Conclusion

The project achieved most of the designated goals. The circuit worked well beyond expectations. The three stage multiplier/rectifier was able to output DC output higher than the AC input. Higher stages will trade current for DC voltage that is multiples of the AC input. The dipoles had the expected impedance of around 75ohms and VSWR of 1.5. The dipoles had higher gain and transmission characteristics than the store bought monopoles. Although the Yagi Uda Antenna Arrays were below expectation, they were nonetheless able to transmit and receive signals. The gain was not able to keep up with the attenuation over distance. Yagi to Yagi transmission requires precise placement of both antennas or it will result in severe loss in power transmitted. The most efficient type of transmission was Yagi Uda transmitting to a dipole antenna. The directional capability of the Yagi Uda allows it to most efficiently transmit the signal, while the dipole scavenges energy more efficiently. Overall, the project demonstrates that attenuation in air makes wireless power transmission using antennas inefficient. Power received drops off exponentially as the distance increases.

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Appendix

Equations:

Friss Equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

Directivity

$$D(\theta, \phi) = \frac{U}{\text{Total radiated power}/\,(4\pi)}$$

Where U = radiation intensity per solid angle such that hich is the power density per unit solid angle such that

$$\text{Total radiated power} = \int_{\phi=0}^{\phi=2\pi} \left(\int_{\theta=0}^{\theta=\pi} U \sin\theta \, d\theta\right) d\phi$$

Transmission Line

$V(x) = V^{+}e^{-\gamma} + V^{-}e^{\gamma}$ where V(0) = voltage at the source,
V^{+} = incident wave, and V^{-} = reflected wave.

I(x)= V(x)/Z(x)

Power = $V(x)^2/Z(x)=V(x)I(x)$

Efficiency

$$\eta = \frac{Pout}{Pin} = P_{in} - P_{reflectedgenerator} - P_{reflectedtransmittingantenna} - P_{reflectedreceiverantenna} - P_{reflectedcircuit} - P_{diodes}$$

Bill of Materials

Material	Number	Cost	Total Cost (before Tax)
Copper tubes	1	$2.99	$2.99
Wood	1	$2.00	$2.00
Coaxial Cable RG58 – 50ft	1	$19.99	$19.99
Aluminum Tubes	6	$2.99	$17.94
Schottky Diodes	6	$0.10	$0.60
100nF Capacitors	6	$1.99 for 2	$5.97
Breadboard	1	$5.00	$5.00
BNC Connector	1	$4.99	$4.99
Total Cost			$59.48

Other Tools

Hacksaw

Drill

Coaxial Stripper

Coaxial Cutter

Soldering Iron

Scissors

Tape