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Flexible and Mobile Near-Field Wireless Power Transfer using an Array of Resonators

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Abstract In this report, we present a technology to realize flexible and mobile wireless power transfer, which is based on the coupling of an array of resonators. Near-field wireless power transfer using resonant coupling has been shown to be a promising technology for many applications. However, the mobility of device while operating is limited to the near-range of the transmitter. We show that, by using an array of resonators, the range of efficient power transfer can be largely extended. More importantly, this new technology can provide wireless power to both static and mobile devices. The principle of this technology will be explained in this paper. Analytical and numerical models will be used to evaluate the performance of a wireless power transfer system with an array of resonators. Advantages and potential applications of the technology will also be discussed.

Keyword Wireless power transfer, Resonant coupling, array of resonators

1. Introduction

In recent years, the demand of wireless power transfer (WPT) technologies is rapidly increasing, largely due to the emerging needs of wireless charging for electronic devices and electric vehicles. Different technologies are under development by physicists and engineers worldwide. Microwave power transmission is targeted for long distance and large scale power transmission (for example, see Ref. [1]). For short-distance applications, where the power transfer distance lies between a few centimeters to a few meters, inductive coupling method has long been pursued (for example, see Ref. [2-3]). Power from a few milliwatts to a few kilowatts can be efficiently transferred with inductive coupling. However the transfer distance is limited to a few centimeters.

Following the renowned experiment of an MIT group in 2007 [4], resonant coupling method has attracted a lot attention for short-distance WPT (see Ref. [5-7]). Compared with inductive coupling, resonant coupling method is more flexible with device misalignment, and more importantly, can achieve longer transfer distance. In the MIT experiment, 40% efficiency is achieved at a distance of 2 m. This is a big advantage compared with inductive coupling. However, the efficiency will drop when the distance increases and the resonators are under coupled [4, 7]. Recently, metamaterials have been applied to resonant coupling system for coupling enhancement and efficiency improvement [8-11]. Experiment result shows that the power transfer efficiency can be greatly improved by a metamaterial slab [11]. With this technology the power transfer range and efficiency can be further improved.

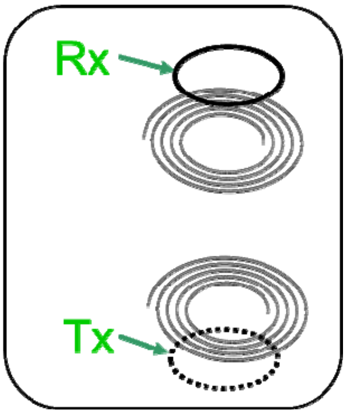
The above technologies are mainly for static power transfer, where the receiving device is not moving and placed in the close range of transmitter. The mobility of receiving device is very limited. These technologies are not suitable for power transfer to mobile devices and equipment, such as moving electric cars and trains. For these applications, a mobile power transfer technology needs to be developed. Mobile power transfer is much more complicated than static power transfer, and is a more challenging task to deal with.

In this report, we propose the use of array of resonators for mobile power transfer. We will show that by using this technology, the effective power transfer range can be greatly extended; more importantly, power can be delivered to multiple moving devices. This technology has great potential in applications such as wireless powered road/lane for electric vehicles, wireless power solution for roaming robots, etc.

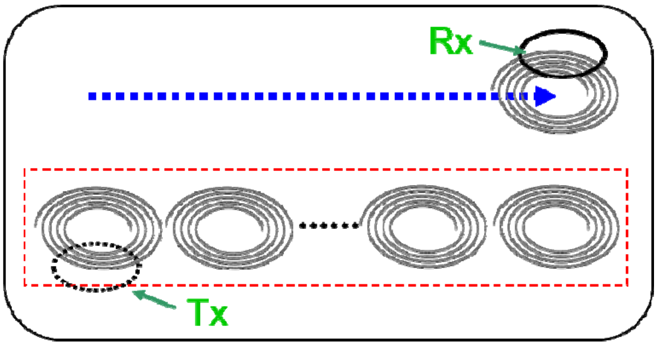
2. Concept of array of resonators for WPT

In a WPT system based on resonant coupling, the essential parts are two resonators tuned to the same resonator frequency, one serves as transmitter and the other serves as receiver. In addition, high-frequency power can be coupled from source to resonator in different approaches. In Fig. 1(a), loop antennas are used to inductively couple power from source to resonator and from resonator to power-consuming device. To achieve efficient power transfer, the receiver needs to be in close range of the transmitter. The system is not suitable for transmitting power to a moving device with traveling distance much larger than the size of resonator.

As shown in Fig. 1(b), an array of resonators is formed by putting resonators of the same or similar resonant frequency in close range. When one of the resonators in the array is excited by an external source, power can be transferred to neighboring resonators via resonant coupling, in a similar procedure as one-to-one WPT shown in Fig. 1(a). Through resonant coupling, power can be transferred to all other resonators in the array. In this sense, the array serves as effectively a waveguide for the near-field surface waves formed on the resonators. When a power-consuming device with a resonator as receiver is in the close range of the array, power can be transferred from the array to the receiver, again through resonant coupling. The receiver can be anywhere along the array. This way the effective power transfer range is greatly extended. More importantly, the receiver can be used for traveling devices, as long as the devices are in close range of the array. Plus, the array system is capable of providing power to more than one device at the same time.



(a) WPT system with one resonator as transmitter and one resonator as receiver.

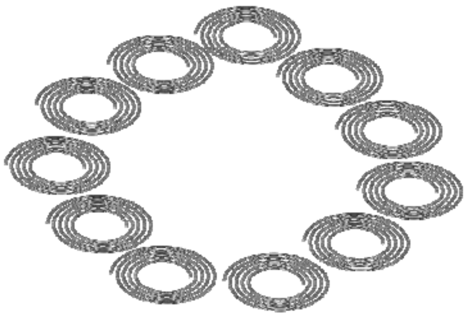


(b) WPT system with an array of resonators as transmitter and one resonator as receiver.

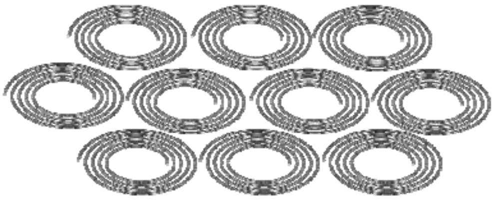
Fig. 1 Illustration of WPT systems.

It is worth to mention that the array can be very flexible and form in different shapes. As a few examples, Fig. 2 shows some of the forms array can take. Depending on the requirements, an array can be formed in a straight line (Fig. 1(b)), a bended line (Fig. 2(a)), a closed loop (Fig. 2(b)), or even a 2d surface (Fig. 2(c)). With this powerful tool, WPT can be used for many potential applications with moving or static devices.

(a) Array of resonator in a bended line.



(b) Array of resonators in a closed loop.



(c) Array of resonators in 2d surface.

Fig. 2 Examples of arrays in different forms.

3. Simplified analytical model

In order to study the performance of a WPT system with array of resonators, a simplified model is used to quickly analyze the power transfer behavior.

In the simplified model, each resonator is modeled as a current-carrying loop, whose inductance can be calculated using

$$L=\mu_0 R\left[\ln\left(\frac{8R}{a}\right)-2\right]$$

Where R is the radius of the loop and a is the radius of wire. A lumped capacitor C is added to the loop in order to give the loop a resonant frequency. The coupling between resonators is modeled by the mutual inductance. For a general case, consider two loops with parameters and relative positions given in Fig. 3, the mutual inductance M of them can be given by the following equation.

$$M=\frac{\mu_0}{4\pi}R_1R_2\int_0^{2\pi}\int_0^{2\pi}\frac{(\sin\phi_1\sin\phi_2+\cos\phi_1\cos\phi_2\cos\theta)}{\sqrt{(R_1\cos\phi_1-R_2\cos\phi_2)^2+(R_1\sin\phi_1-t-R_2\sin\phi_2\cos\theta)^2+(d-R_2\sin\phi_2\sin\theta)^2}}d\phi_1 d\phi_2$$

After the calculation, each resonator is modeled as an RLC circuit, as shown in Fig. 4. The equivalent impedance of i-th loop in the array is modeled as

$$Z_i=R_i+j\omega L_i+\frac{1}{j\omega C_i}$$

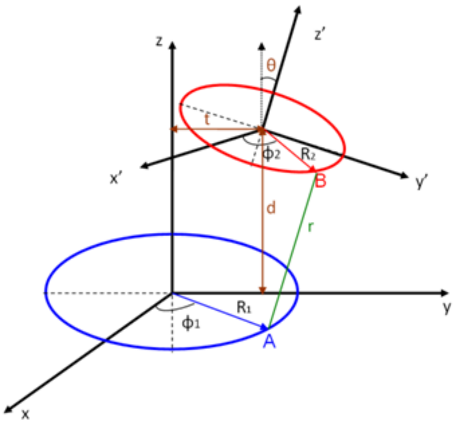


Fig. 3 Geometry of three test examples.

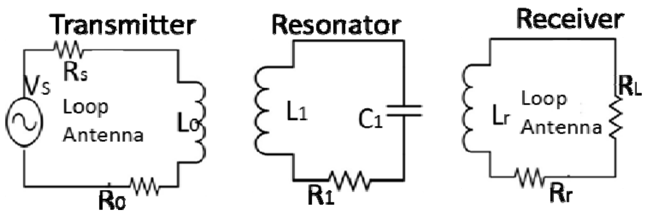


Fig. 4 Equivalent circuits for transmitting antenna, resonant loops and receiving antenna.

For a system with n resonators in the array, and one resonator as receiver, the system can be described by Kirchhoff's law.

$$\begin{pmatrix}V_0\\0\\0\\\vdots\\0\\0\\0\end{pmatrix}=\begin{pmatrix}Z_0 & j\omega M_{01} & 0 & \cdots & 0 & 0 & 0\\ j\omega M_{01} & Z_1 & j\omega M_{12} & \cdots & j\omega M_{1n} & j\omega M_{1r} & 0\\ 0 & j\omega M_{12} & Z_2 & \cdots & j\omega M_{2n} & j\omega M_{2r} & 0\\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots\\ 0 & j\omega M_{1n} & j\omega M_{2n} & \cdots & Z_n & j\omega M_{nr} & 0\\ 0 & j\omega M_{1r} & j\omega M_{2r} & \cdots & j\omega M_{nr} & Z_r & j\omega M_{rd}\\ 0 & 0 & 0 & \cdots & 0 & j\omega M_{rd} & Z_d\end{pmatrix}\begin{pmatrix}I_0\\I_1\\I_2\\\vdots\\I_n\\I_r\\I_d\end{pmatrix}$$

In the above equation, the subscript *0* means the transmitting antenna, subscript *d* means the receiving antenna with load, subscript *r* means the receiving resonator and subscript *i* means the *i*-th resonator in the array. *Z* terms are the impedances of circuits and *M* terms are mutual coupling terms of corresponding circuits denoted by the subscript. Note that only the nearest two neighbors on each side of a resonator in the array are considered for simplification. The current on the load, and hence the power transfer efficiency can be obtained by solving the equation.

As an example, we consider an array of 10 resonant loops in a straight line. A loop antenna is used to excite the first loop, and a receiving resonant loop is at a distance of 0.5R above the array on top of the last loop in the array. The resonant frequency of the loops is 25 MHz. Using the model described above, the power transfer efficiency of the system is calculated as a function of excitation frequency and plotted in Fig. 5. High efficiency (about 90%) is achieved around the resonant frequency. The multiple peaks are due to the mutual coupling between resonators in the array.

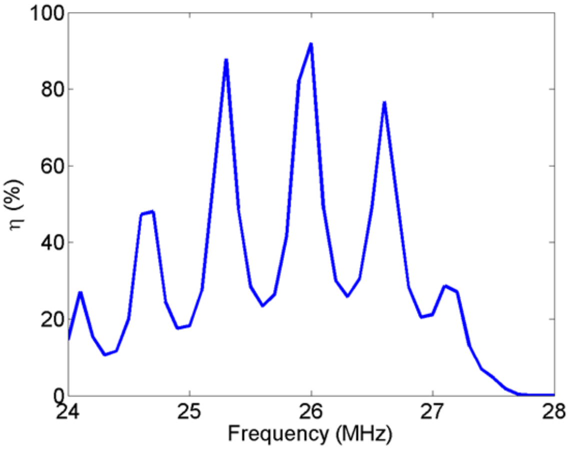
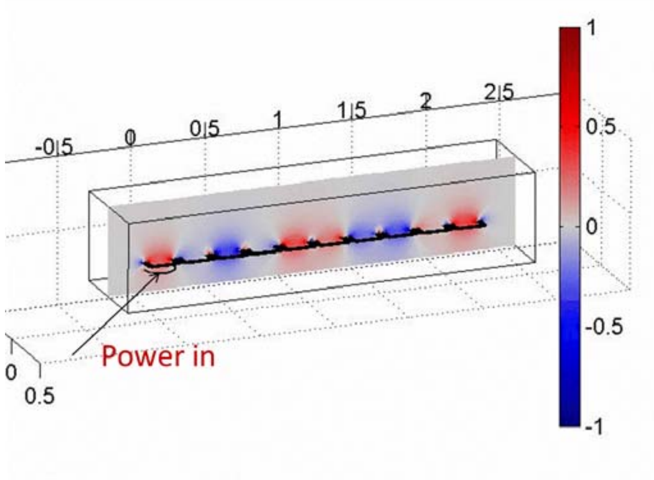


Fig. 5 Calculated power transfer efficiency of a system with an array of 10 resonators.

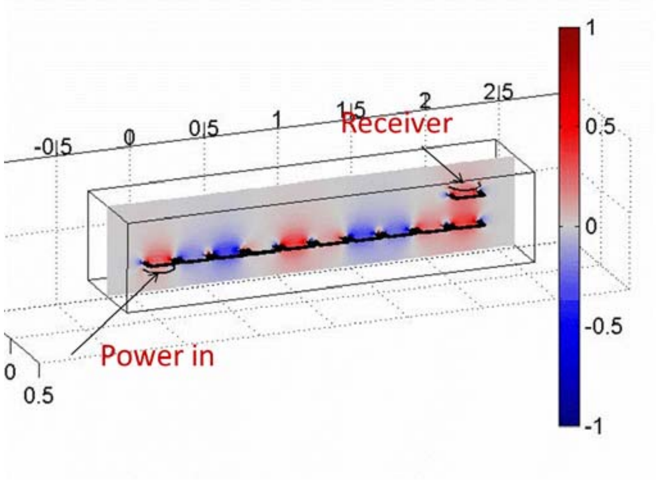
4. Numerical Simulations

In this section, numerical simulations are performed to further study the properties of WPT system with array of resonators. The simulations are done in commercially available package COMSOL.

First, a coil resonator is designed with resonant frequency around 25 MHz. The coil is in square shape with side length of 20 cm and 6 turns of wire. 10 such coils are used to form an array in straight line. A loop antenna is used to provide power to the array by inductive coupling. Fig. 6 plots the field distribution when the system is resonance, which helps to understand the physical principle of the system. As shown in Fig. 6(a), when the loop antenna is coupled the first coil in the array, strong field is seen along all coils in the array, which indicates the resonant coupling behavior in the array. When there is no receiver nearby, power oscillates in the array without radiation to far-field. When a receiver is put close to the array, power is transferred to it via resonant coupling, as shown in Fig. 6(b).



(a) Field distribution without receiver



(b) Field distribution with receiver

Fig. 6 Field distribution of a WPT system with an array of resonators.

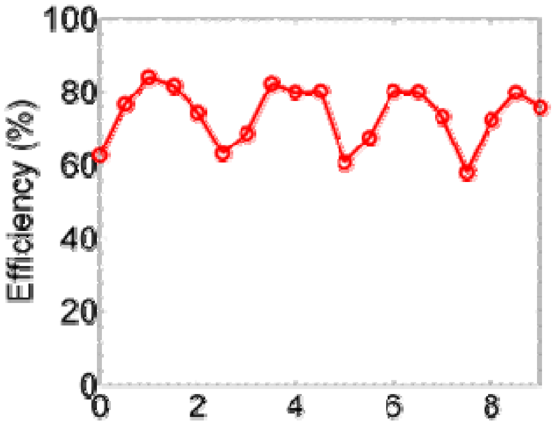


Fig. 7 Simulated power transfer efficiency of the array system as a function of receiver position.

The power transfer efficiency can also be simulated with COMSOL. The simulated structures are shown in Fig. 6. One loop antenna is used to provide power inductively to the array. A second loop antenna is coupled to a receiving resonator for power consumption. The efficiency is calculated as the ratio of power goes to the receiving loop antenna and power transmitted from the first loop antenna. To evaluate the performance of the system for a moving device, the position of the receiver is scanned from one end of the array to the other, and efficiency is calculated for each case. Fig. 7 shows the simulated power transfer efficiency of the described system as a function of receiver position. The position is in unit of unit cell size, which is the distance between the centers of neighboring coils in the array. The distance between receiving coil and the array is 10 cm. From the figure, we can see that very high efficiency (85%) can be achieved with this system. However, the efficiency is not constant when the receiver is at different positions. This is due to the resonant coupling nature of the system. As shown in Fig. 6, the field at resonance forms a standing wave pattern with nodes and antinodes, instead of evenly distributed through the array. Thus when the receiver is at different positions, different coupling is expected between the array and the receiver, leading to fluctuations in the power transfer efficiency. In general, the fluctuation is related to the distance between array and receiver. Less fluctuation is expected with larger distance between array and receiver; however, in this case, the overall efficiency also drops due to weaker coupling. Different approaches can be used to reduce this fluctuation and improve the performance of the system. For examples, improved array and receiver design can help to achieve better coupling at all positions; adaptively tuning the excitation frequency can optimize the system efficiency through modifying the field distribution pattern along the array. These are beyond the scope of this report and will not be discussed in details here.

5. Conclusions

In summary, we have proposed the idea of using an array of resonators for mobile power transfer. The new technology is based on resonant coupling. An array is formed by multiple resonators arranged in close range, without electric connections in between. We showed that by using this technology, the effective power transfer range can be greatly extended. Moreover, the technology has the capability of delivering power to multiple moving devices at the same time. Analytical and numerical calculations both show that >85% efficiency can be achieved with an array of 10 resonators long.

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