

# Analysis and Optimization of Strongly Coupled Magnetic Resonance for Wireless Power Transfer Applications

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**Abstract**—The objective of the proposed research work is to investigate the use of self resonating coils operating in a strongly coupled mode for wireless power transfer applications, study and optimize the results of using coils of different geometries on power transfer efficiency and demonstrate the concept by transferring power wirelessly. Using the theoretical analysis, derived equations and simulations, a structure made of cylindrical coils with source radius 7.5cm capable of delivering wireless output power up to 4 watts at an efficiency of 70% wirelessly over 10cm was built. A further increase in efficiency of about 8% was achieved by using a combination of a cylindrical source and spiral receiver which also has the significant advantage of being easier to implement in future applications due to sizeable reduction in volume required on the receiving side. Finally the wireless power transfer was also given a physical dimension by demonstrating the lighting of bulbs at 20cm at an efficiency of 51% and the wireless charging of an i-pod was attempted.

**Keywords**— Magnetic coupling, resonance, wireless power transfer, cylindrical coil, spiral receiver, electromagnetic simulation software, strongly coupled regime

## 1.INTRODUCTION

Wireless power transfer(WPT) is recently getting much attention as an alternative energy transfer scheme without any physical contact between the source and the load. The genius inventor Nikola Tesla's future envisioned of energy radiation through huge towers and intended for household consumption is the basic behind the WPT process. Although existing 100 years well before the arrival of the electric grid, but in recent past there has been a remarkable progress and research interest in making the WPT scheme commercially viable. In addition to this, surge in use of personal gadgets and consumer electronic devices those require regular charging and battery maintenance, the energy transfer through WPT technique is in demand as convenient and safe methods. It is quite apparent; WPT products will provide better quality of life in term of convenience but lagging much behind in economical point of view. However, there is abundant prospective in use of WPT as it is capable of powering household devices like remotes and clocks which in turn would reduce the use of large no of batteries every year. The chemical batteries being disposed is seen to be a major source which contaminating the ground water and produce toxins even when destroyed by incinerators. Also in some cases where wiring is not cost effective, risky or impossible then WPT may be considered as the only facilitating technology.

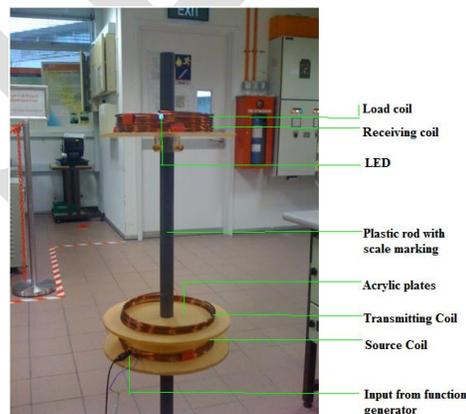


Fig. 1: Strongly coupled magnetic resonance powering the LED.

But unfortunately various methods of radiative, non-directional WPT systems using radio waves have resulted in failure due to the inherent poor efficiencies and other non-radiative techniques using lasers or microwaves are either unsafe or unsuitable for consumer use. Therefore this paper explores the use of a novel WPT technique that utilizes self resonant coils tuned to operate in a strongly coupled regime. This process is both safe for everyday use and highly energy efficient in the dimensions comparable to a typical room

making it greatly suitable for consumer applications.

## 2.CONTENTENTS

The basic idea behind this paper is that two nearby coils resonated at the same operating frequency operates in the strongly coupled regime mode. In this operating mode energy will be transferred between then at optimum efficiency whereas other surrounding non-resonated objects will interact very weakly. Although it seems very much analogous to normal inductive coupling but basic dissimilarity is that the inductive coupling works only for short distance and the receiver should be placed in the field of the transmitter coil. But by resonating both coils efficiency as well as the distance of operation will be enhanced vividly. This phenomenon can be compared to an opera singer shattering a particular glass when he/she sings the right frequency. In strongly coupled regime evanescent coupling is setup between the resonating coils which is electromagnetic equivalent of quantum-mechanical tunneling [2]. This means that energy is transferred from transmitter to receiver in much shorter time intervals than energy can be dissipated through ohmic and radiative losses thus improving efficiencies. In short the energy transfer rate  $\gg$  energy dissipation rate when operating in strongly coupled regime.

For the resonators let us consider a transmitting and receiving coil of cylindrical conducting loops with a capacitor attached to the ends. For this configuration, the resonant angular frequency of the circuit is determined by the well known equation

$$\omega = \frac{1}{\sqrt{LC}} \quad (1)$$

Where,  $\omega$  is the resonant angular frequency,  $L$  is the inductance of the coil and  $C$  is the capacitance of the coil. The coupling coefficient of the coils is given by the following equation. [2]

$$k = \frac{\omega M}{2\sqrt{L_1 L_2}} \quad (2)$$

Where  $L_1$  and  $L_2$  are the inductance of primary and secondary coil respectively and the mutual inductance can be derived from Biot-savart's law using simple approximations as

$$M = \frac{\mu_0 \pi N^2 r^2 r_b^2}{2(r^2 + D^2)^{3/2}} \quad (3)$$

Where  $r$ ,  $r_b$  are the primary and secondary coil radius respectively,  $N$  is number of turns of secondary coil and  $D$  is the distance between coils. By comparing this with the,  $M$  value defined by the Groover's tables, it is verified that, the error due to approximations made are negligible for dimensions comparable to a typical room. The intrinsic loss rate of the system is given by the following equation [2]. And the ohmic or absorption loss and radiation loss are

$$\Gamma = \frac{(R_{ohm} + R_{rad})}{2L} \quad (4)$$

$$R_{ohmic} = \frac{l}{4\pi a} \sqrt{\frac{\mu_0 \omega}{2\sigma}} = \frac{rN}{2a} \sqrt{\frac{\mu_0 \omega}{2\sigma}} \quad (5)$$

$$R_{radiative} = \sqrt{\frac{\mu_0}{\epsilon_0}} \left[ \frac{\pi N^2}{1.2} \left( \frac{\omega r}{c} \right)^4 + \frac{2}{3\pi^3} \left( \frac{\omega h}{c} \right)^2 \right] \quad (6)$$

where  $N$  is the number of turns,  $\sigma$  is conductivity and 'a' is the radius of conductor used in coil.

$$R_{radiative} = \sqrt{\frac{\mu_0}{\epsilon_0}} \left[ \frac{4\pi^5 N^2}{3} \left( \frac{r}{\lambda} \right)^4 \right] = 15600\pi^2 N^2 \left( \frac{r}{\lambda} \right)^4 \quad (7)$$

where,  $\lambda$  is wavelength, which is a function of frequency. The efficiency of the system,  $\eta$ , is function of the coupling-to-loss ratio,  $\kappa/\Gamma$  [2]

The first term is a magnetic dipole radiation term and the second term is due to the electric dipole of the coil. The second term is much smaller than the first term by about  $10^{50}$  times for our experimental parameters and can be ignored for simplicity. Therefore by substituting for  $\omega$  and  $c$  we get

$$\eta = \frac{\frac{k^2}{\Gamma^2} \sqrt{1 + \frac{k^2}{\Gamma^2}}}{\left( 1 + \sqrt{1 + \frac{k^2}{\Gamma^2}} \right) \frac{k^2}{\Gamma^2} + \left( 1 + \sqrt{1 + \frac{k^2}{\Gamma^2}} \right)^2} \quad (8)$$

For the system to be efficient, the system must operate in the strongly coupled region ( $\kappa/\Gamma \gg 1$ ) and as large as possible. Therefore by maximizing  $\kappa/\Gamma$ , it is possible to get max efficiency. By using (1 - 6), the following formula is derived for cylindrical coils of similar dimensions.

$$\frac{\kappa}{\Gamma} = \frac{\mu_0 \pi \omega r^3}{2(r^2 + D^2)^{3/2}} \left[ \frac{N}{\frac{1}{a} \sqrt{\frac{\mu_0 \omega}{8\sigma}} + \frac{\pi N r^3 \omega^4}{16c^4} \sqrt{\frac{\mu_0}{\epsilon_0}}} \right] \quad (9)$$

From (9) the only obvious predictions are that it is possible to increase efficiency by increasing conductivity or radius of conductor 'a' or by decreasing distance D. The rest of the factors do not have a straight forward relationship with efficiency and (9) needs to be differentiated with respect to a variable to maximize efficiency.

### 3.SIMULATION

#### A. Efficiency vs resonant frequency

It is imperative to state that each system has its own optimum efficiency regime i.e strongly coupled region ( $\kappa/\Gamma \gg 1$ ), where power transfer is highly efficient. Using the equations in section II the following simulations are created to verify the concepts. As a starting point two cylindrical coils of 5 turns each of radius 7.5cm connected to a suitable capacitor C is chosen and efficiency vs resonant frequency is simulated in Fig. 2. For this particular setup the band from 1MHz to 100MHz is the strongly coupled region. Fig 3 is the simulation of  $\kappa/\Gamma$  vs frequency. Comparing fig 2 and fig 3, the theory is verified that in the region where  $\kappa/\Gamma \gg 1$ , efficiencies are very high and this is the strongly coupled region for this setup.

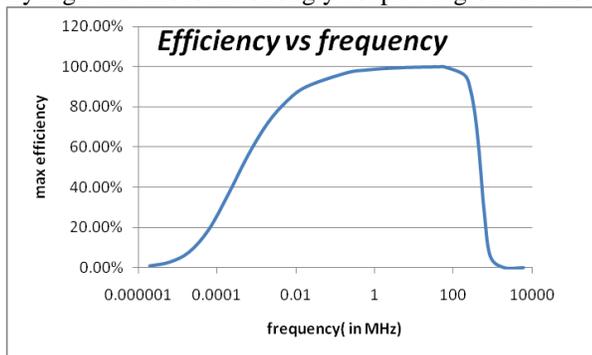


Fig. 1: Frequency characteristics of efficiency

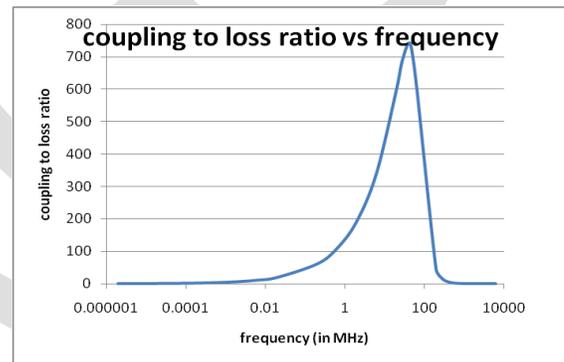


Fig. 2: Coupling to loss ratio versus frequency.

#### B. Efficiency vs coil size

When radius of the cylindrical coil is changed the optimum efficiency band also changes with it. In Fig. 4 the simulation shows the strongly coupled regions for different coil sizes. This phenomenon can be explained with (8) since r has multiple factors in the equation and there will always be an optimum 'r' if other variables are fixed.

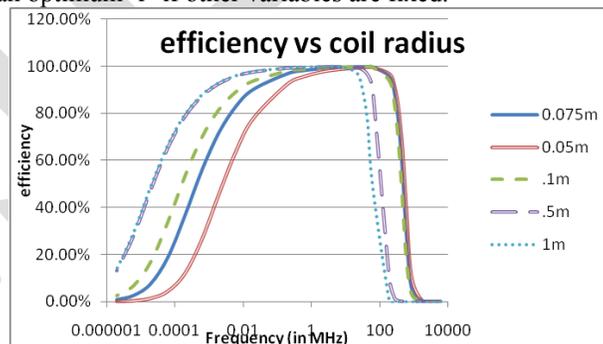


Fig. 3: Efficiency versus coil radius.

#### C. Efficiency vs distance

When the distance is simulated as a variable in Fig. 5, it is seen that the optimum efficiency band does not shift. It rather shrinks down to a peak point because the resonance can no longer compensate for the increase in distance. This is verified from (8).

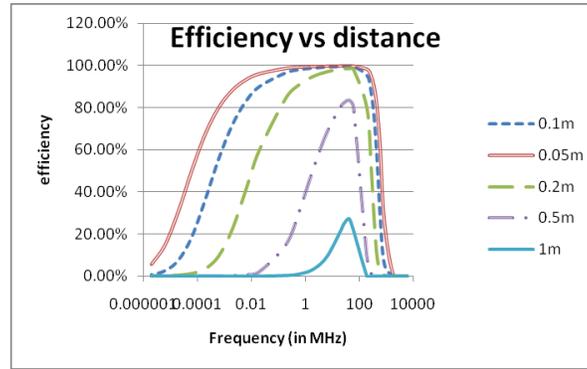


Fig. 5: Efficiency versus coil distance.

#### D. Simulation of magnetic coupling

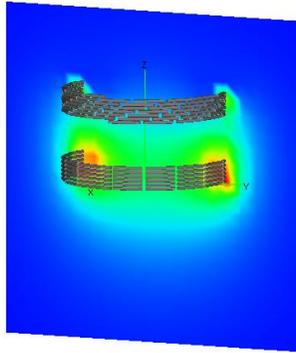


Fig. 4: Red areas indicate strongest magnetic field followed by yellow, green and blue.

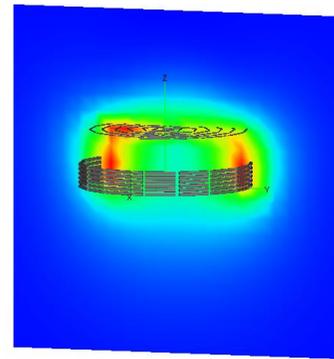


Fig. 5: Better coupling between cylinder transmitter and spiral receiver.

The parameter coupling coefficient is very much important to calculate the efficiency of power transfer and hence is required to consider different coil shape. Traditionally only cylindrical coils are used for coupling purposes but theoretically it is possible to design equivalent spiral coils such that they have a higher coupling coefficient but also higher ohmic losses due to increased length when compared to cylindrical coils. When the first effect dominates over the second there is higher efficiency [5]. Fig. 6 and Fig. 7 using electromagnetic simulation software indicate that spiral receiver combination with cylindrical transmitter shows better magnetic coupling as compared to cylindrical coils.

#### 4. EXPERIMENT AT LOW POWER

The experiment is designed such that the setup is easy to handle. Two cylindrical coils of 7.5 cm radius 5 turns each are inductively coupled to a source and load coil of similar dimensions. Although wires can be directly connected to the resonating coils, it is easier to do it this way. A frequency of 2 MHz is chosen which is in the strongly coupled regime and does not interfere with any allocated spectrum. It is also safer than using very high frequencies like 100MHz which is also in the optimum efficiency band. For this frequency range the appropriate capacitor to be used is 1000pF. The exact resonant frequency is found to be 2.05MHz which is slightly different from the calculated resonant frequency of 1.93MHz (1). This discrepancy is attributed to the coils not being perfect cylinders.

##### A. Efficiency vs load for different distances

Fig 8 shows the graph of efficiency vs load for different distances. As expected according to (8) the efficiency decreases with increasing distance. But by using strongly coupled resonance it is seen that power can be transmitted over distances much larger than any inductive system can.

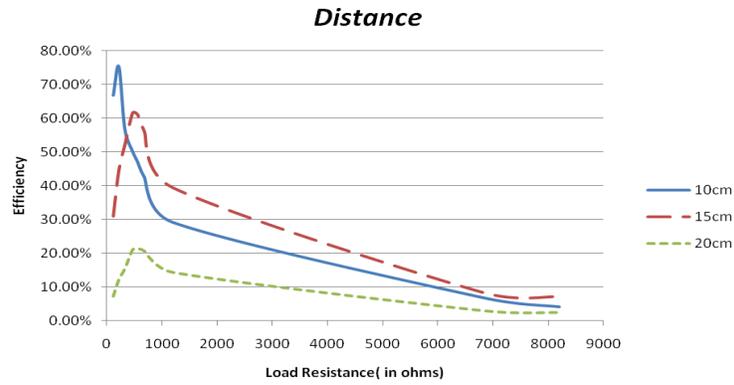


Fig. 8: Efficiency degradation with increasing coil distance

**B. Shape of the coil**

The shape of the coil is more relevant when considering the volume that the receiver coils will occupy in future applications. Different coil sizes and shapes were experimented with but the most efficient configuration was attained when cylindrical transmitter and spiral receiver combination is used. An efficiency improvement of 8% is seen due to increase in mutual inductance which increases coupling coefficient (2) and thus the efficiency. This confirms with the simulation in Fig. 9 shows a graph of efficiency vs load for such a configuration.

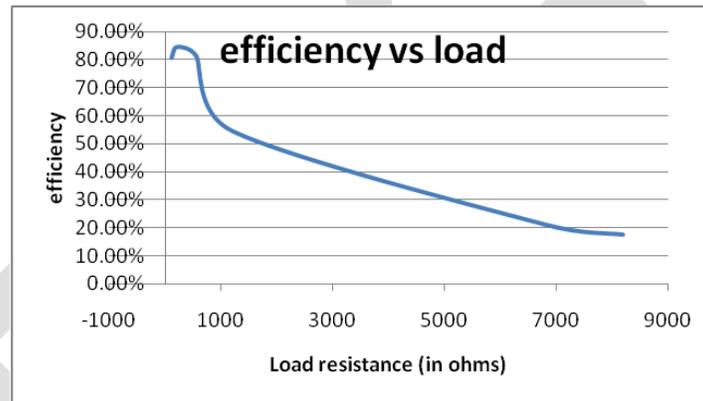


Fig. 9: Efficiency characteristics through a cylindrical transmitter and spiral receiver.

**C. Network of resonators**

It is perceived that when an additional coil resonating at the same frequency is put between the transmitter and receiver coil then efficiency as well as range is enhanced. An intermediate coil can act as a relay of energy source for the next resonator. An analogy can be drawn to WIFI routers and extenders. But it should be noted that each hop will add ohmic losses but still this method can extend range and efficiency when compared to have one pair of transmitter and receiver. Fig. 10 shows the powering of a LED using a network of resonators at 60cm which otherwise would not be possible.



Fig. 6: Practical experimental setup.

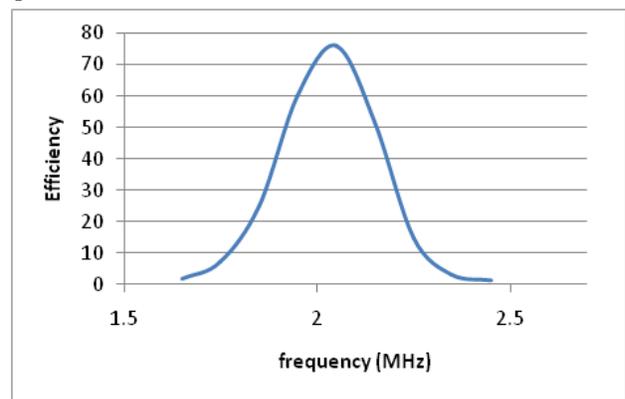


Fig. 7: Powering of a LED using a network of resonators at 60cm.

## 5. EXPERIMENT AT HIGH POWER

Ideally for future applications a crystal oscillator output would be amplified by a power amplifier and connected to a resonator. For this purpose a Colpitts oscillator was built and tested successfully. For the amplification a high speed amplifier HSA4014 was used. Power levels up to 4 watts were experimented with. Efficiency vs frequency. This experiment (Fig. 11) serves to prove that at the resonance point of the system there is a sharp increase in efficiency. At the resonance point of 2.05 MHz the efficiency is largest. This phenomenon is comparable to an opera singer who can shatter a glass by singing the right frequency.

### A. Efficiency vs load for different power levels

With the power amplifier the WPT system can be tested at various power levels. The input power can be increased by increasing the amplitude of signal into the power amplifier. This experiment (Fig. 12) proves that the power input does not have an effect on efficiency. The small reduction in efficiency is due to heating of the wire and capacitors. This can be easily solved by using high power components.

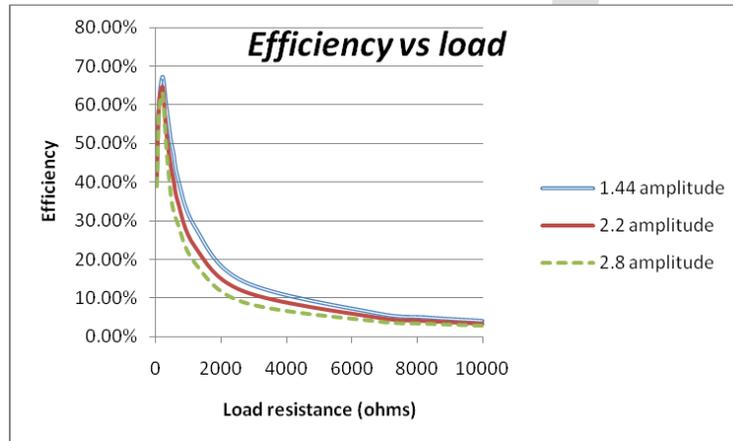


Fig. 8: Effect of input power on efficiency.

### B. Use of cylindrical transmitter and spiral receiver

The concept of using spiral structures to increase efficiency has already been discussed in section II. This experiment (Fig. 13) served to verify that the idea holds good at higher power levels. An efficiency increase of about 8% was achieved consistent with the findings in section 4.

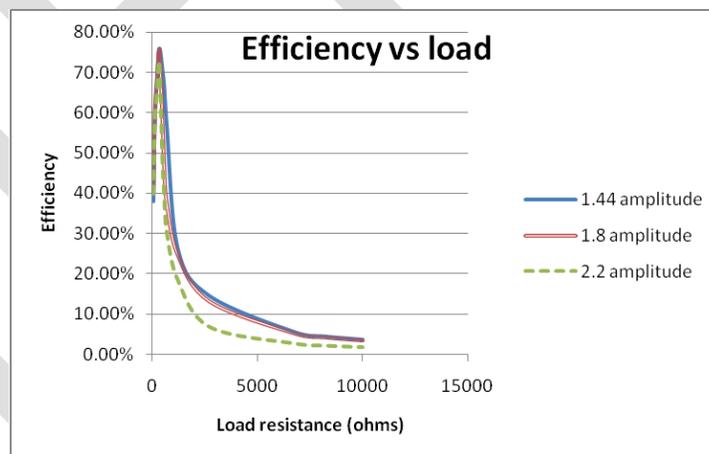


Fig. 9: Spiral receiver coil with cylindrical transmitter.

### C. Powering bulbs

To add a physical perspective to the project bulbs of different rating were lit wirelessly at high efficiencies (Fig. 14). A 12 V bulb was lit at a distance of 20 cm at 51% efficiency with an output power of 1 watt. Other bulbs of rating 2.4V, 3.6V and 7.2V were also powered successfully.

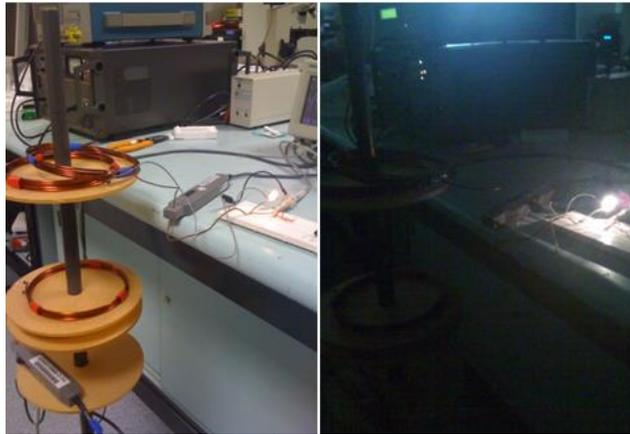


Fig. 10: Bulbs of different rating lit wirelessly with high efficiencies.

**D. Powering multiple loads and effect of extraneous objects**

The following experiment (Fig. 15) is designed to demonstrate for powering multiple devices with different geometry resonated at the same frequency. Here we can see that a single source is able to efficiently power two separate receiver coils of dissimilar dimension operated at same resonant frequency. Note that experimental bench setup comprises the smaller coil and the receiver coil which is out of the line of sight. With an unique advantageous of not interacting with non-resonating object or extraneous objects, the resonant magnetic waves are very much efficient in transferring power wirelessly with loss of very less energy.

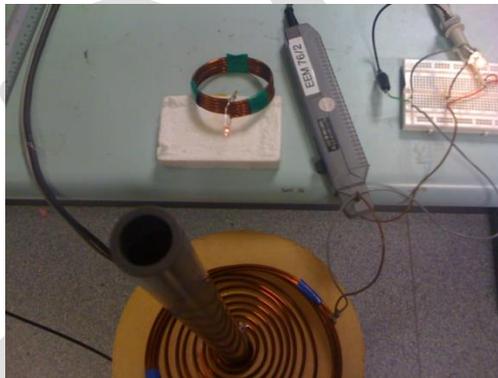


Fig. 11: Using a single source and a spiral receiver to power the bulb and a smaller cylindrical receiver to power the LED.

**E. Wireless charging of an ipod**

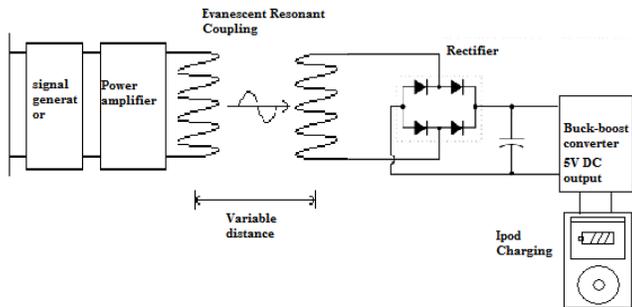


Fig. 16: Full-Bridge rectifier circuit with Buck-boost receiver.

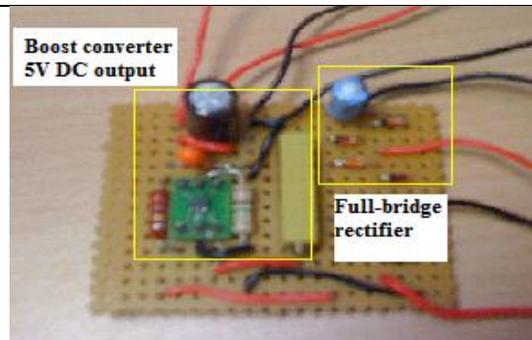


Fig. 12: Suitable high current buck-boost converter with Full-Bridge rectifier circuit

Due to the popularity and prevalence of music players and gadgets, any aspiring wireless charging system should be able to power such devices. The basic idea would be to convert the high frequency power output into a 5V DC form for the Ipod to start charging. Besides to facilitate the mobility of the device, the converter should be able to create a constant 5V DC from a variable AC

supply. But due to difficulties procuring a suitable high current buck-boost converter, a boost converter LTC3429 was used in its place. This circuit (Fig. 17) was tested and worked well at low frequency AC supply and charged the ipod but broke down when 2MHz range frequency is used. The reason for this was identified as the diodes in the rectifier not being able to recover fast enough to rectify the high frequency AC supply. This high frequency rectification is identified as an issue for further development.

## 6.SAFETY AND PRECAUTIONS

Due to the high frequencies nature of this experiment and to explore future commercial applications, it is prudent to verify the safety aspect of the current setup. In general people are very suspicious of electromagnetic radiation and they are right to do so. But by following strict guidelines posed by governmental and other international organizations like the International Commission for Non-ionizing Radiation Protection (ICNIRP), we can ensure safety. With guidelines from these international bodies the safety aspect of this project is analyzed and it is shown that the current setup is completely safe. Within the scope of this project we are only concerned about non-ionizing radiation for which the ICNIRP has published detailed guidelines [11]. According to the report the ways in which electromagnetic radiation can affect living tissue are

- A time-varying magnetic field coupling with living tissue to result in induced circulating currents within the body.
- Exposure to electromagnetic fields above 100 kHz can lead to absorption of energy and temperature increases.

In these cases, the parameter Specific Absorption Rate (SAR) is used to assess health risks. The ICNIRP also estimates that a average person has a resonant absorption frequency close to 70MHz.

It is the view of the ICNIRP that the results from the epidemiological research on EMF field exposure and cancer are not strong enough in the absence of support from experimental research to form a scientific basis for setting exposure guidelines. After incorporating sufficient safety factors, it was concluded that for frequencies between 1-10 MHz the guideline formula is  $B < 0.92/f$ . This constraint was verified in the project setup using a tesla meter to measure magnetic field. This shows that the current setup operating at 2.05 MHz range for applications in the range of tens of watts should be safe for public use. Besides the frequency used is much different from the human body resonant frequency of 70MHz. But it should be noted that there not enough literature to decide if this setup would interfere with pacemakers or critical devices. To the best of the author's knowledge there was no observable effect on mobile phones or other electronics during experiments. Therefore it is the author's opinion that pacemakers would not be affected by the current setup.

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