Harvesting Energy from Ambient Radiation

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Abstract

A method of harvesting energy from ambient radio waves produced by electrical appliances has been conceived, developed and tested. Through the use of magnetic wire, coils were produced of varying length, gauge, and surface area; in addition a rectifying circuit was constructed using 0 – 160 Pico farads variable capacitor and a germanium diode. The ability of these coils to recycle radiation from a laptop computer and other electronic devices was tested; furthermore, the effect of certain attributes of the circuit on the production of power was also evaluated. It was found that a wire of a larger gauge used in combination with a ferrite rod produced the most power. This information was then used to construct a full scale version of the device. This design was effective in producing power from laptop radiation; however, the device produced the most electricity when harvesting energy form the ambient radiation of an LCD TV. Finally, after attaching battery snaps, the device was shown to be capable of charging a AA 1.2 volt battery.

Literature Review

Introduction

This is the modern era, a time period ruled by electronic machines and appliances. As our exposure to electronic objects grows, concerns about radiation have also increased. Although most radiation from everyday devices is harmless, energy of ambient electromagnetic waves remains unutilized. Because there is no way to reduce power loss through radiation, a device must be constructed to recycle this energy. With numerous devices like laptops and televisions being used at a regular basis, one such device would be extremely useful and beneficial; therefore, this project aims to build a device capable of harvesting energy from ambient electromagnetic waves.

History of Wireless Energy

Although radiation might seem to be a relatively new idea, the concept has existed for many years. The theory originated with Heinrich Hertz, who observed that energy existed as invisible and intangible forms of electromagnetic waves. Later, radios and electromagnetic propagation systems were invented, and radio waves, a form of radiation, were transmitted commercially. These systems involved 2 parts, a transmitter and a receiver. The transmitter propagated the waves while the receiver gathered and converted them to audible sound. In this project, the electronic appliance emitting the radiation is the transmitter and the receiver produces electrical energy from the radiation.

Physics of Radio Waves and Radio Wave Propagation

There are many forms of electromagnetic radiation; in fact, visible light is radiation. The electromagnetic spectrum is divided into many sections depending on their traits. In addition to light, there are also radio waves, Gama waves, microwaves etc.

Any electromagnetic wave can be specified by three main characteristics: wave length, frequency, and amplitude. The wave length of a wave is the distance, measured in units of length, between the subsequent crests of the wave. This trait is related inversely to the frequency. The frequency is the number of occurrences of the wave within an amount of time. This is usually measured in Hertz (cycles per second), the SI unit for frequency. Frequency and wavelength are related by this formula:

$$f = \frac{c}{\lambda}$$

In this formula, f is the frequency, λ represents the wave length, and c is the speed of light. Because all electromagnetic waves carry energy through space, the formula mentioned below relates the frequency to the amount of energy contained within the wave:

$$E = hf$$

Where E is the amount of energy in the wave, and the h and f are Planck's constant and frequency respectively (Marshall, 2000).

Radio transmitters operate on the principle that any electric current moving through a wire emits electromagnetic radiation. A simple transmitter can be made by connecting and disconnecting an electric circuit, thereby producing a fluctuating voltage. This signal can be picked up by another wire a several centimeters away; however, this configuration is not ideal and is not very efficient. By turning the above circuit on and off, a square wave of radiation is developed. A square wave modulates between 0 and a certain voltage. A more effective design would transmit sine waves. These are produced when the voltage fluctuates between a certain voltage and its negative counterpart. This suppresses the fluctuation and establishes smoother waves. As a result of these modified waves, the transmitter becomes more efficient. A simple sine wave can be produced by using a capacitor and inductor in combination (Brain, 2000). Capacitors (strength measured in farads [f]) are electrical parts that impede the flow of electrical current by storing the energy as an electrical field. Inductors (strength measured in Henrys [h]) also constrain the flow of current; however, unlike capacitors, they store energy as a magnetic field. These two components have inverse reactance (inductor has positive reactance and capacitors have negative reactance) and therefore are able to produce the sine waves necessary for radio transmitting (Jassat, 2010). When an inductor and a capacitor are combined in a circuit and provided with a power source, the current travels back and forth between these components and produces a sine wave. Ideally, the strength of the capacitor and inductor should be equal, which will cause the system to resonate and operate maximum efficiency; however, it is not likely that all these conditions are met (Gibilisco, 1999). Because most common electronic appliances are not designed to propagate radiation, they are not optimized for this function; however, some electrical power is converted to radiation so it is important to reuse this energy.

Frequencies of electromagnetic waves range from 10^4 to 10^{20} Hz. These frequencies are categorized into band designations, or groupings. Higher frequency waves are called ultraviolet, x-ray, and gamma rays. The categories range from 10^{15} to 10^{16} hertz, 10^{16} to 10^{18} hertz, and 10^{18} to 10^{20} hertz respectively. Higher frequency will yield more power; however, it is not feasible to change the radiation that is emitted from electronic appliances. Usually these electromagnetic waves are in the high radio waves or low microwave frequencies (“Radio”, 2010).

Antenna Structure and Design

Antennas are ultimately elements of radios and transmitters that aid in the propagation or collection of radio waves. An antenna is simply a copper wire with flowing current that helps transmit the radio signal farther and more efficiently. Although there are many types of antennas, they all operate on the principle that an alternating current moving though a conductor develops radio waves that are transmitted through the air.

The concept of antennas is basic; however, there are many characteristic that must be taken into account when designing an antenna including polarization. This refers to the orientation, such as vertical, horizontal etc., of the waves produced by the transmitter. Polarization should always be parallel to the antenna; therefore, antennas and waves with similar polarizations are extremely compatible. Vertical and horizontal polarizations are collectively considered linearly polarized because the polarization always maintains a certain configuration. On the other hand, a polarization that rapidly changes is said to be elliptical. If the rate of change is also constant then the wave is polarized circularly, a subtype of elliptical polarization. Although vertical and horizontal orientations may be useful for lower frequencies, only elliptically and circularly polarized antennas are useful at higher levels. At any mode of polarization, ideally, both the transmitting and receiving antennas should be similarly polarized (Gibilisco, 1999).

There are many types of types of antennas in the real world that have very specific uses; however, some of the most basic antennas include the Marconi, vertical, and dipole antennas. These antennas are extremely simple but are not as efficient as other models. The Marconi design is simply a long wire that is stretched across a distance that receivers and transmits radio waves. A vertical antenna is extremely similar to the Marconi antenna except this antenna is oriented vertically. A dipole antenna is simply two quarter wavelength antennas attached at the center to a base forming a T. The usage of wavelength units is very common in the field of antennas; this simply compares the length of the antenna to the length of the wavelength of the signal it is designed to receive or transmit. These antennas are linearly polarized and their efficiency varies directly with their length (Edwards, 1997).

Some antennas are more specialized to work in the higher frequency bands; one example is the parasitic antenna. These antennas are used at HF, VHF, and UHF to achieve directivity (direction) and forward gain (range). When multiple antennas are used in parallel the interactions between them cause the signal improvement in one direction and results in a lesser signal in the other direction. One of these antennas acts as a director for the other, sending signals in a particular direction. For higher UHF frequencies and microwaves, dish antennas are used; however these antennas require a large amount of space to work effectively (S. Makarov, personal communication, November 20, 2010).

The helical antenna has high gain, directivity, and the ability to work extremely well. This antenna is circularly polarized, which means that it is ideal for higher frequencies. It is also unidirectional and has high gain so most of the radio waves can be directed toward the receiver. These antennas have a reflector on the back that helps focus the radio waves in one direction and are made up of a coil wrapped in a helical formation. The dimensions and components of the helical antenna can be seen in Figure 1.

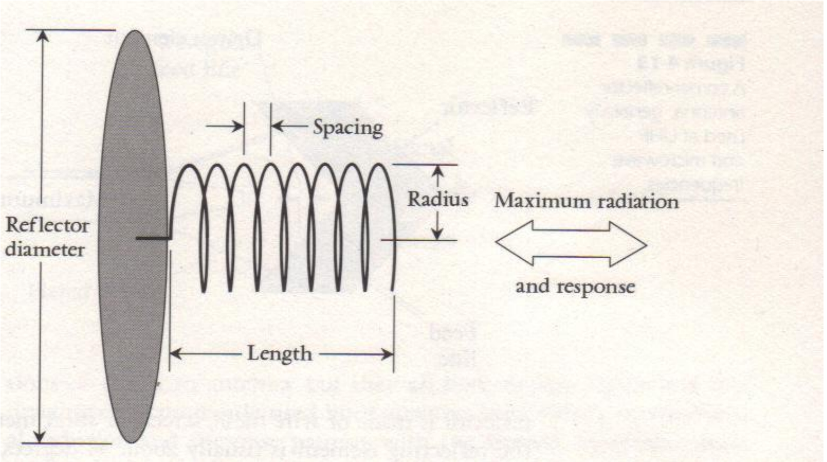

Figure 1. The components of the helical antenna. This diagram shows the components of the helical antenna. The diameter of the reflector should be 0.8 wavelengths. The radius should be 0.17 wavelengths. The spacing should be 0.25 wavelengths and the length must be 1 wavelength (Giblisco, 1999).

Past research on helical antenna performance has shown that the optimal frequency for a 4 turn antenna is at approximately 2.4 GHz. At this setting the efficiency seems to be approximately 77 percent. The ideal helical pitch was also found to be around 12.5 degrees. The data from this study can be seen in Figure 2 and 3.

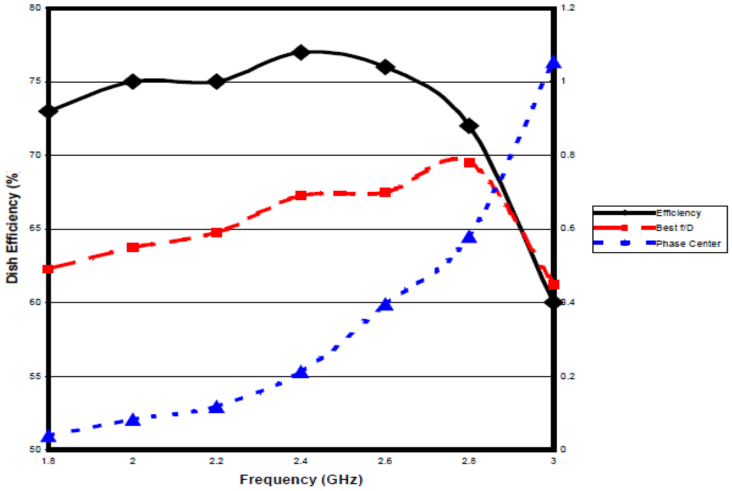

Figure 2. Helix feed-43 turns, 12.5 degrees, 0.94 lambda GP. This graph shows the efficiency of the antenna over the several frequencies. 2.4 GHz provided the best efficiency (Wade, 2002).

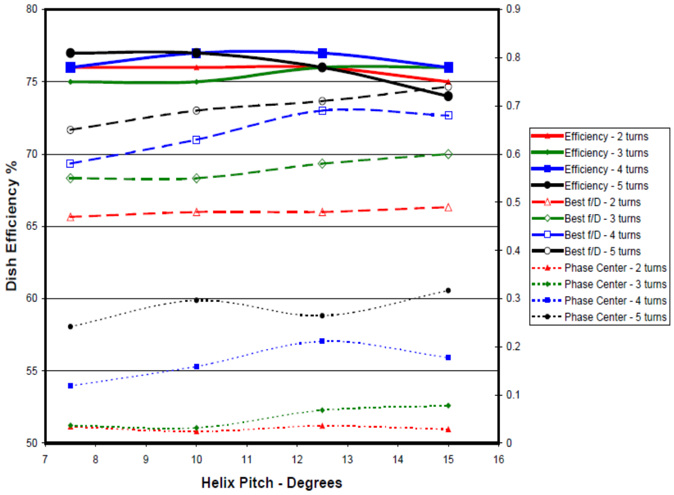

Figure 3. Helix Feeds at 2.4 GHz. This graph shows the effect of helical pitch on efficiency. As seen in the graph, 12.4 degrees yielded the highest efficiency (Wade, 2002).

In addition to this data there is more information on the effect of certain components of the antenna on the wave it propagates. For example it is possible to affect the gain and beam width of an antenna simply by changing the number of turns in the helix. As the number of turns increase, the gain and the range also increase. On the other hand, beam width decreases, producing a narrower and more focused beam (“Helical Antennas”, 2003).

In this project it is not possible to change the design of the transmitting antenna because it is essentially the circuitry inside the electronic appliance. This functions similarly to a Marconi or Vertical antenna, producing linearly polarized electromagnetic waves. The only antenna that can actually be modified is that of the receiver. Because the radiation is going to be linear, a compatible antenna must be used. However, some aspects of the helical antenna must also be incorporated because it is effective at focusing the received radiation. So a combination of a Marconi and Helical antenna would be suitable for the goals of this project.

Rectenna Structure and Design

Rectennas are types of antennas that are used to convert electromagnetic waves directly into electricity. In essence, the receiver for this project will be a rectenna. These were first conceptualized by Nicolas Tesla, the father of wireless energy. A rectenna comprises of an antenna array and a diode that when used in combination convert radiation to useable energy. The simplest rectenna is made up of a Schottky or another diode between the dipoles of an antenna. This diode rectifies the current induced in the antenna by electromagnetic waves. Schottky diodes are preferred because they have an extremely low voltage drop and therefore result in minimum voltage loss. These diodes tend to be extremely efficient; in laboratory tests, researchers have shown that they are 90 percent efficient (Prado, 2002).

The Schottky diode, invented by Walter H. Schottky, is a semi-conductor diode with very little forward voltage drop. While normal diodes cause a voltage drop of approximately 1.7 volts, this diode only causes a 0.45 voltage drop. These diodes also have high speed; this allows them to operate at very high frequencies. The capacity of these diodes has been increasing, the most significant of these improvements is the silicon carbide Schottky diode invented by Siemens in 2001. These newer Schottky diodes can operate at 1200 Volts and 7.5 Amps, a significant improvement from previous designs. These diodes have efficiencies above 90 percent (Poole, n.d.).

Rectenna Research

Many rectennas have been engineered for the purpose of wireless energy transfer; however, these designs are still extremely relevant and important to this project.

One recent study was done by the students of the Nanyan Technology University in Singapore in 2009. The researchers conducted a study in which they attempted to use wireless energy technology to remotely power sensors with low amount of energy. Patch antennas were used to receive the signals and a rectenna was used to rectify the power. In addition, the researchers found that the addition of a low pass filter helped concentrate the power received and improved the overall efficiency of the system. In their study they gathered the data shown in Figure 4 (Selvakumaran, 2009).

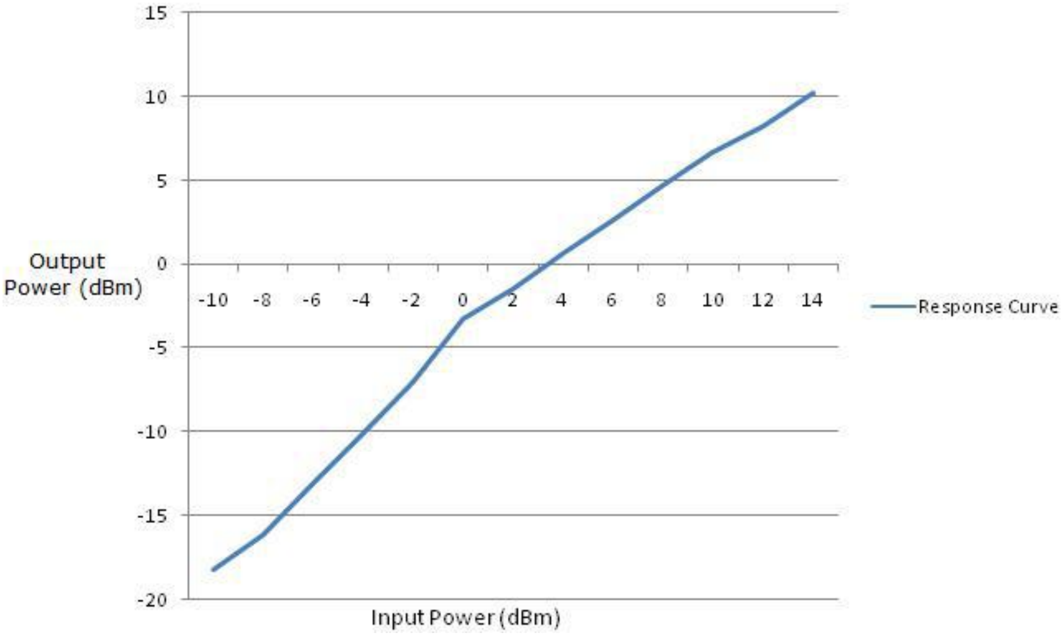

Figure 4. Output vs. Input Power. This graph displays the results of the experiment in terms of efficiency. For this graph it can be calculated that the approximate efficiency was 70 percent (Selvakumaran, 2009).

Another similar study was conducted in which a miniature rectenna system was developed. In this study however, a band reject filter was used to control the harmonics of the waves that rectenna rectifies. In addition, researchers were able to find that the efficiency of the system increases drastically with the power density. So as the power being transmitted increases, the efficiency also increases; however, this trend does not extend infinitely. As shown in Figure 5, the steep increase in efficiency stabilizes at approximately 2mW/ cm.

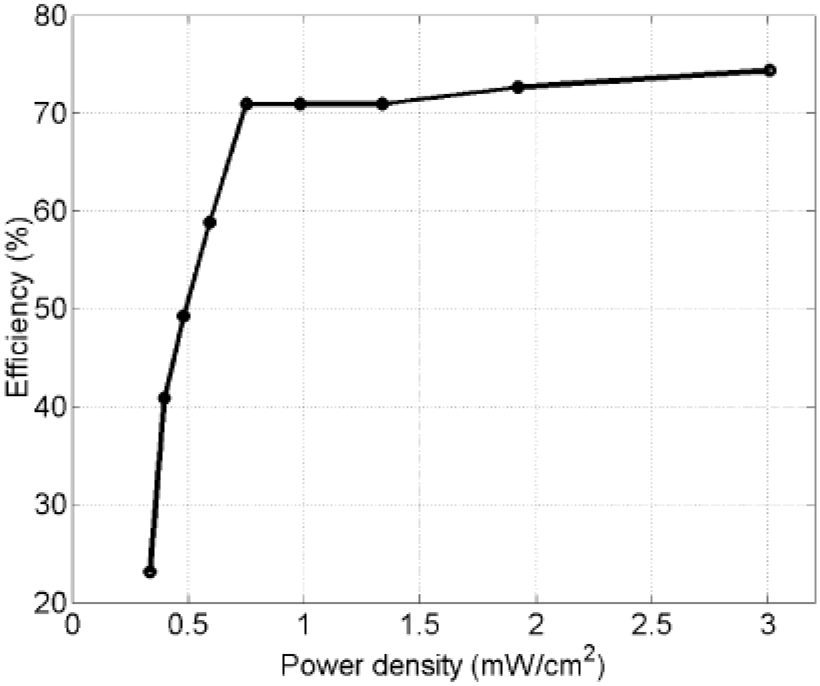

Figure 5. Conversion efficiency vs. power density. This graph shows the steep increase in the efficiency of the conversion of radio waves electrical power. This trend soon changes at around 1 mW/cm2 (Ali, 2006).

A team of scientists at the Texas A&M University was able to design a rectenna with extremely high conversion frequency. These researchers constructed a rectenna to operate at 5.87 GHz and through the usage of newer Si Schottky diodes were able to achieve efficiencies of 85 percent and higher. The scientists used dipole antennas to transmit and receive electromagnetic signals. They also employed a low pass filter to stabilize the rectification. Figure 6 shows their rectenna element.

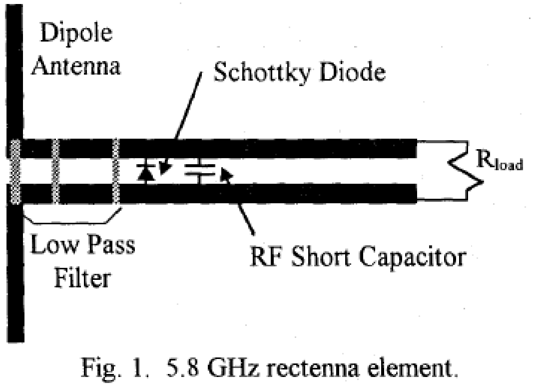

Figure 6. 5.8 GHz rectenna element. This diagram shows how the rectenna and low pass filter were incorporated into the antenna (Mcspadden, 1997).

The researchers were able to verify the results of the prior experiments and were able to find the maximum efficiencies within this frequency band. They were able to conclude that this wireless electricity transmission system achieved highest frequency at 5.78 GHz (Mcspadden, 1997).

Research Proposal

A. Engineering Problem:

The energy of electromagnetic radiation from electronic appliances, although harmless, is not utilized.

B. Engineering Goal:

The goal of this project is to engineer a pad-like device that will convert ambient radiation to useable electrical power through rectification.

C. Methods and Procedures:

In order to build this device, a rectenna will be constructed and tested. Using small scale rectennas, the effects of a few variables on power production will be determined. Some of these variables will include surface area of the antenna, gage of the antenna wire, the insertion of a magnet, etc. In addition, the circuit of rectenna will also be tested by varying the diodes, inductors, and capacitors. Finally, using the information from these tests, a full scale rectenna that is capable of charging a battery will be constructed.

Data will be collected in three main ways. The effectiveness of the device will be measured in terms of voltage (V), current (A), and power (W).This data will be analyzed using Excel and other software.

This device will also have to comply with several other secondary constraints. It must be of reasonable cost, and it must also be safe. The whole device should also be of reasonable size and relatively inexpensive to build.

Methodology

Test Pad Methodology

To construct the coil (inductor and antenna), 6 rectangles (11cmX5.5cm) were cut from standard corrugated cardboard (.40 cm thick) using scissors with standard blades (20.28cm). In addition, 6 rectangles (2cmX1.90cm) were also cut from the same material using the pair of scissors. Using a hot glue gun (Sure Bonder H-270C) and compatible glue cartridge, 2 smaller rectangles were glued on top of a horizontally positioned rectangle (11cmX5.5cm) along its left and right hand edges. It was also ensured that these rectangles were equidistant from the top and bottom. Another rectangle (11cmX5.5cm) was hot glued on top of the current assembly to form the structure of the pad. This process was repeated two more times to produce a total of three pads. Enamel-coated magnetic wire (RadioShack, 02A10) of gauges 22, 26 and 30 were acquired. Fifteen centimeters from its end, the 22 gauge wire was attached to the top right hand corner of the pad with standard electrical tape. Starting from 4 cm from the right edge of the horizontally positioned pad, the wire was wound towards the left edge in a counter clockwise fashion producing a coil. It was ensured that the wire did not overlap and that there was minimal space between the wires. After the coil had acquired a width of 2 cm, it was cut from the excess wire after leaving 15cm of extra cordage. Using standard sand paper (60 grit), 3 cm of wire from the beginning and the end of the coil was sanded in order to remove the enamel. Using a soldering iron (RadioShack, 64-2802B) and 60/40 rosin-core solder (RadioShack 64-005); each sanded end was then soldered to a 5cm electronic wire jumper (Jameco, JE10). Wires of gauges 26, and 30 were wound around the reaming pad structures in a similar fashion to produce a total of three completed pads.

A standard variable capacitor (0-160 Pico farads), a standard germanium diode (1N34A), and one standard piezoelectric ear phone were obtained. The germanium diode was soldered to one end of the piezoelectric ear phone. The free end of the diode and a wire jumper (5cm) were soldered to the right hand lead of the capacitor while another jumper (5cm) and the remaining end of the earphone were soldered to its center lead. Finally, the variable capacitor was tuned to 180 degrees counter clockwise. This became the rectifying circuit, see Figure 7 (Fields, “Crystal Radio”).

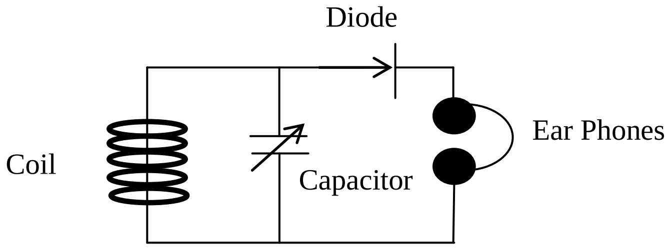

Figure7. Original Circuit. This is a simple circuit made up of inductors, capacitors, and diodes.

Gauge Experiment Methodology

A 15cm Modular IC breadboard (Radio Shack, 276-002) was obtained. The free jumper ends of the completed circuit were connected in parallel with the free jumper ends of the 22 gauge test coil using the breadboard. This coil was then placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the wire coil matched up with the bottom right corner of the touch pad of the laptop. The laptop was turned on, and it was ensured that no programs were running. Using a 29-range digital multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted. These steps were repeated to obtain data for the 26 and 30 gauge coils. In addition, the resistances of wires and circuit were measured and noted using the multimeter.

Diode Experiment Methodology

A 15cm Modular IC breadboard (Radio Shack, 276-002) was obtained. The free jumper ends of the completed circuit were connected in parallel with the free jumper ends of the 30 gauge test coil using the breadboard. This coil was then placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the wire coil matched up with the bottom right corner of the touch pad of the laptop. The laptop was turned on, and it was ensured that no programs were running. Using a 29-range digital multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted. These steps were repeated after replacing the germanium diode with a standard Schottky diode (IN5819).

Thickness Experiment Methodology

The 22 gauge coil was remade using the same process; however, the number of rectangles (2cmX1.90cm) was changed to achieve a thickness of 0.3 cm. A 15cm Modular IC breadboard (Radio Shack, 276-002) was obtained. The free jumper ends of the completed circuit were connected in parallel with the free jumper ends of the 22 gauge coil using the breadboard. This coil was then placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the wire coil matched up with the bottom right corner of the touch pad of the laptop. Using a 29-range digital multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted. These steps were repeated for thicknesses of 0.6cm, 2.8cm, 4.5cm, and 7.0 cm.

Ferrite Modification Experiment Methodology

A 15cm Modular IC breadboard (Radio Shack, 276-002) was obtained. The free jumper ends of the completed circuit were connected in parallel with the jumper ends of the 30 gauge coil using the breadboard. This coil was then placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the wire coil matched up with the bottom right corner of the touch pad of the laptop. The laptop was turned on, and it was ensured that no programs were running. Using a 29-range digital multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted. These steps were repeated with a standard ferrite magnet (2.2cmX4.6cmX.5cm) centered widthwise inside the coil, between the large rectangular faces of the pad. Similarly, the same process was repeated with a standard ferrite rod (1.5cmX7cmX.5cm) centered widthwise inside the pad.

Reflection Experiment Methodology

A 15cm Modular IC breadboard (Radio Shack, 276-002) was obtained. The free jumper ends of the completed circuit were connected in parallel with the free jumper ends of the 30 gauge coil using the breadboard. This coil was then placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the wire coil matched up with the bottom right corner of the touch pad of the laptop. The laptop was turned on, and it was ensured that no programs were running. Using a 29-range digital multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted. These steps were repeated with an aluminum sheet metal circle (diameter

4cm) placed over the center of the coil. Similarly, the test was redone with a circular mirror (diameter 4cm).

Distance Experiment Methodology

A 15cm Modular IC breadboard (Radio Shack, 276-002) was obtained. The free jumper ends of the completed circuit were connected in parallel with the free jumper ends of the 30 gauge coil. This coil was the placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the wire coil matched up with the bottom right corner of the touch pad of the laptop. The laptop was turned on, and it was ensured that no programs were running. Using a 29-range digital multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted. These steps were repeated after elevating the pad 0.4 cm, 0.8cm, 1.0cm, and 2.0cm using rectangular pieces of standard corrugated cardboard (2cmX1.90cm).

Final Pad Methodology

Standard corrugated plastic was cut into 3 rectangles (10cmX6cm) using standard scissors (20.28cm blade).A smaller rectangle (1.5cmX7cm) was cutout of one of these rectangles (10cmX6cm), leaving a rectangular hole. Using a hot glue gun (Sure Bonder H-270C) and compatible glue stick cartridge, one rectangle (10cmX6cm) was glued onto the rectangle with the hole so that the outer edges of the rectangles lined up. A standard ferrite rod (1.5cmX7cmX.5cm) was placed into the slot (1.5cmX7cmX.5cm) formed by the two rectangles. The final rectangle was then glued to the other rectangles so that the ferrite rod was completely enclosed, produce structure of the pad. After leaving a 1cm margin on the right and left hand sides, enamel-coated magnetic wire (RadioShack, 02A10) of gauge 30 was wound in a counter clockwise fashion around the horizontally positioned pad. After ensuring that there was 15 cm of extra wire on each end of the coil, the excess wire was cut using standard scissors. A standard AA battery snap with wires connected to the positive and negative leads were hot glued to one side of the pad (1.5cmX6cm). Using standard sandpaper (grit 60), the excess wire at the beginning and end of the coil was sanded completely. A standard germanium diode (1N34A) was soldered 5 cm from the end of the extra wire at the beginning of the coil using a soldering iron (RadioShack, 64-2802B) and 60/40 rosin-core solder (RadioShack 64-005). The end of this wire was then soldered to the right had lead of the variable capacitor. The remaining lead of the diode was then soldered to a standard resistor (560), which was in turn soldered to the negative lead wire from the battery snap. The positive battery snap lead wire was then soldered 5cm from the end of the remaining coil wire. This wire was then soldered to the center lead of the variable capacitor, producing the rectenna circuit (Figure 8). After tuning the variable capacitor tuning knob 180 degrees counter clockwise, all loose wires and the circuit were taped to the pad using standard electrical tape according to the picture (Figure 9). This became the final pad design.

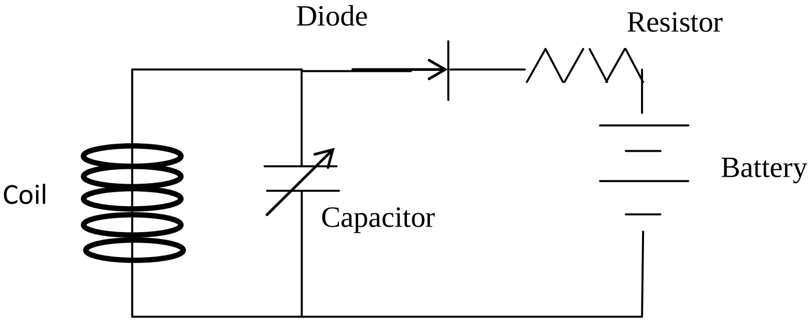

Figure 8. Final Circuit. This is a rectifying circuit with a batter and resistor.

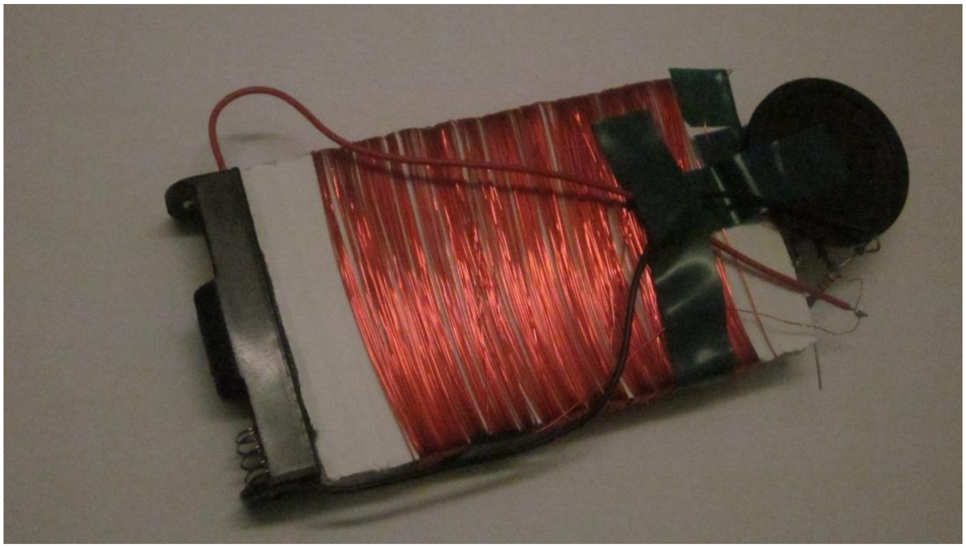

Figure 9. Final radiation pad design. This is the final model for the energy harvesting device with circuit and battery snaps attached.

Appliances Experiment Methodology

The final pad was the placed widthwise on the touch pad of a laptop (Dell Inspiron 14) so that the bottom right hand corner of the coil matched up with the bottom right corner of the touch pad of the laptop. The laptop was turned on, and it was ensured that no programs were running. Using a 29-Range Digital Multimeter (RadioShack, 22-813), voltage was measured between the diode and the coil and recorded. In a similar fashion, 20 trials were conducted.

Then, the final pad was taped to the back of a LCD TV (Sony Bravia 46in) using the electrical tape so that the top left corner of the pad was 7cm from the top and 14 cm from the left edge of the TV. After the TV was powered on and set to “S-Video Input”, data was collected using the above process.

Then, the pad was taped to the side of a microwave oven (Haier, MWG10051TSS) using the electrical tape so that the bottom right corner of the pad was 3cm from the bottom and 10 cm from the right edge of the microwave. The microwave was set on "high" and allowed to run for 1 min while data was being recorded using the established process. If all the required data was not collected, then the microwave was reset and run once again.

Next, the final pad was taped to the of a top of a cathode TV using the electrical tape so that the bottom right corner of the pad was 6cm from the back and 13 cm from the right edge of the TV. The TV was turned on and set to "Front" and the above process was repeated to collect data.

Lastly, the pad was taped to the top of a PS3 (Sony 20GB) using the electrical tape so that the bottom right corner of the pad was 3cm from the back and 7 cm from the right edge of the PS3. The gaming system was turned on and allowed to idle while data was collected using the established process; in addition, the resistances of the circuit was also measured and noted using the multimeter.

Results

Gauge Experiment Data

Table 1. Voltage produced by different gauges of wire.

	Gauge (AWG)	V_1 (V)	V_2 (V)	V_3 (V)	V_4 (V)	V_5 (V)	V_6 (V)	V_7 (V)	V_8 (V)	V_9 (V)	V_{10} (V)	V_{11} (V)	V_{12} (V)	V_{13} (V)	V_{14} (V)	V_{15} (V)	V_{16} (V)	V_{17} (V)	V_{18} (V)	V_{19} (V)	V_{20} (V)	V_{avg} (V)	(k)	P (mW)	STDEV (V)	95%Cl (V)	%RSD of V
IV1	30	0.753	0.768	0.757	0.756	0.776	0.753	0.753	0.742	0.761	0.771	0.743	0.770	0.755	0.761	0.753	0.746	0.754	0.756	0.745	0.743	0.756	5.47	0.138	0.010	0.004	1.292
IV2	26	0.649	0.653	0.639	0.646	0.741	0.737	0.694	0.731	0.723	0.743	0.737	0.715	0.754	0.704	0.708	0.717	0.643	0.659	0.718	0.711	0.701	5.46	0.128	0.038	0.017	5.485
IV3	22	0.054	0.146	0.068	0.101	0.141	0.062	0.112	0.160	0.169	0.103	0.183	0.201	0.121	0.171	0.156	0.251	0.104	0.201	0.103	0.124	0.137	5.46	0.025	0.051	0.022	37.375

Gauge: 30, 26, 22

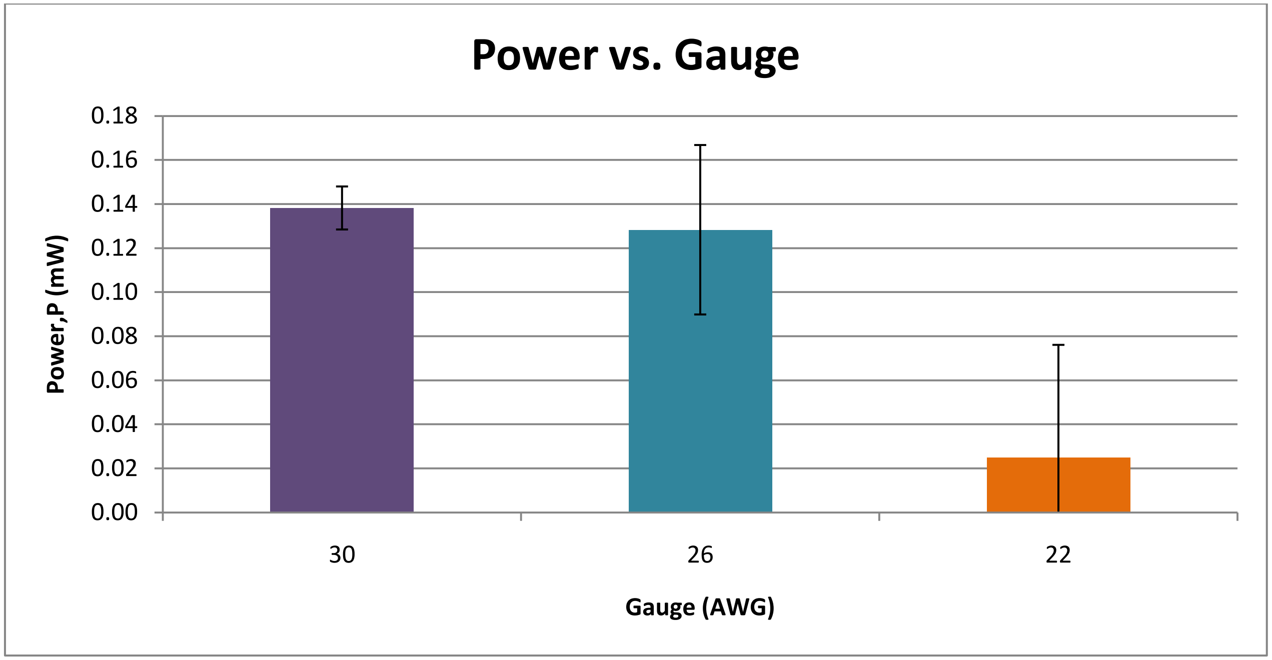

Figure 10.Power output of 30, 26, and 22 gauge wire. The 30 gauge ye the most power, averaging 81.9% more than the 22 gauge wire.

Diode Experiment Data

Table 2. Voltage produced by the germanium and Schottky diode.

	Diode	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{avg}	STDEV	95%Cl	%RSD
		(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	of V
IV1	Germanium	0.711	0.703	0.711	0.860	0.724	0.648	0.829	0.705	0.818	0.742	0.607	0.770	0.751	0.668	0.786	0.792	0.717	0.662	0.808	0.776	0.739	0.064	0.028	3.810
IV2	Schottky	0.378	0.330	0.342	0.349	0.324	0.273	0.345	0.338	0.263	0.286	0.312	0.304	0.369	0.342	0.303	0.292	0.331	0.307	0.364	0.304	0.323	0.031	0.013	4.181

Gauge: 30

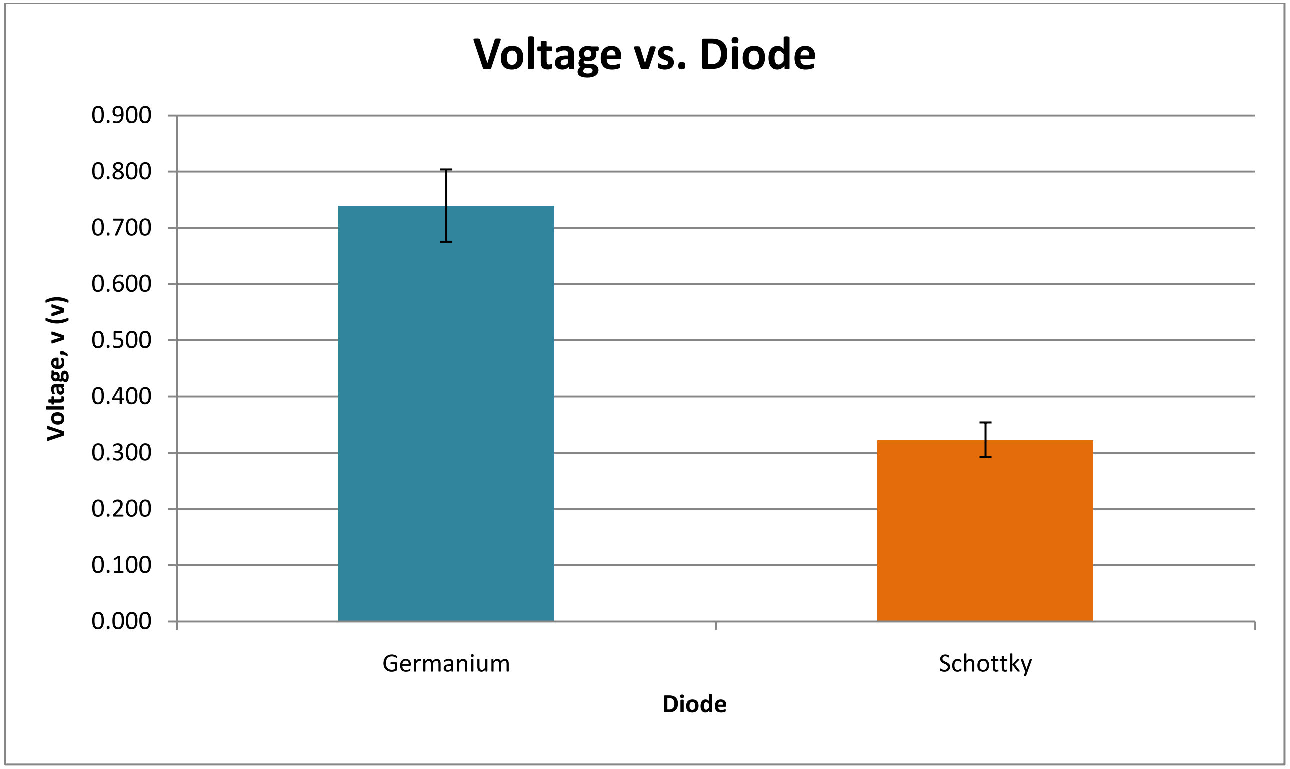

Figure 11. The effect of different diodes on voltage production. The germanium diode is clearly better suited for this purpose; it produces about 56.3% more volts than the Schottky diode.

Thickness Experiment Data

Table 3. The Effect of the thickness of the pad on the voltage produced.

	T	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{avg}	STDEV	95%Cl	%RSD
	(cm)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	(mV)	of V
IV1	0.3	60.8	83.9	58.2	48.1	37.8	59.8	49.7	82.7	86.5	60.0	40.1	60.7	71.8	32.6	59.2	49.2	45.9	35.9	49.9	50.8	56.2	15.6	6.8	27.7
IV2	0.6	77.7	114.4	74.1	90.4	119.7	87.4	109.7	130.0	76.1	80.0	70.2	83.8	74.9	59.2	70.4	122.4	73.2	62.7	96.6	59.3	86.6	21.8	9.5	25.1
IV3	2.8	87.6	182.3	103.3	171.4	174.2	109.3	98.5	89.9	141.9	136.0	162.8	147.3	101.5	140.3	94.3	184.1	163.5	123.8	125.9	148.8	134.3	32.3	14.1	24.0
IV4	4.5	164.0	168.1	216.8	164.2	215.2	253.6	199.6	200.1	205.7	187.2	224.6	159.8	170.6	153.2	202.5	215.1	136.7	171.4	167.5	186.6	188.1	29.0	12.7	15.4
IV5	7.0	196.3	171.0	135.7	182.2	242.3	169.8	202.4	189.8	173.4	217.5	235.3	213.8	195.5	213.5	164.5	214.7	244.4	178.0	211.5	219.7	198.6	28.3	12.4	14.2

Gauge: 22

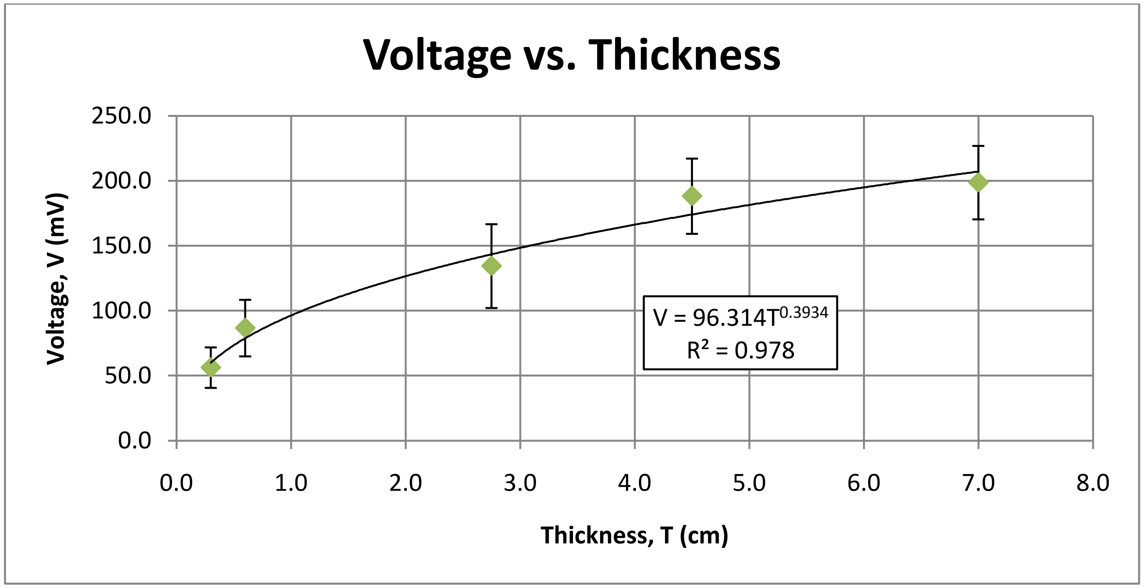

Figure 12.The voltages produced by pads of different thicknesses. The device was test for thickness of 0.3 cm, 0.6cm, 2.8cm, 4.5cm, 7.0cm. Voltage increase was rapid at first, but then gradually decreases.

Ferrite Modification Experiment Data

Table 4. The effect of ferrite modification techniques on the voltage produced.

	Ferrite Modification	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{avg}	STDEV	95%Cl	%RSD
		(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	of V
IV1	None	0.786	0.874	0.786	0.687	0.512	0.746	0.776	0.750	0.951	0.721	0.694	0.767	0.904	0.829	0.724	0.965	0.797	0.780	0.609	0.708	0.768	0.107	0.047	13.969
IV2	Ferrite Magnet Inside	0.720	0.682	0.898	0.799	0.767	0.716	0.723	0.846	0.923	0.696	0.643	0.808	0.898	0.792	0.723	0.686	0.757	0.842	0.689	0.787	0.770	0.081	0.035	10.460
IV3	Ferrite Rod Inside	0.876	0.869	0.845	0.840	0.830	0.898	0.891	0.885	0.802	0.897	0.844	0.832	0.870	0.824	0.898	0.821	0.887	0.869	0.903	0.872	0.863	0.031	0.013	3.537

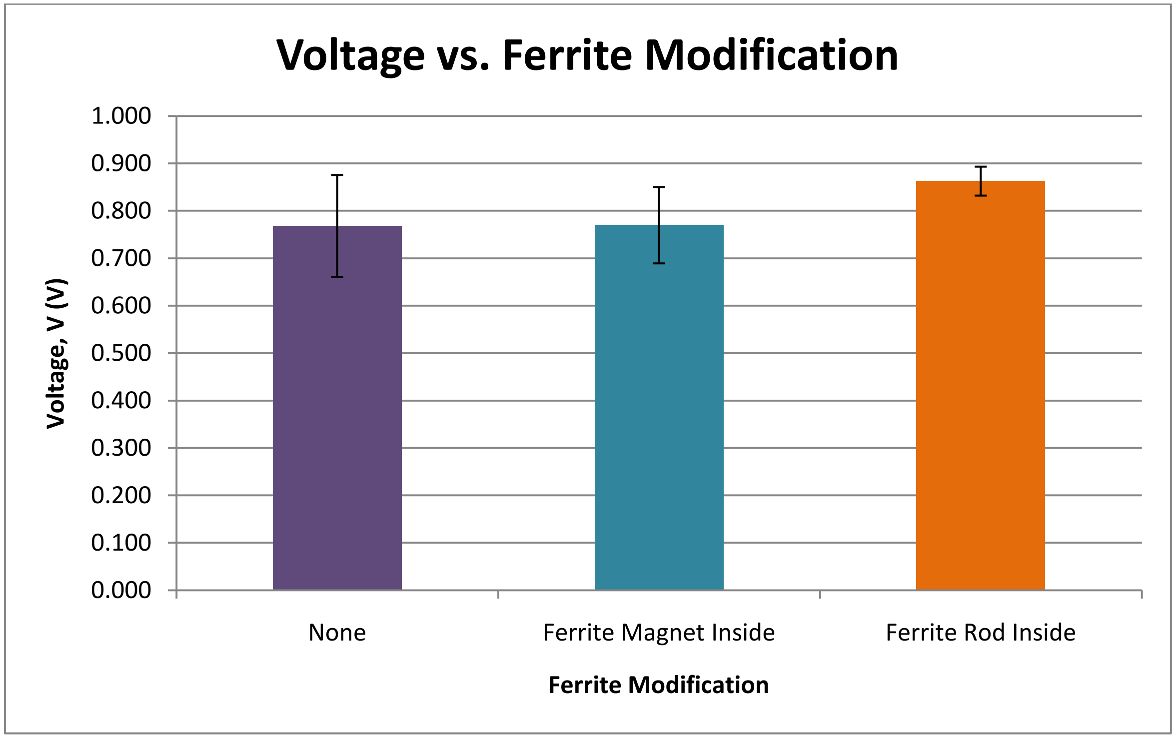

Figure 13. Voltages produced by different ferrite modifications. The test was conducted with no modification, a ferrite magnet inside and a ferrite rod inside the pad. Although all modification increased voltage production, the ferrite rod was the most successful producing 10.3% more volts.

Reflection Experiment Data

Table 5. The effect of methods of reflection on the voltage produced by the radiation pad.

	Method of Refection	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{avg}	STDEV	95%Cl	%RSD
		(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	of V
IV1	None	0.723	0.758	0.765	0.785	0.787	0.790	0.706	0.882	0.806	0.774	0.833	0.812	0.768	0.739	0.882	0.805	0.731	0.806	0.804	0.774	0.787	0.046	0.020	5.852
IV2	Mirror	0.635	0.816	0.943	0.843	0.764	0.898	0.793	0.984	0.620	0.779	0.689	0.678	0.727	0.799	0.613	0.887	0.795	0.854	0.719	0.616	0.773	0.110	0.048	14.267
IV3	Sheet Metal	0.990	0.891	0.939	0.823	0.873	0.902	0.935	0.966	1.123	0.768	0.798	0.873	0.846	1.173	0.915	0.809	0.783	0.927	0.823	0.976	0.907	0.105	0.046	11.635

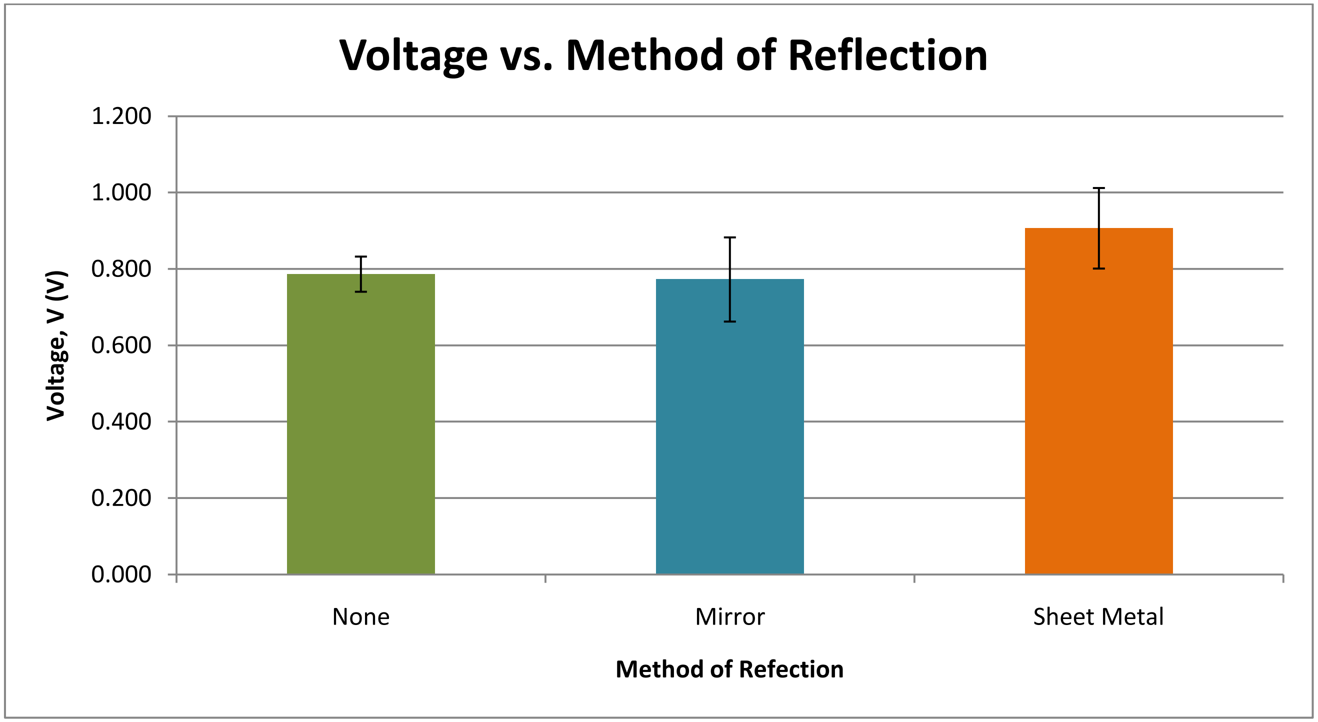

Figure 14. Voltage produced by different methods of refection. Mirrors and sheet metal were tested for reflective properties. Sheet metal was found to be more the most successful, producing 13.2% more volts.

Distance Experiment Data

Table 6. The Effect of the distance from the radiation source on the voltage produced.

	x	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{avg}	STDEV	95%Cl	%RSD
	(cm)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	of V
IV1	0.00	0.678	0.542	0.554	0.590	0.689	0.643	0.632	0.432	0.545	0.478	0.523	0.629	0.580	0.499	0.457	0.479	0.505	0.577	0.607	0.666	0.565	0.076	0.033	13.514
IV2	0.40	0.591	0.593	0.690	0.568	0.520	0.459	0.601	0.554	0.532	0.576	0.438	0.478	0.505	0.597	0.612	0.611	0.534	0.540	0.598	0.570	0.558	0.060	0.026	10.671
IV3	0.80	0.231	0.239	0.569	0.438	0.423	0.221	0.530	0.447	0.436	0.380	0.277	0.267	0.289	0.301	0.390	0.414	0.512	0.532	0.384	0.390	0.384	0.107	0.047	27.930
IV4	1.00	0.329	0.356	0.366	0.322	0.393	0.287	0.355	0.347	0.398	0.273	0.276	0.289	0.291	0.290	0.385	0.333	0.296	0.267	0.387	0.289	0.326	0.044	0.019	13.554
IV5	2.00	0.167	0.232	0.200	0.156	0.198	0.202	0.206	0.187	0.221	0.207	0.178	0.186	0.174	0.206	0.165	0.202	0.185	0.178	0.194	0.213	0.193	0.020	0.009	10.139

Gauge: 30

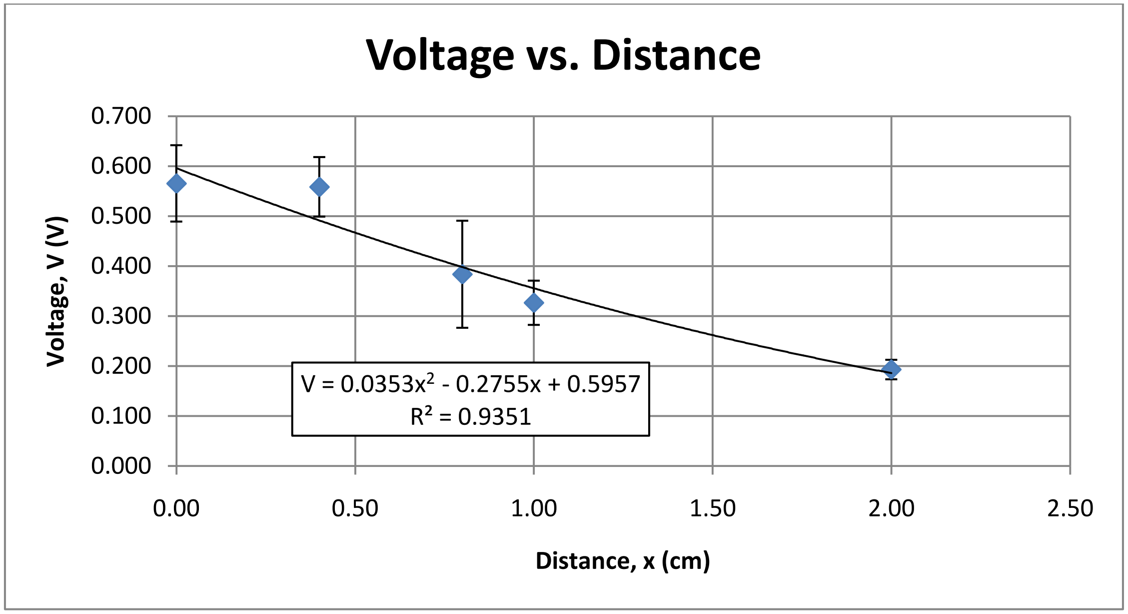

Figure 15. The voltage produced by the pad at different distances from the source. Distances of 0.0cm, 0.4cm, 0.8cm, 1.0cm, and 2.0 cm were tested. The drop in voltage was most significant at smaller distances; the voltage continued to decrease at greater distances but the rate was much lower.

Appliances Experiment Data

Table 7. The Voltage produced by different electrical appliances.

	Source	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{avg}	I_{avg}	P_{avg}	STDEV	95%Cl	%RSD
		(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(V)	(mA)	(mW)	(V)	(V)	of V
IV1	Laptop	1.325	1.402	1.532	1.585	1.570	1.609	1.671	1.547	1.578	1.942	1.822	1.864	1.883	1.850	1.685	1.627	1.793	1.764	1.612	1.683	1.667	0.299	0.498	0.162	0.071	9.695
IV2	LCD TV	12.86	14.18	12.22	12.86	12.18	11.75	12.79	12.23	12.99	11.86	12.26	12.01	13.04	13.22	12.89	12.70	12.44	13.45	12.52	12.47	12.65	2.27	28.66	0.58	0.25	4.594
IV3	Microwave Oven	0.210	0.201	0.178	0.256	0.154	0.187	0.198	0.104	0.164	0.207	0.154	0.166	0.234	0.210	0.187	0.143	0.279	0.237	0.184	0.194	0.192	0.034	0.007	0.041	0.018	21.084
IV4	Cathode TV	0.803	0.748	0.790	0.727	0.818	0.847	0.798	0.725	0.713	0.853	0.827	0.824	0.876	0.783	0.780	0.764	0.817	0.789	0.741	0.826	0.792	0.142	0.113	0.045	0.020	5.730
IV5	PS3	2.066	2.269	2.786	2.758	2.806	2.803	2.665	2.831	2.751	2.804	2.888	2.920	2.511	2.714	3.219	2.838	2.779	2.401	3.008	3.256	2.754	0.493	1.359	0.281	0.123	10.211

Gauge: 30

: 5.58 k

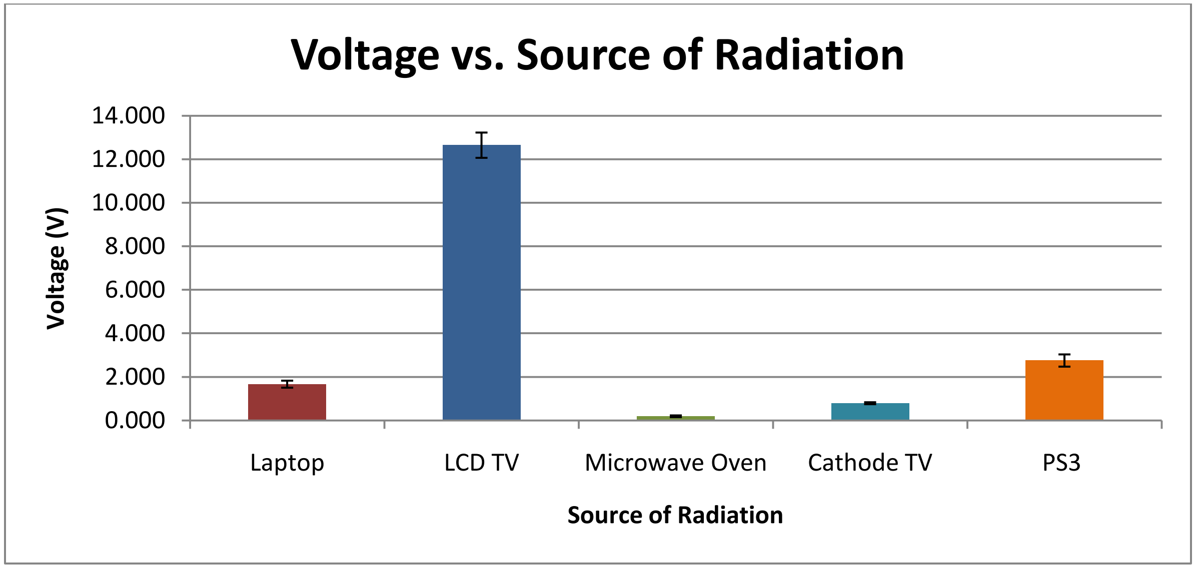

Figure 16. Voltage produced from several sources of radiation. A laptop, LCD TV, microwave oven, cathode TV, and a PS3 were tested. The LCD TV, producing 12.65 volts, was the best radiation source.

Data Analysis and Discussion

These sets of data and experiments were very crucial in determining the final specifications of device. These test ultimately dictated how the final energy harvesting device would be made. Each characteristic of the pad was tested to determine its effect on the ability of the device to produce energy.

One main trait that could be modified in this device was the gauge of the wire used to produce the coil. The specific experiment conducted in this research project tested wire of gauges 30, 26, and 22. The results showed that the largest gauge, 30, produced the most power, .138 mW. This was approximately 7.2% greater than the power produced by the 26 gauge wire and 81.9% more that of the 22 gauge coil. This trend is reasonable because the amount of energy collected depends on the surface area of the coil. Although all the coils were of the same surface area, the thicker 22 gauge wire did not cover the area as evenly as the 30 gauge coil; therefore, it left gaps in the wire. The failure to cover the entire surface area mostly likely caused the decreased power production. Because inductance is partly a function of wire size, another explanation could be that the inductance of the 22 gauge wire did not match the frequency of the radiation emitted by the source. Through statistical analysis, 30 gauge wire was found to be the most consistent because it had a %RSD of 1.29% whereas the 22 gauge wire had a value of 37.38%, which indicates a lack of regularity (Table 1, Figure 10).

The type of diode used in the circuit could also affect its effectiveness. The purpose of the diodes in the circuits is to rectify the current. The germanium and Schottky diodes are two possible diodes that were tested. Although the Schottky diode was hypothesized to function more effectively, the germanium diode was able to produce 56.3% more voltage. It is suspected that the Schottky diode did not perform as well because it was not very compatible with the circuit or the frequency of the radiation being collected. The analysis also showed that the germanium diode was more consistent because it had a %RSD value of 3.81%, which is less than that of the Schottky diode (Table 2, Figure 11).

Theoretically, the thickness of the pad should affect its ability to produce power, so this attribute was tested. When thicknesses of 0.3cm, 0.6cm, 2.8cm, 4.5cm, and 7.0cm were evaluated using 22 gauge wire, it was found that an increase in thickness also resulted in an increase in voltage production; however, it was also shown that the rate of increase decreases with increasing thickness. This data could be represented by the function $V = 96.314T^{0.3934}$, where V is voltage and T is thickness. It could also be inferred that greater thicknesses also provided more regularity because statistical analysis revealed that the thicker pad also had smaller %RSD values (Table 3, Figure 12).

The ferrite modification was also tested to examine its effect on voltage production. When the voltages of the modified and control pads were compared, the ferrite rod produced the most voltage whereas the ferrite magnet barely had any effect on the electrical output. The ferrite rod increased power production by 11.0%; however, the magnet only caused an increase of 0.3%.The rod also greatly increased reliability because it resulted in a %RSD value that was 10.4% less than that of the control. This result was expected because although both the magnet and the rod core concentrated the magnetic field, the ferrite magnet also resulted in a sharp increase in inductance, which was not compatible with the frequency of radiation emitted from the source (Table 4, Figure 13).

Because all electromagnetic waves can be reflected, methods of reflecting the radiation that was not captured by the coil back towards it were investigated. It was found that sheet metal actually increased the voltage output by 13.2% whereas the mirror actually lead to a drop in energy production. Although the sheet metal increased the output power, it also made the device less consistent, increasing its %RDS by 5.8% (Table 5, Figure 14).

Because a case was most likely going to be placed around the device increasing the distance between the coil and the radiation source, the effect of distance on power production was also explored. By testing distances of 0.00cm, 0.40cm, 0.80cm, 1.00cm, and 2.00cm, it was found that voltage production dissipates greatly with distance. Just a 2cm increase in distance from the source, greatly inhibited the ability of the device to produce power, reducing it by 65.8%; however, statistical analysis revealed that distance had no effect on the consistency of the deceive because the changes in %RDS were largely random. It was also found that this relationship could be loosely modeled by the function $V = 0.0353x^2 - 0.2755x + 0.5957$ where x is distance and V is voltage (Table 6, Figure 15).

Using the information from these tests, a final full scale radiation energy harvesting pad was constructed. It was made of a 30 gauge wire, a ferrite rod core, an increased width, and a germanium diode to maximize its ability to produce energy from radiation. Although the sheet metal reflector resulted in increased power production, it was omitted because it was inferred that the updates to the design, especially the ferrite rod, would trap most of the radiation, nullifying the purpose of a reflector. Because the goal of the device was to charge a 1.2 volt battery, a resistor was added to the circuit to maintain a voltage of more than 1.2 V, allowing it to accomplish this task. The effectiveness of the final pad was tested with several household appliances including a laptop, LDC TV, microwave oven, cathode TV, and a PS3. It was found that the device worked most effectively on the LCD TV, producing an average of 28.66 mW. The LCD TV also yielded the lowest %RSD; therefore, statistical analysis revealed that it was also the most consistent. The pad was least effective on the microwave oven, only producing 0.0007 mW. This ineffectiveness was predictable because a microwave is made to reduce radiation emissions; in addition, it is also possible that the frequency of the electromagnetic waves from the microwave oven were not compatible with this device. The pad performed moderately well on the Laptop computer, the cathode TV, and the PS3, producing 0.498mW, 0.113mW, and 1.359mW respectively. In comparison, the LCD TV yielded 98.2% more power than the laptop computer (Table 7, Figure 16).

Conclusion

By systematically approaching the problem, the engineering goal of building an energy harvesting device to harness the power of ambient radiation was achieved. Many experiments were performed and the results of the test help determine the ideal characters for the device. After identifying advantageous characteristics, a design matrix was used to evaluate the importance and influence of each trait. This process proved to be extremely helpful because the final product performed its intended actions very well.

Under ideal settings, the radiation pad was able to produce 28.66 mW, an extremely large amount of power for a relatively small sized device. As long as the radiation source is active, this power will be continuously produced; therefore, there is a wide array of uses for this energy harvesting pad. In addition to exceptional performance, the device also adhered to many design constraints. This radiation pad is inexpensive, small, portable, safe, and most importantly, harvests waste energy; therefore, it will also have very high market appeal. The data also shows that this device has the potential to conserve large amounts of energy if used by a large population of people. Assuming that the number households in the United States is 76,751,637, and that 50% percent of the households own or will own a LCD TV's in the future, this device can save approximately 1.09 Giga Watts if all the TVs are on at the same time("Population",2011). Because the energy produced by this device is free, it can save a significant amount of money if implemented correctly.

Limitations and Assumptions

The major assumption that was made in the construction of device was that it would always be used in contact with the electronic device or laptop. Distance is an important limitation because the strength of radiation dissipates greatly with distance. It was also assumed that the effect of radiation from radio stations was negligible. In addition, it was assumed that the radiation emitted from the laptop while performing a particular task was consistent.

The data from the present investigation is not completely accurate because while some aspects of the experiment could be controlled, some conditions could not be regulated. For example, the surface area, electronic circuit, radiation source, and location on the radiation source could be regulated. On the contrary, aspects of the experimentation such as the regularity of the radiation could not be controlled; however, it was ensured that the computer and other electronic appliances were performing identical operations and under identical conditions to minimize variation. Possible human error in the experimental data was also uncontrolled. These conditions would also act as sources of error.

Applications and Future Experiments

This research has great potential in the future because the use of electronic devices will only increase. In addition to the tested appliances, the device could be modified to encompass a wider array of devices. This will greatly increase its versatility. The technology from this project could also be applied to other fields such wireless energy transmission and green energy. The techniques and circuits from this research project could also be used in developing wireless energy transfer devices.

As demonstrated, this device has many practical applications. For example, this device can be used to charge batteries, and possibly iPods, and cell phones; in addition, this technology could also be integrated into devices like wireless mice so that they would not need to be powered with a battery.

Although the current prototype accomplished the task, it could be made more user friendly and aesthetically appealing. The next step in the process of designing this device would be to make it into a flexible pad that is both light weight and functional. Then this device could be inserted into a gel sleeve to increase its appeal. In addition, the device can also be made bigger in order to produce more power.

In the future, the efficiency and other applications of the technology can be explored. For example, the feasibility of inserting the device inside electronic appliances to collect more radiation can be examined.

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