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Wireless Power Transfer

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EXECUTIVE SUMMARY

Wireless power transmission (WPT) devices are on the forefront of electronics technology making them potentially marketable products. WPT devices have been thought to be possible since Nikola Tesla’s transmission model in 1897. The newest technologies rely on inductive coupling techniques to transmit power between transmitting and receiving coils. The frequency at which the device transfers power between the transmitter and receiver is dependent on the size of the coils. The higher the frequency at which the device is transmitting, the smaller the transmitting and receiving coils must be.

Current wireless power transmitters are capable of transmitting current at distances of less than one inch up to one foot. These distances allow for use in small consumer electronic devices such as electric toothbrushes and razors. While these applications have proven to be profitable, the market still remains open for use in larger electronic devices. An aspect of WPT that has been largely unexplored is the ability to charge batteries and other electronic circuits. Grids can also be integrated into new construction designs to provide large scale wireless power coverage to all electronic devices and building utilities.

The design team implemented an oscillator at high frequencies (10MHz) producing inductive coupling between two 60 cm inductive coils, thus WPT was achieved. The illuminating of a 0.18 W light bulb was achieved and the charging of 1.2 V battery was accomplished using a rectifying circuit that canceled harmonics and therefore transferred the maximum amount of power. This method of WPT can propagate power over a distance of 1.27 m meters providing functionality that is not readily available in other WPT devices in the consumer market.
1. INTRODUCTION

In 1897, Nikola Tesla discovered that he could transmit up to 20 MV or more power wirelessly [1]. This was done by sending a signal into the upper stratosphere at a frequency of 925 Hz to distances thousands of miles away from the transmitter, as stated in his “System of Transmitting Electrical Energy” patent [2]. Wireless power transfer (WPT) receivers are devices that can wirelessly transmit power to electrical devices. This is a proof of concept technology that paves the way for charging cell phones, laptops, and many other electronic devices wirelessly. Wireless power technology is in high demand because of its convenience to consumer and industrial marketplaces. The goal of the device prototype is to eventually cost less than $100.00 and be a fully operational and completely independent of any other device.

1.1 Objective

Wireless power transfer was achieved via resonant inductive coupling between the transmitting and receiving coils in the near field. To demonstrate that power was successfully transferred wirelessly, an incandescent light bulb and a battery was charged. The device was able to transmit 0.18 W of power over a distance of 1.27 m. Charging a battery was accomplished using a rectifying circuit that canceled harmonics due to non-linear components, therefore transferring the maximum amount of power.

1.2 Motivation

While wireless power devices have already been created by other companies and institutions, they are still basic and not practical. Wirelessly charging a battery has also been
accomplished before by small home appliance companies. The difference in this WPT technique and the new proposed wireless power system is its ability to send power wirelessly over longer distances. This gives it an edge over what is currently available on the market. WPT is convenient for the user because it is accessible and gives the users more versatility with their electronic devices. This system is marketable on many levels. For the individual consumer, this technology allows powering and charging of portable devices such as cell phones and laptops. Building designers would integrate WPT technology into the walls or floors of new construction to allow for the distribution of wireless power.

1.3 Background

Currently there are few wireless power transmitters on the market. MIT was the first to demonstrate wireless power using resonant near field inductive coupling in the summer of 2007. In 2008, Intel also achieved wireless power though inductive coupling [3]. These methods consist of two coils which are configured to have the same resonant frequency, with an oscillator that sends a sinusoidal signal transmitting the power at the resonant frequency.

The primary components in any WPT system are the coils. The amount of power transmitted and effectively received will depend on how well the coils are designed. What ever application that may be utilized with coils radiated energy, the major factor in determining which coils to use for any given application will usually depend on polarization, gain, bandwidth, and impedance matching. This project had a twofold objective. The first goal is to explore previous research and the current state of WPT coils. The second goal was to view the underlying technology to ascertain the best coils for use in near field WPT.
There are many different methods to transmit power wirelessly but the most well known techniques include sending the signal by using the Tesla effect, microwaves, or by resonant coupling. According to patents and technical literature, each of these methods has worked and show promise to be used in mainstream applications but one problem arises. Is it safe for humans to be in the vicinity of these devices while they are in operation? The researchers at MIT successfully tested a method of transmitting power wirelessly by using the technique of resonant coupling. Since this was done at midrange distances, this technique could be applied to power hand held mobile electronics in the near future. Keeping this application in mind, MIT researchers devised a more safety conscious design that will pass the IEEE standard for human exposure to Radio Frequency.

2. PROJECT DESCRIPTION AND GOALS

The design team has developed a wireless power apparatus that is capable of powering an incandescent light bulb and charging a household battery. The wireless power system could be marketable to electrical engineers who wish to power or charge electronics without wires. WPT has achieved using the following parts:

- Agilent 33220A Function generator
- Microchip 25 dB RF power amplifier
- Hewlett-Packard DC power supply
- Copper coils
The wireless power apparatus has achieved the following goals:

- Transmit power over a distance less than two meters
- Light a 0.18 W light bulb
- Charged a 1.2 V rechargeable battery
- Measure the relative near fields around coils
- Compare power vs. distance of WPT with standard electromagnetic radiation patterns.

The purpose of the project is to demonstrate a wireless power transmitter and receiver system. Several coils were constructed from copper and were tuned to 10 MHz using the physical parameters of the coils. Several iterations of coils sizes were tested. The wireless power receiver was designed to illuminate a small light bulb and charge a battery by simply switching the loads on the receiving coils. The high frequencies produced by the wireless power transmitter were measured to ensure that they were contained. Since this is a proof of concept design, the focus was on efficiency, practicality, and safety. The device was able to provide a useful amount of power on the receiving coil. The system is not practical enough to implement in common household and commercial electronic devices due to its large size.
3. **TECHNICAL SPECIFICATIONS**

The technical specifications of the wireless power device are listed below in Table 1.

| Component          | Proposed Specs | Achieved Specs | Description                   |
|--------------------|----------------|----------------|-------------------------------|
| Coils              | 50 cm diameter | 60 cm diameter | Helical coils                 |
| Distance           | 2 m            | 1.27 m         | Distance between coils        |
| Oscillation Frequency | 10 MHz       | 9.9 – 12.2 MHz | Resonant frequency of the coils |
| Power              | 60 W           | 0.18 W         | To power a light bulb         |
| Rechargeable Battery | 1.5 V        | 1.2 V          | AA rechargeable battery       |

Wireless power transmitter and receiver (TX\RX) used 60 cm coils as the helical coils for transmitting power. The 60 cm coils achieved the goal of having a resonant frequency of approximately 10 MHz. The distance that power could be transmitted was 1.27 m. An Agilent 33220A function generator was implemented as an oscillator with a frequency ranging between 9.9 and 12.2 MHz for the 60 cm coils; this was due to variations in the environment in which the coils were being tested. The incandescent light which was illuminated fell short of our 60 W goal due to limitations in equipment and uncertainty about the electromagnetic radiation pattern. The rechargeable battery used was 1.2 V instead of 1.5 V.
4. DESIGN APPROACH AND DETAILS

4.1 Design Approach

The wireless power device was designed with three main components: Oscillator, transmitting coil, and receiving coil. These sections are outlined below in Figure 1.

The function generator is connected to the transmitting coil. A sine wave is generated and transmits power of a distance 1.27 m to the receiving coil which the load is attached to.

**Coils**

Transmitting signals over a distance requires that the transmission beam have a high degree of directionality and a large gain requiring a larger size coil. For purposes of the far field or long distance WPT, wide angle dipole coils are better suited for the task. While for near field or short range WPT, helical coils provide better gain and power transfer.
For this application two helical coils were used. In order to illuminate a 0.18 W light bulb and charge a 1.2 V battery, the frequency must be kept high (10 MHz). To achieve this, the diameter of the helical coils was 60 cm. The helical coils must have the same resonant frequency in order to achieve inductive coupling. The purpose of using a helical coil is to get higher gain through better directionality and longer wavelength which allows the signal to travel farther [5].

Battery Charger

In order to charge a battery a standard rectifying circuit could not be implemented. Half wave and full wave rectifiers cause harmonics, which leads to transmitting power at various frequencies which would not be received by the load. Canceling out these harmonics was a priority while designing the charger. Figure 2 shows the circuit which was implemented.

![Figure 2. Circuit schematic of battery charger.](image-url)
The diodes arranged in opposite directions from each other cancel out the harmonics which would normally be generated due to their non-linearity. Figure 3 shows a Fourier analysis of the charger demonstrating that the only frequency present is 10 MHz.

![Fourier Analysis]

**Figure 3.** Fourier analysis of battery charger.

This simulation was done with ideal diodes. In actuality there will be some harmonics present however these will be far less than with a normal rectifier.

**Light Sensor**

In order to achieve an accurate measure of the power dissipated through the light bulb, a sensor was needed that did not require the user to be within immediate proximity of the coils. The circuit used is shown in Figure 4.
A cadmium sulfide light detector was chosen for its sensitivity. The op-amp (TL741LN) is simply there to amplify the voltage to enable a large range of values for different levels of light.

4.2 Codes and Standards

While no specific standards for wireless power transmitters exist, several relevant general standards for consumer electronics apply. Several FCC codes, such as FCC Title 47, Part 15 govern the operation of unlicensed RF devices in the United States [6]. The wireless power transmitter will be producing RF-wavelength signals; therefore, compliance with these codes should be assumed. According to the WHO (World Health Organization), short term exposure to extremely low frequency fields could cause "nerve and muscle stimulation and changes in nerve cell excitability in the central nervous system" and increase the risk of childhood leukemia [7]. Referencing the IEEE safety standards, if the frequency is 9.9 MHz, the maximum permissible exposure for humans to an electric field is 186.1 V/m (rms) and magnetic field 1.65 A/m (rms).
For a frequency range of 1 – 30 MHz, the electric field is 1842 V/m and the magnetic field is 16.3 A/m as can be seen in Figure 5 [8]. Each of these values have frequency ranges in megahertz.

\[
\text{Frequency range: } 1 - 30 \text{MHz} = E_{\text{field}} = \frac{1842}{\text{frequency in megahertz m(rms)}} V
\]

\[
\text{Frequency range: } 1 - 30 \text{MHz} = \text{Magnetic Field} = \frac{16.3}{\text{frequency in megahertz m(rms)}} A
\]

**Figure 5.** Frequency range calculations for acceptable IEEE frequency levels.

### 4.3 Constraints, Alternatives, and Tradeoffs

**Constraints**

Cost arises as a major constraint in building a WPT system. This is largely a result of other constraints that increase the cost of sub-components of the system. In particular is the use of coil design and simulation software. There is great software on the market specifically for the purpose of designing the coil and modeling its radiation pattern. However, the most applicable software usually costs thousands of dollars. Another constraint related to the cost is the size of the helical coil used.

**Alternatives**

Alternatives ways to design our system would be to utilize a software package such as Advanced Design System by Agilent. These kinds of packages are expensive and have a steep learning curve. If time and money were not an issue, a software package would have been the best design approach. Other alternatives include using an automated system to measure the
fields to eliminate human errors in data collection, but once again this would be expensive. Alternate coil designs could also be implemented. A tapered helix coil was considered, but would have been difficult to construct.

**Tradeoffs**

By implementing the aforementioned alternatives we reduce costs, but it comes with a tradeoff of reducing the distance over which power can be transmitted. The limited scope of the free software can also increase the time needed to design the coils. However, if software allows for an adequate tapered helical coil model, the gain and efficiency could prove to be a more ideal than previously expected.

5. **Schedule, Tasks, and Milestones**

A Gantt chart containing the proposed tasks and schedule for completing the project is shown below in Figure 6. Figure 7 shows the actual Gantt chart.

Figure 6. Proposed Gantt chart for wireless power transmitter and receiver.
The most difficult tasks for this project included finding equipment suitable to our design, and taking accurate measurements. Tasks that did not work out include: the Colpitts oscillator, and the 100 MHz coils.

6. PROJECT DEMONSTRATION

Experiments demonstrated

The design team demonstrated the following items with the system.

- Illuminating a 0.18 W incandescent light bulb
- Charging a battery
- Determining the power dissipated through the light bulb
- Graph the electric filed as a function of distance between the two coils

Illuminating the light bulb involved connecting the function generator to the 25 dB RF power amplifier which was connected to the transmitting coil. A DC power supply was used to power the amplifier at 24 V and 0.5 A. The function generator was set to generate a sinusoidal signal at 12.2 MHz and a peak to peak voltage of 20 V. Once the system was connected, the light bulb
was attached to the receiving coil and the output was enabled on the function generator and the bulb illuminated.

To test the battery charger, a simple experiment was conducted. The initial voltage of an Energizer 1.2V 2300mAh battery was measured and recorded as 0.586 V. The charger was placed on the receiving coil for one hour and the final battery voltage was 0.929 V after the fluctuation in voltage stopped.

Measuring the power dissipated in the light bulb proved to be challenging. Probing the coils with any devices or having a person near the coils affects the entire system. A means of measuring without having to be physically close to the system was needed. In order to measure the power through the light bulb, several steps were taken. In order to normalize for radiation from the coils, a measurement was taken with the lights off and the coils off. Then a measurement was taken with the lights off and the system on. The difference between the two was then subtracted from every data point to normalize the data. First the lab was ensured to be as dark as possible. A magnifying lens was then used to focus the light emitted into a focal point onto the light detector. Figure 8 shows a picture of the experimental setup.

**Figure 8.** Picture of experimental setup to measure power of light bulb.
Using a DMM, a voltage was recorded from the light sensor circuit. Then using a DC power supply, the light was illuminated in the same position and the voltage and current were recorded. From this data the power could be calculated. The main experiment that we conducted was to see how our coils coupling dissipated as a function of distance between each other. Using the same method mentioned previously, the coils were separated 0.5 inch increments between every data point to generate Figure 9.

Figure 9. Field as a function of distance.
Plots of $1/r$, $1/r^2$, $1/r^3$, were included for a comparison between standard electro-magnetic field dissipation in the near field. It was also desirable to calculate the efficiencies at each of the previous data points. In order to do this, the input power was needed. To estimate the input power the light bulb was connected directly to the RF power amp which was connected to the function generator. Using the same method mentioned earlier a figure of the input power was obtained. Due to our frequency range, the light bulb will have a reactance component and the team did not account for reflected power; therefore this figure of input power may not be accurate. Table 2 displays all of the data collected during both of these experiments. The efficiencies listed are approximate wall to load efficiencies.

| Measurement (inch) | $1/r$  | $1/r^2$  | $1/r^3$  | Data[V] | Correction | Norm. Data | Voltage[V] | Current[mA] | Power[mW] | Efficiency  |
|-------------------|--------|---------|---------|---------|-----------|-----------|-----------|-------------|---------|------------|
| 1                 | 1      | 1       | 1       | 0.478   | 0.438     | 1         | 3.72      | 47.326      | 176.05272 | 18.241%     |
| 1.5               | 0.6666667 | 0.444444 | 0.296296 | 0.394   | 0.354     | 0.808219178 | 3.47      | 45.429      | 157.63863 | 16.333%     |
| 2                 | 0.5    | 0.25    | 0.125   | 0.258   | 0.218     | 0.4977106895 | 2.9       | 40.851      | 118.7579 | 12.305%     |
| 2.5               | 0.4    | 0.16    | 0.064   | 0.21    | 0.17      | 0.388127854 | 2.59      | 38.258      | 99.08822 | 10.257%     |
| 3                 | 0.333333 | 0.111111 | 0.037037 | 0.196   | 0.156     | 0.356164384 | 2.46      | 37.185      | 91.4751 | 9.478%      |
| 3.5               | 0.285714 | 0.081633 | 0.023324 | 0.179   | 0.139     | 0.317351598 | 2.27      | 35.446      | 80.46242 | 8.337%      |
| 4                 | 0.25   | 0.0625  | 0.015625 | 0.178   | 0.138     | 0.315066493 | 2.24      | 35.19       | 78.8256 | 8.167%      |
| 4.5               | 0.222222 | 0.049933 | 0.010974 | 0.169   | 0.129     | 0.294520548 | 2.1       | 33.867      | 71.1207 | 7.959%      |
| 5                 | 0.2    | 0.04    | 0.008   | 0.167   | 0.127     | 0.289954338 | 2.04      | 33.347      | 68.02788 | 7.048%      |
Experiment not demonstrated

Measuring the electric fields around the coils was done not only for experimental purposes, but for safety purposes. Since we planned on using a power amp when illuminating the light bulb, it was necessary to determine if the fields were contained within the system or not.

In order to measure the relative magnitudes of the electric field around the coils an electromagnetics professor, Dr. Peterson, suggested using a BNC cable with the center lead extended. A PVC stand was constructed to hold the BNC probe at a specific height. To map the field, the floor tiles of our lab were utilized as our x and y axis. With the probe height adjusted to the midpoint of the coils, the probe was incremented in the x axis, along the coils, and then the y axis, away from the center of the coils. The data was collected in an excel spreadsheet and a three dimensional graph was constructed as seen in Figure 10 and Figure 11. The z axis in this graph is the magnitude of the field. It is not a three dimensional representation of the radiation pattern.

![3D view of relative magnitude of electric field plot.](image)

**Figure 10.** 3D view of relative magnitude of electric field plot.
From Figure 11 it can be inferred that the near fields are relatively contained.  Note the large spike in between the coils and on the receiving coil.  Also note that the fact that the system was being probed with a physical cable which limits the validity of the data due to the fact that a cable will pick up some radiation from the coils.
7. MARKETING AND COST ANALYSIS

7.1 Marketing Analysis

This type of wireless power transmitter is not a product that is presently available on the consumer market. There are several small electronic consumer devices that provide wireless charging capabilities but none are of this scale and potential. Small electric toothbrushes and razors implement an inductive charging technique however the effective charging distance is less than six inches. This new cutting edge wireless power application will open up a new aspect of wireless charging devices. This device increases the effective charging distance to 1.27 m and improves the voltage that is transmitted wirelessly.

The wireless power transmitter will be sold as a complete unit. It will be compatible with several electronic devices that are inside the design specifications, be it a 0.18 W light bulb or a 1.2 V battery.

7.2 Cost Analysis

Presuming the average electrical engineer’s salary is $65,000 dollars a year, the individual hourly rate of the design team members would have been $31 an hour. The six members of the wireless power team spent an average of 10 hours a week developing the system. The cost of copper coils was $115 dollars for 100 ft of coil. This brings the total cost of development to $20,015 dollars with the cost of each subsequent unit costing $30 should it go into production.
The suggested selling price is determined based on 1,000,000 units expected to be sold over the course of 5 years. Based on the development of $25,336 and 1,000,000 units being sold, the suggested price is $33. At this price, the development costs would be regained after 844 units were sold with the remaining balance going to profit and future developments.

8. SUMMARY

Initially the team proposed to demonstrate that power was transferred wirelessly by illuminating a 60 W light bulb and charging a 1.5 V battery. The goals were met but at lower than proposed power levels due to limitations of lab equipment and time. The power levels were measured using a light sensor while illuminating a 0.18 W light bulb. The battery charger was successful in eliminating most harmonics and charging a 1.2 V battery. The relative electric field strengths around the coils were measured by using a coaxial cable with the center lead extended.

For future testing and measurements made on the WPT system, an automated six axis traverse should be utilized to help ease the process of taking data while measuring the electric field. With this new setup that is under development, a programming script will be written to control the locations of the traverse with the probe attached and the data will be taken in the x, y, and z directions. This will give a true representation of the radiation pattern of the helical coils. Also an auto turner will be implemented to aid with impedance matching to maximize the amount of power being transferred between the coils.
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