Wireless Evanescent Coupling and its Connection to the Latest Developments Presented by Researchers at MIT

by Gerald DeJean

The increased interest in using wireless technology to charge or power devices has led to greater understanding of the principles of wireless evanescent coupling. Evanescent wave coupling describes how the coupling of an electromagnetic wave can be sent from one device to another by way of a decaying electromagnetic field. Researchers at MIT have recently proposed a plan for wireless power transfer based on this idea and the idea of releasing stored electromagnetic energy in the near-field region at resonance. Although, using resonance to maximize coupling at resonance is not a new or unique technique, applying it to power transfer may possibly be unique. Before you run out and buy wireless power generators, there are still a few issues that need to be addressed concerning this technology. These are safety, physical limitations, crosstalk, and efficiency. Although it might be difficult to provide solutions that could equally solve each of these concerns, if these issues can be properly addressed, then we may be closer to realizing this technology than we expect.

Introduction

Recently, there have been some news and interest about the recent release of using evanescent coupling as a means to charge or power devices. This has been proposed as a way to wirelessly send and receive power from a local transmitter to a receiver that is in the vicinity of the device. In 2007, Marin Soljacic of MIT and his team of researchers have demonstrated how a 60 Watt light bulb could be powered up from a distance of 2 meters [1]. They used a technology termed "WiTricity" to describe this phenomenon of evanescent wave coupling. In this short document, the idea of evanescent wave coupling is examined more closely with respect to the current technology that exists for transmitting wireless energy. Before the idea of evanescent wave coupling is addressed, it is helpful to present a short background of the regions in which electromagnetic waves are radiated and stored.

Stored Energy or Radiated Power: Which region am I in?

The distance between a radiator (antenna) and a particular field point out in space (denoted R) determines the mechanism of electromagnetic coupling. There are three field regions of interest: the reactive near-field region, the intermediate (or radiating) near-field (Fresnel) region, and the radiative far-field (Fraunhofer) region. To better understand the three regions, it is necessary to briefly take a closer look at expressions for the electric and magnetic fields of an antenna. For this, dipole of constant current that lies on the z-axis (Fig. 1) is the example we'll consider.

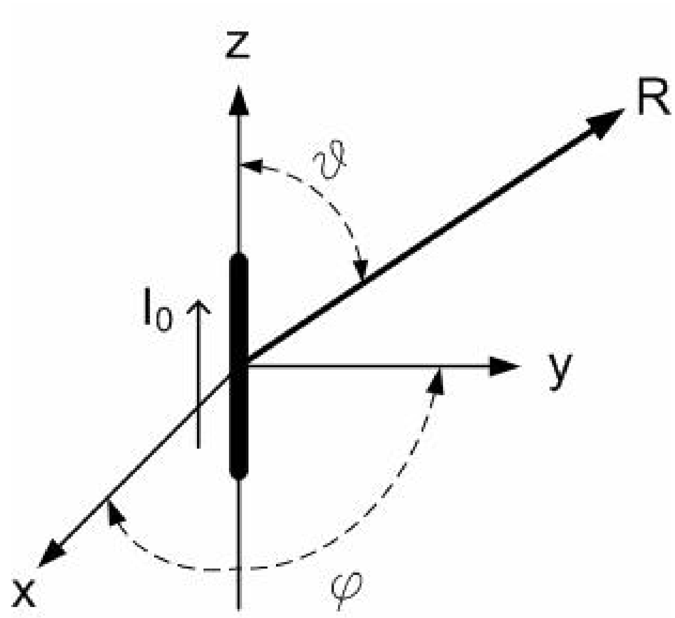

Fig. 1 Illustration of dipole antenna of constant current.

An expression for the total current on the dipole for this example is shown below:

$$I = I_0 \hat{z} \tag{1}$$

Let's remember that line current is a vector with magnitude and direction. I_0 represents the magnitude and $\vec{z}$ represents the travel of current in the z-direction. Equations for the electric and magnetic fields can be derived generically for any field point in space. (For this example, it will be easier to express the electric field components (E_R, E_θ, E_φ) and magnetic field components (H_R, H_θ, H_φ) in spherical components as opposed to rectangular coordinates.) These are shown below [2]:

$$\begin{aligned}
&E_\varphi = H_R = H_\theta = 0 \\
&E_R = \eta \frac{I_0 l \cos\theta}{2\pi R^2}\left[1 + \frac{1}{jkR}\right] e^{-jkR} \\
&E_\theta = j\eta \frac{k I_0 l \sin\theta}{4\pi R}\left[1 + \frac{1}{jkR} - \frac{1}{(kR)^2}\right] e^{-jkR} \\
&H_\varphi = j \frac{k I_0 l \sin\theta}{4\pi R}\left[1 + \frac{1}{jkR}\right] e^{-jkR}
\end{aligned} \tag{2}$$

where η is the intrinsic impedance (equal to 120π ohms in free space), l is the length of the dipole in meters (m), k is the wavenumber in units of m^{-1} (equal to 2π/λ), R is the distance from the source to any position in space in meters (m), and j is an imaginary number ($j^2 = -1$). Based on these equations, three regions can be separated based on the value of the product kR.

When kR is much less than 1 ($\ll 1$), the field equations can be simplified as follows,

$$
\begin{aligned}
&E_\varphi = H_R = H_\theta = 0 \\
&E_R \simeq -j\eta \frac{I_0 l \cos\theta}{2\pi k R^3} e^{-jkR} \\
&E_\theta \simeq -j\eta \frac{I_0 l \sin\theta}{4\pi k R^3} e^{-jkR} \\
&H_\varphi \simeq \frac{I_0 l \sin\theta}{4\pi R^2} e^{-jkR}
\end{aligned}
\qquad (3).
$$

From these equations, the Poynting vector (that represents the power density in W/m^2) can be computed as $S = \vec{E} \times \vec{H}$. Keeping in mind that one is relatively close to the source of the wave (or in the near-field) when $kR \ll 1$, it can be seen that the power density is totally reactive (purely imaginary). Therefore, this region is termed the reactive near-field region. The energies of the magnetic and electric fields are stored.

When kR>1, the field equations reduce to

$$
\begin{aligned}
&E_\varphi = H_R = H_\theta = 0 \\
&E_R \simeq \eta \frac{I_0 l \cos\theta}{2\pi R^2} e^{-jkR} \\
&E_\theta \simeq j\eta \frac{k I_0 l \sin\theta}{4\pi R} e^{-jkR} \\
&H_\varphi \simeq j \frac{k I_0 l \sin\theta}{4\pi R} e^{-jkR}
\end{aligned}
\qquad (4).
$$

In this case, the Poynting vector is complex; in other words, it has real and imaginary components. The real valued component will be the power that is radiated and released into the atmosphere, a portion of which will be captured by a receiving device. The imaginary component accounts for the reactive power density. Since this region is still close to the source of the wave (but not as close as in the reactive near-field), this area is termed the intermediate (or radiating) near-field (Fresnel) region, named after physicist Augustin Jean Fresnel.

The last region occurs when one is far from the source of the wave ($kR \gg 1$). The field equations for this region are

$$
\begin{aligned}
&E_R \simeq E_\varphi = H_R = H_\theta = 0 \\
&E_\theta \simeq j\eta \frac{kI_0 l \sin\theta}{4\pi R} e^{-jkR} \\
&H_\varphi \simeq j \frac{kI_0 l \sin\theta}{4\pi R} e^{-jkR}
\end{aligned} \quad (5).
$$

Here it is seen that the E_θ and H_φ components essentially stay the same, but the E_R component that varies inversely as the square of the distance ($1/R^2$) vanishes well before the other two components. The Poynting vector for this region is purely real and the power is radiated into space. Hence, this region is called the radiative far-field (Fraunhofer) region. Table I presents a rough approximation that describes which region you are resting in as it relates to how far you are from a source.

Table 1. Approximations for Region of Operation

Region	Distance (R) from the source
Reactive near-field region	$R < 0.62\sqrt{\frac{D^3}{\lambda}}$
Intermediate (or radiating) near-field (Fresnel) region	$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda}$
Radiative far-field (Fraunhofer) region	$R > \frac{2D^2}{\lambda}$

λ is the wavelength of the antenna, and D is the longest dimension of the source. (For the dipole of length l in Fig. 1, D = l.)

So what is Evanescent Wave Coupling?

Evanescent wave coupling is a way to describe how the coupling of an electromagnetic wave can be sent from one device to another by way of a decaying electromagnetic field. Evanescent waves commonly occur in the "near-field" of a wave. So we will only be considering the near-field regime for this concept, more specifically, the reactive near-field (per equation 3 above). Some in the field have stated that evanescent wave coupling is simply the near-field coupling of magnetic fields or electric fields from a transmitter to a receiver. Let's look at the classic example of the coupling mechanism of two loop antennas of constant current (Fig. 2).

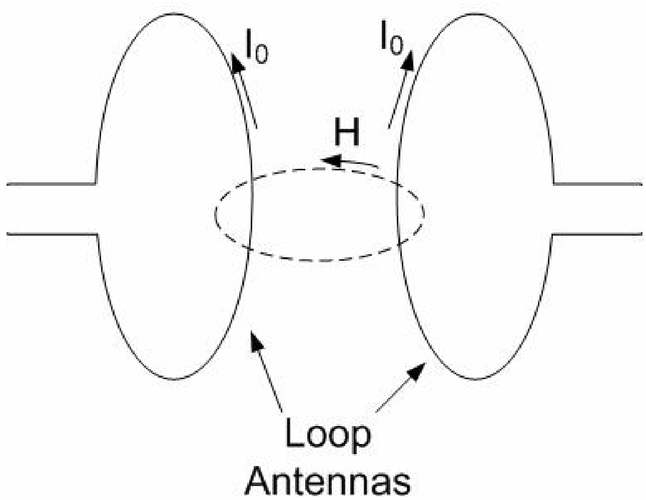

Fig. 2 Illustration of the coupling between two loop antennas.

When a current is excited in one of the loops (let's say on the transmitter side), a magnetic field, H, is created that circles the loop. Conversely, the magnetic field from that loop excites a current in the receiver loop if it is close to the strength of the magnetic field. Hence, magnetic field coupling is occurring between two loops in the near field. This is the major source of energy coupling used in the charging of devices such as electric toothbrushes. Keep in mind that this is an extremely close coupling that is taking place. Actually, in devices like these, this is the reason why the device that needs to be charged (the electric toothbrush) sits on the charger in a fixed position. The coupling of electric field energy can be similarly viewed through the interaction between two charged metallic plates (or electrodes) that funnel electric fields between them. An example is shown in Fig. 3.

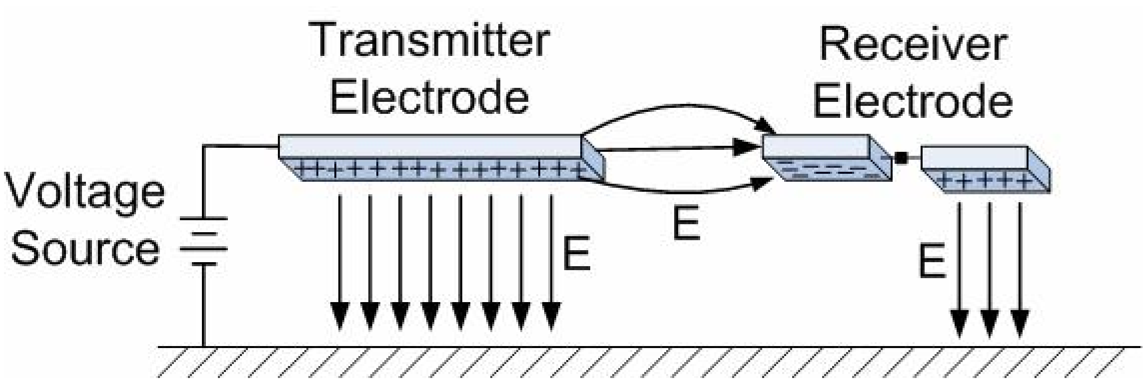

Fig. 3 Illustration of the coupling between charged electrodes.

In this scenario, the positively charged electrode on the transmitter side couples electric fields (E) with the one of the electrodes on the receiver side, specifically the negatively charged electrode [3]. With evanescent coupling, electromagnetic fields can be coupled from any arrangement of a charged platform and a current flowing through a wire.

So is this what MIT researchers are doing?

Well, somewhat. It is true that the proposed plan of MIT researchers does involve evanescent wave coupling in the near-field, but they are proposing this concept with a twist. The MIT researchers are proposing a plan of evanescent wave coupling at resonance. Resonance is a condition in which a system or device will oscillate at maximum amplitude at a certain frequency. At resonance, the stored electric energy and stored magnetic energy are equal. Circuits consisting of inductors and capacitors have a certain resonant frequency at which the stored energy is released. That frequency is the given below (in Hz):

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

At this frequency, maximum power transfer is conducted between two devices. For instance, if a large transmitting coil resonates at 1 MHz per se, then only devices that resonate at 1 MHz (or at frequencies within a small band around 1 MHz) can optimally receive energy from the transmitter. Larger size coils can couple their magnetic fields at longer distances. In addition, larger size coils have larger values of inductance which results in a decreased resonant frequency. Similarly, larger electrodes can couple electric fields at longer distances, and this increase in size results in larger capacitances, which also decreases the resonant frequency. So by operating at a "low-enough" frequency, the range of coupling energy (maximum distance between elements that can still facilitate coupling) can be significantly increased in comparison the necessary close distance of the coils in the charging of electric toothbrushes. However, there is a tradeoff between the coupling distance and the size of the coupling device. The inductance and capacitance needs to be large enough to couple at a long distance without significantly increasing the size of the coupling devices.

It would be irresponsible to mention resonant frequency without saying a few words about quality factor. The quality factor (or Q-factor) is a dimensionless quantity that measures the amount of energy stored in the reactive components to the power lost due to resistance. Equations for the quality factor of a series and parallel LC network with associated resistance (whether internal or external) are presented below in addition to the relationship between the bandwidth (BW) around the resonant frequency and the Q-factor [4]:

$$Q_{series} = \frac{\omega_{res} L}{R} = \frac{1}{\omega_{res} RC}, \qquad Q_{parallel} = \frac{R}{\omega_{res} L} = \omega_{res} RC, \qquad BW = \frac{1}{Q_{series\_or\ parallel}} \tag{7}$$

A higher Q-factor means that less power is lost at resonance. Also, a device with a higher Q-factor results in a narrower band of frequencies in which energy will be released from its stored state at resonance. For evanescent wave coupling at resonance, it is necessary to design the transmitter and receiver resonators with as high a Q-factor as possible (bandwidth as low as possible) so devices operating at frequencies close to the band around the resonant frequency will not be unintentionally excited, but the band has to be large enough to account for frequency shifts in the handling and manufacturing of the device.

The positive point of view of this approach is that the distance between coupling elements can be larger than that required in some current device-charging methods. In addition, since the region of operation is not in the far-field, you do not have to worry about wasted power being radiated into free space. As far as the physics is concerned, one could loosely think of this approach as "RFID for power", but only in terms of how electromagnetic fields are used to couple energy to devices. The coupling mechanisms are essentially the same. With passive RFIDs, the premise is for the transponder (tag) to receive energy from the magnetic field of the reader and subsequently modulate the load resistor and send back the information to the reader. Here, evanescent wave coupling is basically the same process. The difference is that when the receiver receives the energy, it uses that energy to charge up the device. RFID readers and tags that comply with ISO 15693 and ISO 14443 operate at a resonant frequency of 13.56 MHz. The use of resonance to maximize the coupling between the reader and the tag is not a new or unique application. Therefore, it is the author's opinion that MIT researchers or any other researchers cannot claim uniqueness by using resonance in this manner. There are literally millions of resonant readers and tags being utilized daily around the world.

What are the underlying issues concerning this technology?

Although the research that MIT researchers have presented may be promising, there are a few underlying issues that are concerned with this technology. Before we start to heavily invest in this technology, here are some of the concerns that are addressed in this section: safety, physical limitations, crosstalk, and efficiency.

a. Safety

There is a possibility of unintentional circuits being formed or present in the coupling space next to the human body. Many times humans are unaware of their ability to create or become a part of a circuit. Common items that we wear, such as a necklace or bracelet, can act as loop antenna. There is the scenario of a person wearing a pacemaker in a room when coincidentally, some circuitry in the pacemaker oscillates at a frequency that is exactly the same as that of a large power transmitter. If this situation happens then, let's just say, a person starts to receive much more than a heartbeat. Although one may briefly chuckle at this scenario, the truth of the matter is that this is a true concern that should not be glanced over.

b. Physical Limitations

The two physical limitations that still exist with this technology are the size of the device and the coupling distance between transmitter and receiver. The size of a coupling device is always a critical concern due to the inversely proportional relationship between the frequency and the size of the radiator. To get idea of this, consider this. Generally speaking, a half-wavelength dipole radiating in free space (without an external capacitors connected to it) that has a resonant frequency of 4 MHz requires a length of 37.5 meters. This may be too large for receivers to handle. However, this problem can be overcome by using a much shorter length of wire and loading it with a high value capacitor. Although the shorter length of wire increases the frequency, the high valued capacitor tunes it back down to the desired resonance. Research is continually being conducted on solutions to reduce the size of antennas and coils without compromising their performance. The coupling distance between the transmitter and the receiver of circular coils are limited by the near-field magnetic field strength (H) of the devices that decreases as the cube of the distance between the two (R^3) increases. Based on the desired maximum distance that one would like to receive power, the magnetic field strength would have to be large enough to accommodate that distance.

c. Crosstalk

Crosstalk is defined as the unintentional coupling of electric or magnetic energy from one device to another device. This is a very realistic problem that could happen if a device unintentionally resonates at a frequency that is close to a transmitter inside a room (or even in an adjacent room within the near-field of the transmitter). The author has not found any information to suggest that coupling of this form is not possible. Hence, there is always the possibility of other devices malfunctioning (or total device destruction) due to crosstalk. To date, the author has not seen any information in the public domain or from the MIT research team that addresses this question. The author would like to perform some electromagnetic computer simulations in the near future that could give some insight into addressing this issue.

d. Efficiency

While it is attractive to eliminate wires such as charging cables for many products, the desire to transfer substantial levels of power can become very wasteful. In some instances, you may be looking at transferring watts of power from a transmitter to deliver milliwatts of power to the receiving device. In addition, the coupled device in the receiver will need to be properly aligned to the coupled device in the transmitter to maximize the efficiency of power transfer. This concept is termed “the polarization loss factor”. If the transmitter and receiver coupling devices are circular loop antennas, in an ideal coupling scenario, a parallel alignment theoretically results in total (100%) coupling. A perpendicular alignment theoretically results in zero coupling between the devices.

Conclusion

In conclusion, the researchers at MIT have presented some research that has the potential to become a break-through in wireless technology, but before we all rush out to buy wireless power generators, there are still some issues that need to be addressed from the standpoint of safety. This is however a great starting point to begin the discussion about the platform of future wireless technologies. The good thing is that research in RFID technology and other near-field coupling technologies is relatively mature at this stage, and the need to reinvent the wheel may not truly exist. Therefore, we may be closer to the development of wireless power generators than we expect.

This document is intended to provide the reader with a better knowledge of some of the principles that are involved in wireless evanescent coupling. The references provided give a much more thorough analysis of this topic. The author would like to acknowledge Mike Sinclair and Sean Mercer for their technical assistance, specifically, their brainstorming of ideas through numerous conversations about the subject presented in this document.

Gerald R. DeJean, Ph.D.
Microsoft Research
September 27, 2007

References

1. Available at http://www.msnbc.msn.com/id/19098305/.

2. C. Balanis, Antenna Theory: Analysis and Design, New York, John Wiley & Sons, Inc., 1997.

3. K. Finkenzeller, RFID Handbook, England, John Wiley & Sons, Inc., 2003.

4. D. Pozar, Microwave Engineering, New York, John Wiley & Sons, Inc., 2005.