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Abstract

This article discusses the use of metamaterials and resonator arrays to improve the range and efficiency of wireless power transfer, including both predicted and actual experimental results with single and multiple coupled resonators and metamaterial structures.

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Metamaterials and Coupled Resonant Wireless Power Systems

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Abstract— This article discusses the use of metamaterials and resonators to improve the efficiency of wireless power transfer, including both predicted and actual experimental results including single and multiple coupled resonators and metamaterial structures.

I. Introduction

In 1902, Nicola Tesla patented the Tesla Coil[1], a resonant power transfer device and the first step in commercial wireless power transfer. However, turning that first demonstration into an effective, economically successful method has been an elusive goal. We present here two improvements toward that end: the use of metamaterials to improve efficiency, and the use of coupled resonator arrays to increase the free motion range.

II. Metamaterials

Here, we use the term *metamaterial* to mean a material that achieves an electromagnetic characteristic that is otherwise unobtainable. In particular, a metamaterial may have an electrical permittivity less than that of vacuum ($\varepsilon < \varepsilon_0$), and/or a magnetic permeability less than that of vacuum ($\mu < \mu_0$). In particular, both ε and μ may be less than zero, which provides a material that has negative index of refraction $\mathbf{n < 0}$. In such a "negative index" material, the propagation of electromagnetic radiation is time-inverted, and evanescent waves in such a material increase rather than decrease with distance. [2]

Such characteristics cannot be achieved by ordinary materials; instead a metamaterial creates these properties by structural means. Typically the structures are arrays of small resonant structures, tuned to achieve resonance at either just slightly higher or just slightly lower frequencies than the desired operating frequency. To achieve a "smooth" behavior of the metamaterial, these structures are much smaller than the free-space wavelength of the electromagnetic waves (the unit cell size α of each resonator is smaller than $\lambda/10$, and for radio frequencies the structures are much smaller ($< \lambda/100$)

III. Coupled Resonators

Metamaterials provide a local method of manipulating the electromagnetic field of a wireless power system. However, they do not provide a sufficient range for most applications, including mobile applications.

To improve on the range, we also consider the use of multiple coupled resonators. These coupled resonators are not driven by direct connection, instead the energy is carried between resonators by wireless means (typically, by the magnetic field). By careful design of such resonators, the zone of effective reception of wireless power can be made very large – 10-20x larger than the dimension of any individual resonator, with very high efficiency.

IV. Simulation and Analysis

We will now consider computer-based simulations of a wireless power system using a pair of resonators (classic Tesla configuration) and examine the impact of a metamaterial on efficiency.

We modeled the following structure in COMSOL – a pair of non-resonant drive and receive loops, each 0.25m in diameter and driven at a "thin" insulating gap in the ring, spaced 0.25m from a pair of 0.5m diameter capacitively-loaded single-turn resonant loops; the loops were spaced 1 meter apart.

The control for this experiment is the system as described; we then re-simulate the identical system, but with the addition of a slab of metamaterial with the properties $\varepsilon = -1$ and $\mu = -1+0.05i$. Figure 1 shows a visualization of this arrangement.

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1 US patent 1,119,732, "Apparatus for Transmitting Electrical Energy"

2 It should be noted that this is not a "time machine"; causality is maintained. It is the phase velocity that becomes negative, not the group velocity or the information and energy flows.

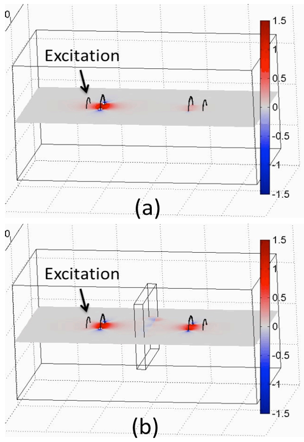


Figure 1: Field intensity in a wireless power system, before and after the introduction of a metamateral slab. Note that the receive coil on the right is excited much more effectively with the addition of the metamaterial

To confirm the behavior of the material, we constructed several realizations of the metamaterial using printed circuit technology on Rogers RO4003C substrates, with spiral resonators. The unit cell is 6.5cm x 6.5cm. A via connects the two opposing spirals, to form the equivalent of a doubly-wound coil. The RO4003C material itself forms the capacitor dielectric between the copper circuit traces on each side, giving these spiral structures a nominal resonance at approximately 24 MHz. At our desired operating frequency of 27 MHz, the material has an effective μ very close to -1. We tested both a full 3-dimensional metamaterial slab as well as a 1-dimensional slab of two sets of coils separated by approximately 2 cm (exhibiting negative ε and μ only in the Z direction, between the transmit and receive coils, as shown in figure 2; the completed test system is shown in figure 3.

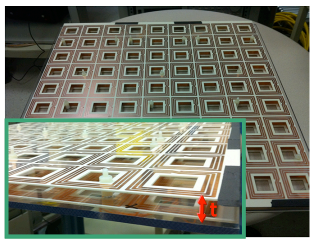


Figure 2: Metamaterial slab

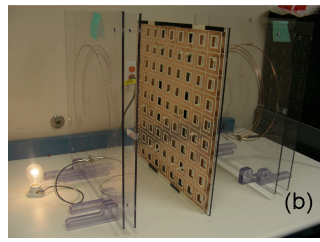


Figure 3: metamaterial test jig

The Z-only slab actually had considerably lower losses, as the X and Y orientations carry essentially no power to the receiver.

IV: Metamaterial Slab Results

The results showed the viability of this method; with a 50 cm gap between the 50 cm spiral resonator loops and a Z-only metamaterial, the efficency of the system went from 17% with no metamaterial up to 47%. Of course, the metamaterial itself was frequency sensitive and so as the frequency varied, so did the index of refraction of the metamaterial, which caused the efficiency to fluctuate as shown in figure 4.

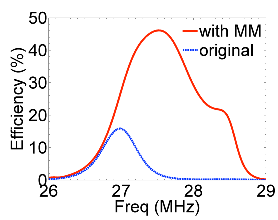


Figure 4: Transfer efficiency versus frequency for metamaterial slab

The frequency of most efficient transmission of the metamaterial-based system was neither the resonant frequency of the metamaterial (24 MHz) nor the frequency of optimal transmission without metamaterial (27 MHz); the peak efficiency of 47% occurred at 27.5 MHz.

With this effect in mind, we then considered the problem of producing a much longer range wireless power system.

V. Repeated Resonant Transfer Arrays

Although the metamaterial-based system allows transfer of energy at reasonable efficiencies over distances roughly equal to the resonant loop size, there are many situations where the motion of the receiver during operation may be much larger. For example, many factory automation systems presume the use of mobile industrial robots carrying workpieces from one machine tool to another, or from the machine tool area to the storage area and vice versa. Although batteries are a possible solution, a vehicle that must be recharged regularly is a liability in a 24-hour industrial process.

Toward that end, we considered the possibility of continuous wireless power transfer to a moving vehicle by a planar array of resonators. Figure 5a and 5b give a schematic view; in 5a we see the classic axial resonant transfer, and in 5b the planar form. The buried Tx antenna couples energy into the planar array, while the mobile resonator and pickup loop extract the energy for the mobile robot's operation.

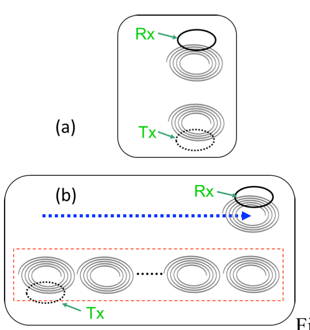


Figure 5: Planar resonator array (schematic view)

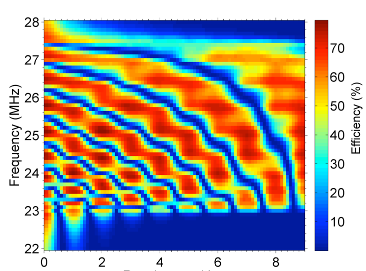
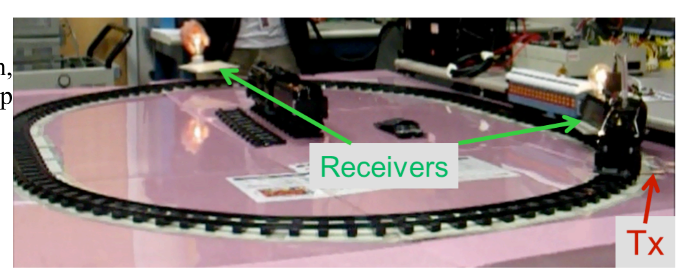


Figure 6: Predicted efficiency of resonant transfer array

We then simulated the linear array in COMSOL to determine the likelihood of actual functionality. Figure 6 shows the result; a relatively high efficiency, varying with position and drive frequency. Multiple simultaneous power recievers are supported.

To verify this concept, we modified a children's toy train set with tracks equipped with resonators (forming the planar array); the resonators were again of Rogers RO4003C and were coupled together only magnetically. The train carried a moving resonator and a nonresonant pickup loop. On board the train, a Shotty diode bridge rectified the 27 MHz RF from the pickup loop



into relatively high voltage (50 – 200 volt) DC, and a switching power supply converted that voltage down to 5VDC to operate the traction motor. A telemetry system uplinked the operating voltages continuously during operation. This system is shown in figure 7. The system operated as predicted, with nulls and peaks as expected; the positions of the nulls were dependent on the RF drive frequency (26.5 to 27.5 MHz).

We then implemented a frequency-optimization program for maximizing energy transfer to the moving train via extremum-seeking and linear prediction algorithms. However, the phase margin and telemetry rate of our system (~1 Hz) was inadequate to validate the results with statistical significance.

VI. Conclusions and Further Work

We conclude that metamaterial-assisted resonant transfer over ranges less than or equal to the dimensions of the resonant coil can approach 50% efficiency. More usefully, a resonant-transfer array can provide brushless, human-safe energy transfer to mobile platforms at useful efficiencies and scale.