Constructing and Experimenting on a Magnetic Metamaterial Lens for Improved Wireless Power Transfer Efficiency

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INTRODUCTION

Wireless power transfer is an interesting topic due to the many conveniences it can bring to daily life. Wirelessly charging phones, laptops and possibly even electric vehicles will eliminate fumbling with wires and greatly increase the versatility of these technological marvels. Although promising, wireless charging faces the difficult task of overcoming the challenge posed by rapidly decaying transfer efficiencies as the distance between the energy transmitter and receiver is increased. Magnetic field lines expelled by the transmitter coil will naturally spread out in all directions as they exit one side of the transmitter and thus the magnetic fields felt by the receiver become weaker and weaker with increasing distance. One approach to counter this problem attempts to "bend" magnetic field lines back toward the center as they radiate away from the transmitter by means of a material with a negative magnetic permeability.

This technical paper details the design, construction and testing of various "metamaterial" lens based on the metamaterial cell design described in "Magnetic Metamaterial Superlens for Increased Range Wireless Power Transfer" by Urzhumov et al. as published in Nature journal January 2014. The described cell consists of a tank circuit capable of capturing and reproducing magnetic fields over a large distance when driven at its resonant frequency. Conductive traces on both sides of the cell form inductances with a capacitor sandwiched between the coils with the printed circuit board's substrate backbone acting as the capacitor dielectric. The conductive traces are wound in such a way that a varying magnetic field impacting the cell induces a voltage and a current which moves charge to one end of the conductive loop and creates the capacitive effect. If driven at its resonant frequency the cell can accumulate and reradiate energy in the form of a farther reaching magnetic field.

TECHNICAL APPROACH

The single 4cm^2 cell was designed using the PCB Artist software provided by Advanced Circuits according to specifications detailed in the aforementioned paper. The single metamaterial slice is essentially a two layer, 10mil (.0254 cm) thick square PCB with conductive traces wound into inductive loops on either side of the board. The substrate is Rogers4350 laminate, chosen for its low dielectric loss constant. The design features 17 turns of .2cm PCB on each side, wound in a continuous pattern when viewed from the same side of the slice (a monotonic magnetic field will induce currents that can travel continuously through the top and bottom traces.)

Once printed, the cells were assembled into a 3D array held together by a plastic skeleton designed in SolidWorks and printed on a 3D printer. A major requirement of the array was reuse capability which meant that the lens could not be held together via permanent means (i.e. glue.) The skeleton was thus designed to be held via friction (and four optional rubber bands around the perimeter of the completed lens.) Identical X-shaped pieces were printed and assembled together to form the face of the lens, with slightly larger pieces used to hold the lens together longitudinally. The entire design required no adhesives and can thus be disassembled and reassembled at any point for maximum versatility.

A miniature version of the lens described in the paper was built and analyzed during different tests. The constructed lens had dimensions of 9x9x2 single cells and was assembled from individual cell elements held together by the plastic skeleton. Additional tests were also performed to analyze the performance of individual cells and smaller cell combinations on wireless power transfer of coils of different sizes. All the performed experiments measure the output voltage of the receiving coil as a function of the distance between the receiver and transmitter and some also include the frequency at which the test was performed (every setup had its natural frequency that is constrained by its physical layout). The coils are facing each other i.e. they are located in planes whose normal vectors are parallel and have identical physical characteristics (diameter, number of turns, wire gauge and type, etc.). For each test, the transmitting coil is driven by signal generator and the receiving coil is connected to a

1Mohm oscilloscope channel. The results are measured with 64 averages done by the oscilloscope and with an input voltage of 21.6 volts peak to peak.

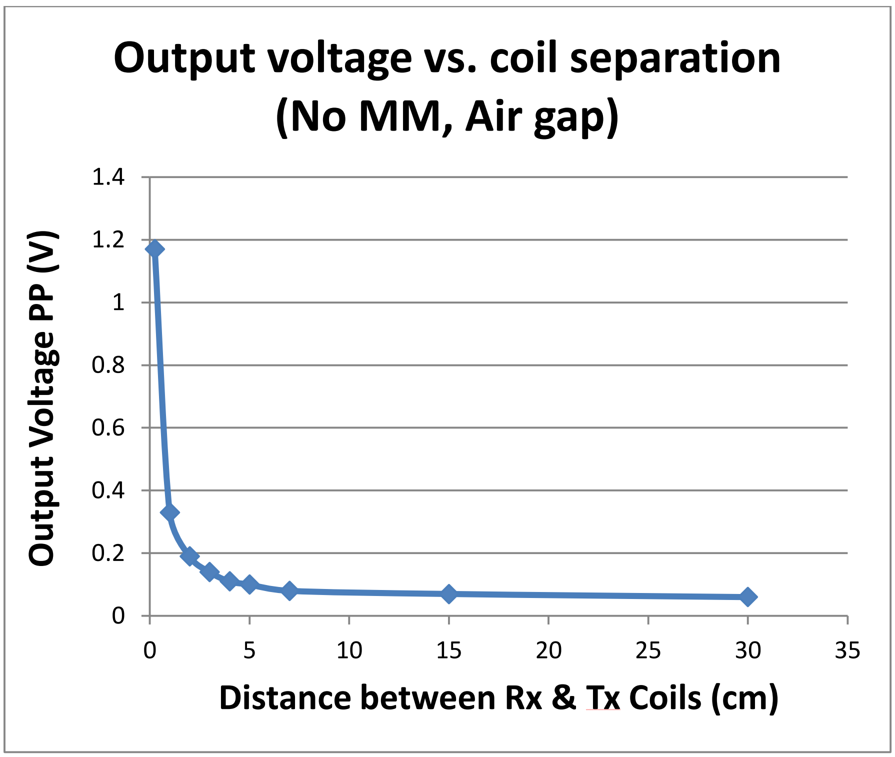
Three coil designs are used in these experiments (all distance measurements in cm):

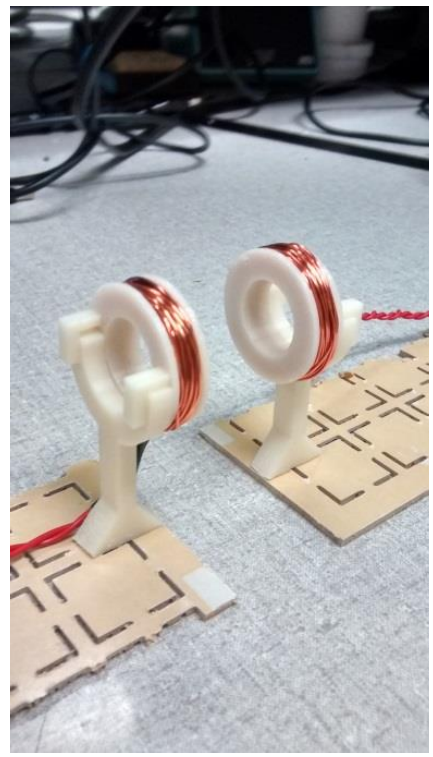
Minimum diameter	2	4	15
AWG (Wire diameter)	21 (.071)	21 (.071)	27 (.036)
Number of wire turns	49	13	49
Length	.58	.58	.58
Inductance (uH)	68	not measured	

EXPERIMENTATION & DATA

Experiment 1

2cm diameter coils, no metamaterial structures between coils





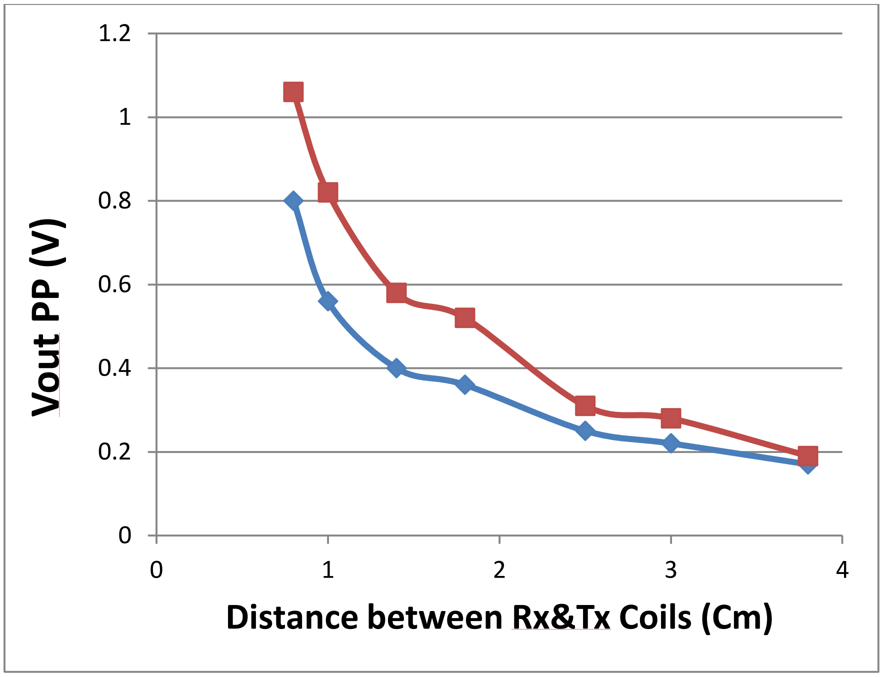
This test measured the output voltage of the receiver versus distance from the transmitter. The coils are wound on 3D-printed bobbins held by plastic stands and are driven by a 13.56MHz since wave. Stray inductances are minimized by using a twisted pair of wires leading to and away from the coils.

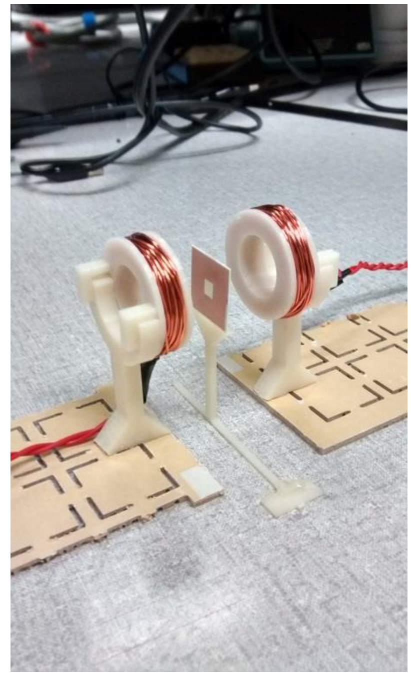
The results of this experiment demonstrate the rapid decay of transfer efficiency with increasing transfer distance. The measurements made at distances above 5cm are at the noise limit which is represented by a horizontal asymptote.

Experiment 2

2cm diameter coil, single MM (metamaterial) slice

This test measured the output voltage of the receiver versus distance from the transmitter. The diameter of both coils is 2cm. The transmitting medium between coils is air and a single slice of metamaterial that is always located halfway between the receiver and transmitter coils. The normal vectors of the planes of the coils and the slice are parallel. The coils are wound on 3D printed bobbins held by plastic stands. The coils are of the following specifications: 49 Turns, 21 AWG wire (D = .028"), minimum diameter = 2cm, Length = .23”, L=68uH. The test is performed at a constant frequency of 11.8 MHz, sine wave.

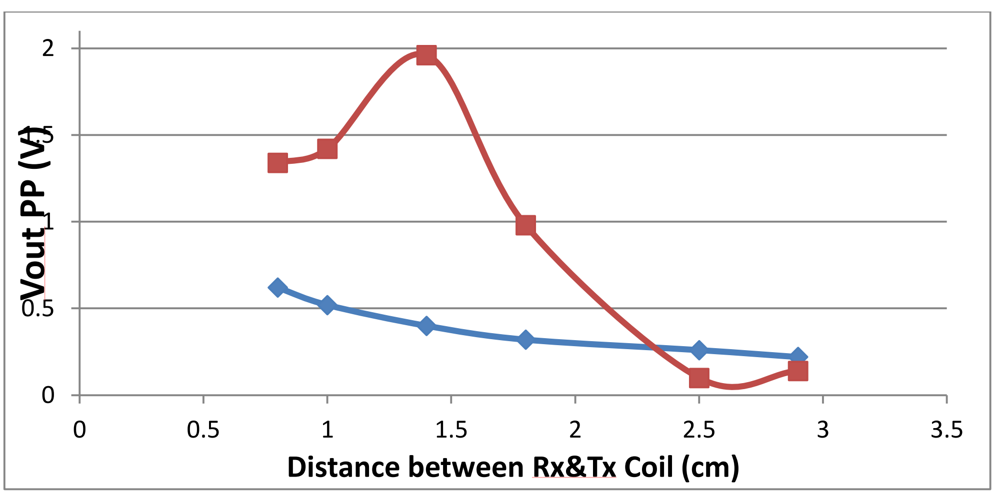




This test demonstrates the slight increase in output voltage with the presence of a metamaterial cell between the receiver and transmitted coils. As this earlier test was performed at the resonant frequency described in the Nature paper, it did not operate at the optimal frequency for this particular setup. The red curve shows the output with the MM slice present and the blue, without.

Experiment 3
2cm diameter coil, single MM (metamaterial) slice

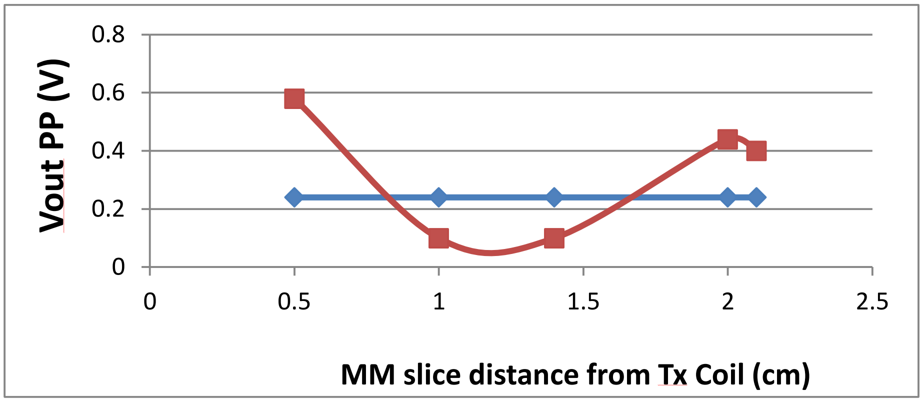
This test measured the output voltage of the receiver versus distance from the transmitter. The transmitting medium between coils is air and a single slice of metamaterial located at the midpoint between the receiver and transmitter coils. The transmitter coil is driven by a 12.885MHz sinusoid. In the following graph, the red curve shows the output with the MM slice present and the blue, without.



This test demonstrated the large improvement in efficiency achieved via the metamaterial slice at smaller (less than a diameter of the coils) distances. As the coil separation increases past one coil diameter, the efficiency decreases. Since this test was performed at a constant frequency that did not vary with coil separation, it is expected that the efficiency improvement would not be consistently high. The efficiency peak at approximately 1.5cm separation distance can likely be attributed a resonance achieved with that particular geometric configuration of the metamaterial slice and coils.

Experiment 4

2cm diameter coil, single MM (metamaterial) slice at varying distances from transmitter coil

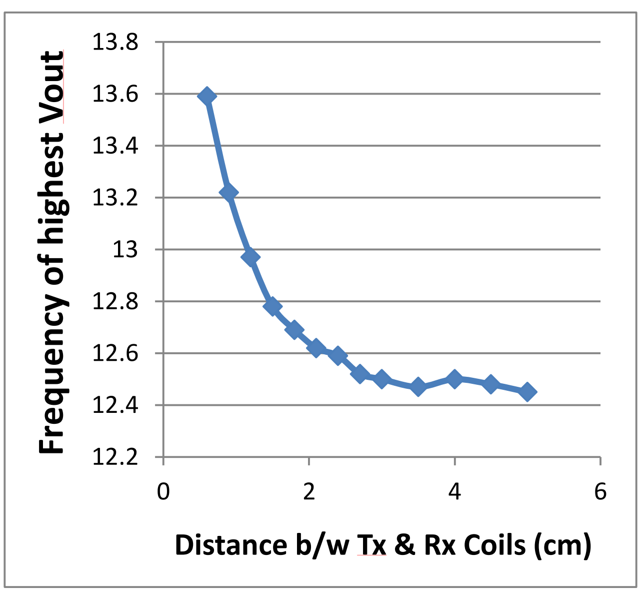


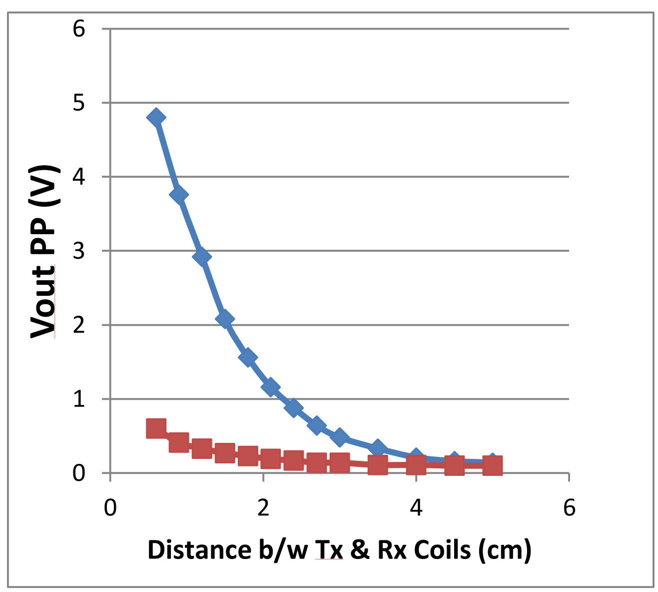
This test measured the output voltage of the receiver versus the MM slice's distance from the transmitter coil. The transmitting medium between coils is air plus a single slice of metamaterial that is located at various distances from the transmission coil. The coils themselves are held at a constant separation of 2.5cm. The transmission coil is driven with a 12.885MHz sinusoid. The red curve shows the output with the metamaterial slice present and the blue, without.

This tests demonstrates that, for this particular frequency, the output voltages are higher when the metamaterial slice is closer to one of the coils than when the system is symmetric. The data shows that the metamaterial may even have a detrimental effect on efficiency (as opposed to none at all) if the frequency is chosen poorly for each physical setup.

Experiment 5

2cm diameter coil, single MM (metamaterial) slice halfway between coils with frequency adjustment



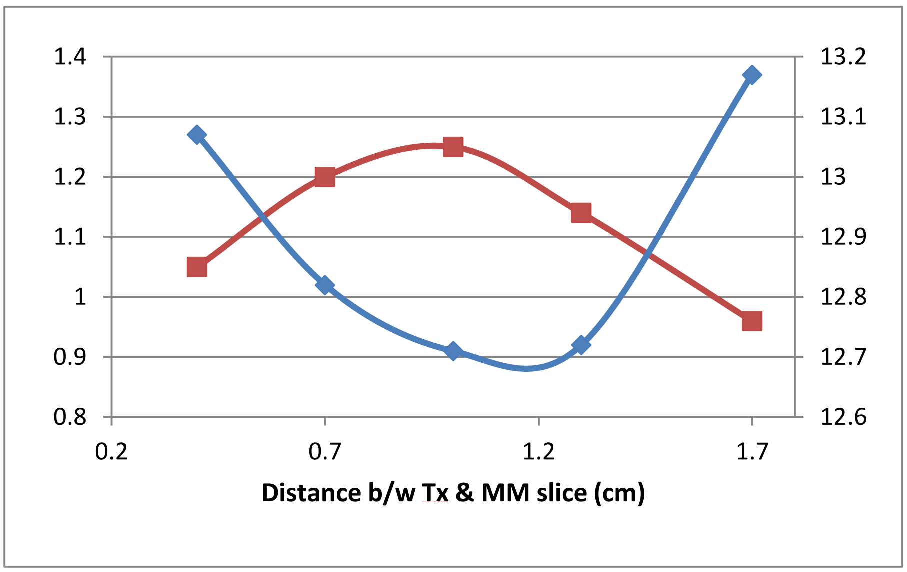


This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The transmitting medium between coils is air plus a single slice of metamaterial that is located halfway between the receiving and transmitting coils. This test was performed by first adjusting the frequency for every separation distance until the maximum output voltage was measured (with the MM slice inserted) and then recording that output voltage – the optimal frequency is recorded on the left chart and the corresponding voltage levels on the right. The blue curve shows the output with the metamaterial slice present and the red, without.

This test demonstrates that adjusting the frequency of operation for every separation has a big impact on the output voltage and thus efficiency. Increasing the coil separation decreases the optimal frequency, which is expected. With this method, an improvement in transfer efficiency can be seen at distances up to twice the coil diameter. The metamaterial slice most likely provides noticeable improvement even beyond the ranges measured here but due to the noise asymptote the true voltage levels could not be observed with the present setup.

Experiment 6

2cm diameter coil, single MM slice at varying distances between coils with frequency adjustment



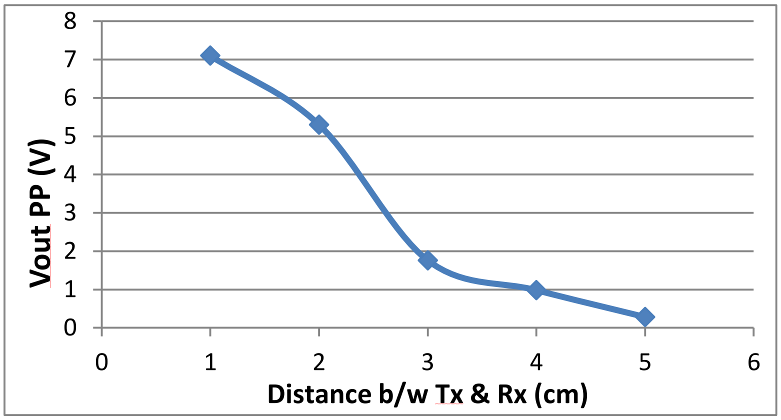
This test measured the output voltage of the receiver versus the MM slice's distance from the transmitter coil. The transmitting medium between coils is air plus a single slice of metamaterial that is located at various distances from the transmitting coil. The coils themselves are held at a constant separation of 2.5cm. The coils are wound on 3D printed bobbins held by plastic stands. For every MM distance, the optimal frequency (with MM slice inserted is found and the output voltage is measured at that frequency. The blue curve plots frequency (right axis, in MHz) and the red curve plots output voltage peak-to-peak in Volts.

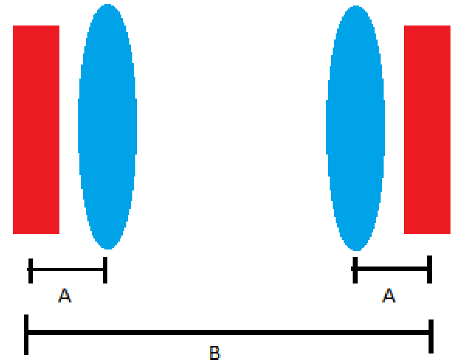
This test shows that the case with symmetrical placement of components yields the best results when adjusted for frequency. Placing the MM cell half way between the receiver and transmitter and yields best results when the driving frequency is tuned to the optimal frequency of the setup.

Experiment 7

2cm diameter coil, single MM slice in front of each coil (two slices total) with frequency adjustment

This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The transmitting medium between coils is air plus a single slice of metamaterial located in front of each coil. In the diagram on the right the red rectangles represent coils and the blue ovals the single slices. The x-axis variable (distance between transmitting and receiving coils (cm)) is dimension B and dimension A (distance between each coil and its MM slice) is fixed at .25cm. The frequency was also adjusted for every separation but it turned out that the optimal frequency for every value of dimension B was 13.31MHz.

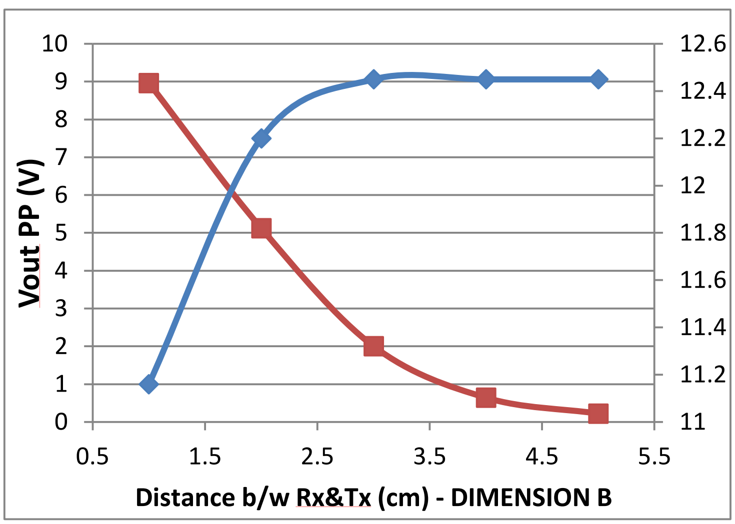


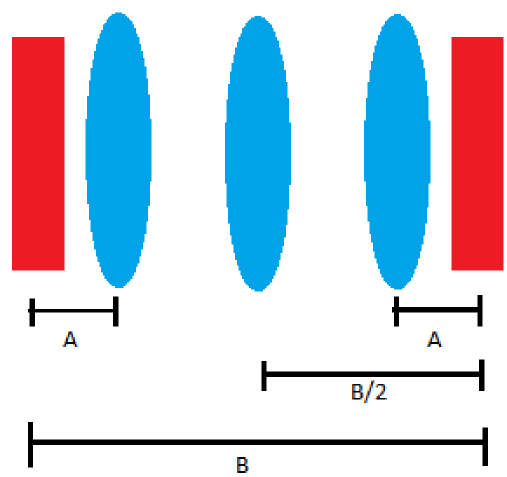


This test shows that using two cells yields much better results than a single slice in the middle. At a separation of 4cm, which is twice the coil diameter (a significant distance for such small coils), the output voltage is 1 volt, which is slightly lower than 5% efficiency. This experiment also shows that the optimal frequency of such a setup depends on dimension A and not on dimension B.

Experiment 8

2cm diameter coil, single MM slice in front of each coil and third slice halfway between (three slices total) with frequency adjustment



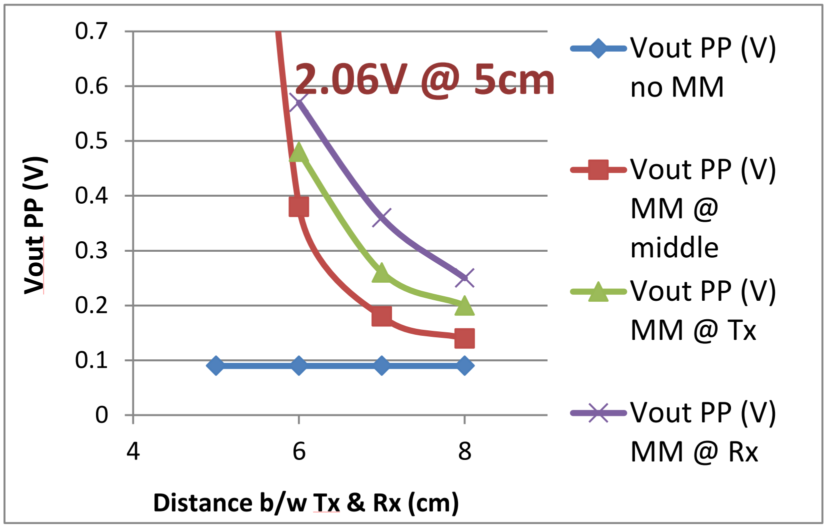


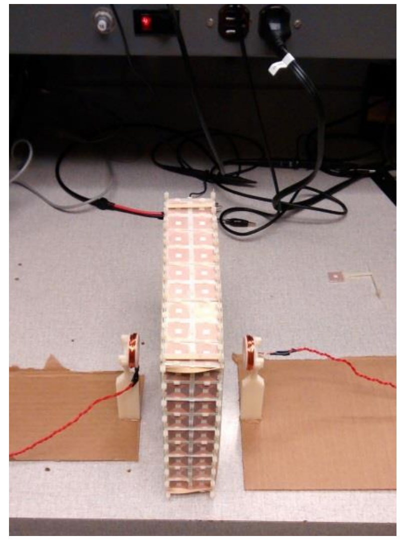
This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The transmitting medium between coils is air plus three MM slices – one in front of each coil and one in the center. The x-axis variable (distance between the transmitting and receiving coils (cm)) is dimension B and dimension A is fixed at .15cm. The frequency at each separation was adjusted and the output voltage recorded at the optimal frequency for the setup. On the left chart the blue curve represents frequency of measurement (right axis) and the red curve represents output voltage at the frequency (left axis).

This test shows that using three slices works better than two slices for shorter distances but the effect appears to decay more rapidly for larger distances. Interestingly, the optimal frequency increases for larger distances which is contrary to previous results. However, this may be because the higher frequency peak (of the multi-peak resonant system) was captured in this experiment due to it producing a higher output voltage.

Experiment 9

2cm diameter coil, 9x9x2 MM lens between coils with frequency adjustment





This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The transmitting medium between coils is air plus a single 9x9x2 MM lens. The voltage chart displays three different curves for output voltage in the presence of the MM lens: MM @ middle = MM lens halfway between coils, MM@Tx = MM lens up against and as close as possible to the transmitter and MM@Rx = MM lens up against and as close as possible to the receiver.

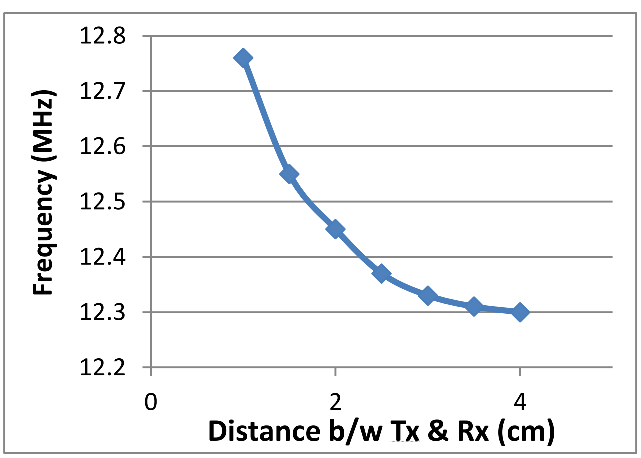
This test shows that the metamaterial has a large impact on the transmission efficiency. Filling up the inter-coil space with the metamaterial lens instead of air gives a more than 20x improvement over noise, which may correspond to an even larger improvement over actual signal voltages. Varying the location of the metamaterial within the space also seems to make a difference in the transmission efficiency. The frequencies at which the above measurements were adjusted for optimum with the MM lens inserted and are as follows, in MHz: 5cm = 13.14, 6cm = 13, 7cm = 12.89, 8cm = 12.89.

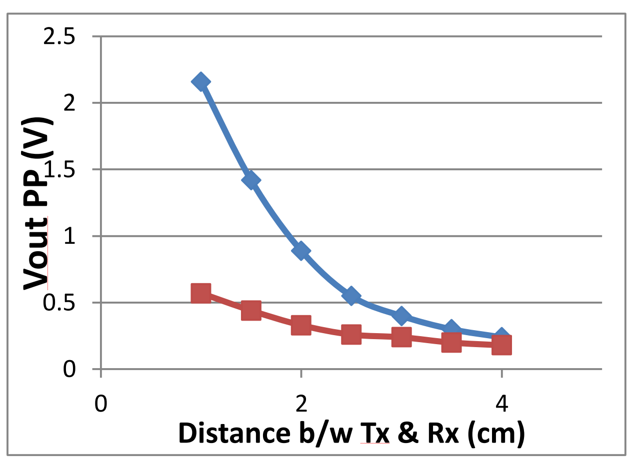
The data acquired form this test is very supportive of the metamaterial's role in increasing the efficiency of wireless power transmission.

Experiment 10

2cm diameter coils, 3x3 MM slice between coils

This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The transmitting medium between coils is air plus a 3x3 MM slice (i.e. an array of single slices three slices wide and three high.) As in previous tests, the optimal frequency for every separation is found and plotted on the left – the voltage measurement is then done at this frequency and plotted on the right.

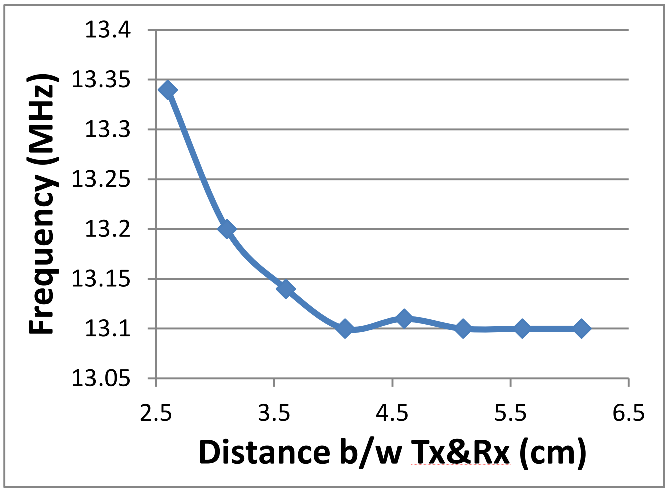


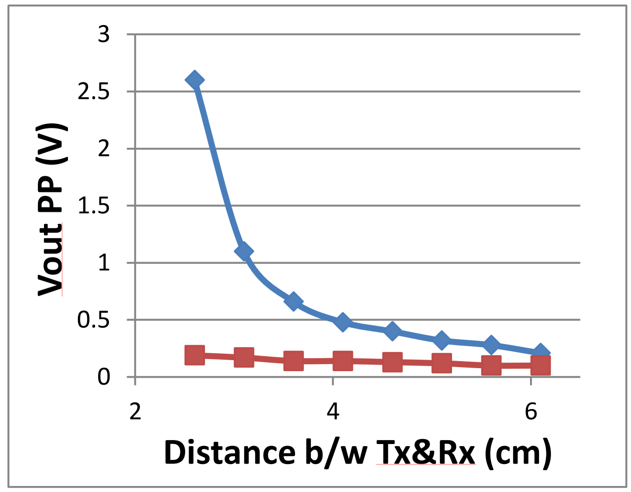


This test shows that using a 3x3 slice made of nine MM cells does not yield a significant improvement in transfer efficiency over a single MM cell for coils of this size. This is likely due to the already large ratio of slice to coil size. From this and the single MM slice tests it is shown that the cross-sectional locations of the MM cell versus the coil are more important aspects. The 3x3 setup in this test yields slightly worse results than a single MM slice possibly because it was not ideally centered with the coil and thus does not optimally capture and re-radiate the magnetic flux.

Experiment 11

2cm diameter coils, 3x3x1 mini MM lens between the coils with frequency adjustment



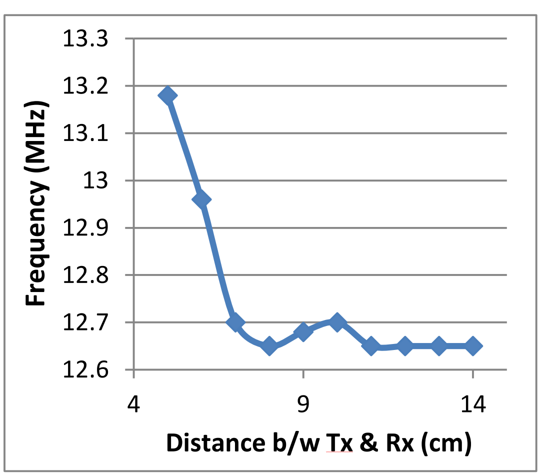


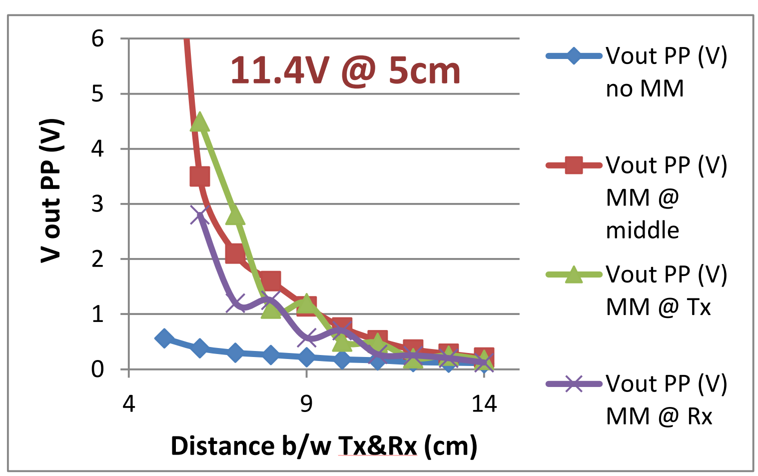
This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The transmitting medium between coils is air plus a single 3x3x1 (essentially the above structure but 1 slice thick) mini MM lens. As in previous tests, the optimal frequency for every separation is found and plotted on the left – the voltage measurement is then done at this frequency and plotted on the right.

This experiment shows that the performance of a 3x3x1 lens is comparable to that of a 9x9x2 lens for comparable distances between the coils and the lens. The small size of the coils means that the fields that radially extend past the 3x3 array are not significant in the system and do not carry much energy. The thickness of the lens is the deciding factor of absolute efficiency over any range, and inserting a thicker lens into a system of fixed distance between the coils yields larger efficiency but keeping the distance of the air path in the system constant does not appear to impact the efficiency regardless of the lens thickness used.

Experiment 12

4cm diameter coils, 9x9x2 MM lens between coils with frequency adjustment



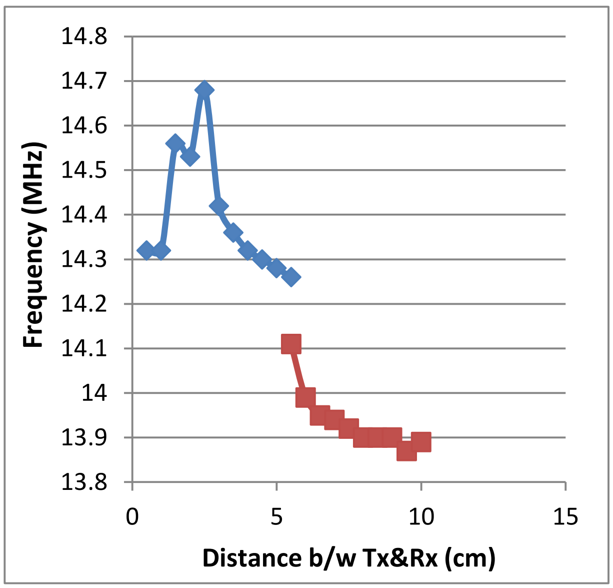


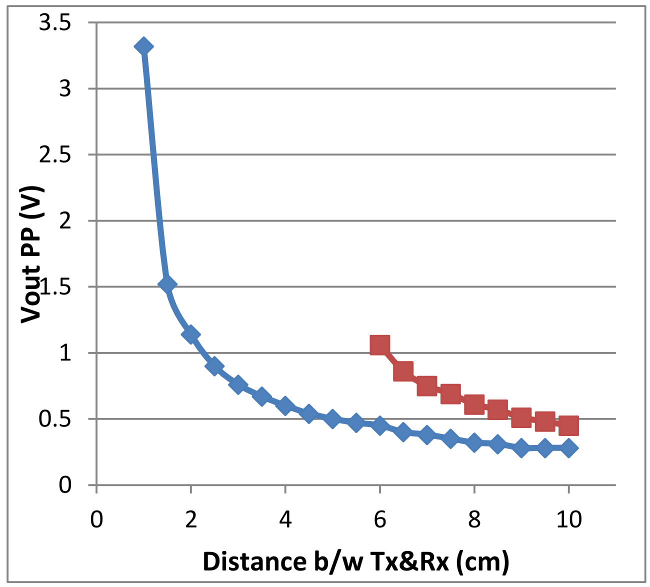
This test measured the output voltage of the receiver versus the distance between the receiver and transmitter coils. The diameter of both coils is 4cm. The transmitting medium between coils is air plus the full 9x9x2 MM lens. The normal vectors of the planes of the coils and lens are parallel. The coils are wound on 3D printed bobbins held by plastic stands. The coils are of the following specifications: 13 Turns, 21 AWG wire (D = .028"), minimum diameter = 4cm, Length = .23. As in previous tests, the optimal frequency for every separation is found and plotted on the left – the voltage measurement is then done at this frequency is plotted on the right. The voltage chart displays three different curves for output voltage in the presence of the MM lens: MM @ middle = MM lens halfway between coils, MM@Tx = MM lens up against and as close as possible to the transmitter and MM@Rx = MM lens up against and as close as possible to the receiver.

This test demonstrates that using a larger coil with the metamaterial lens yields much larger output voltage for distances close to the metamaterial. This occurs because equivalent distances for a larger coil provide (to an extent) greater coupling and "look like" shorter distances for an equivalently sized coil. Of interest is the behavior of the curves that display the efficiency for the cases when the MM lens is not perfectly in the middle. The curves oscillate and periodically dominate and subside under the other. This is an interesting phenomenon and is mostly likely somehow caused by the driving frequency of the system.

Experiment 13

15cm diameter coils, 9x9x2 MM lens between coils with frequency adjustment





This test measures the output voltage of the receiver versus the distance between the receiver and transmitter coils. The diameter of both coils is 15m. The transmitting medium between coils is air plus the full 9x9x2 MM lens. The normal vectors of the planes of the coils and lens are parallel. The coils are wound on 3D printed bobbins held by plastic stands. The coils are of the following specifications: 49 Turns, 27 AWG wire (D = .014"), minimum diameter =15cm, Length = .23. As in previous tests, the optimal frequency for every separation is found and plotted on the left – the voltage measurement is then done at this frequency is plotted on the right. The frequency plot is divided into two curves – the blue curve are the optimal frequencies for distances less than the metamaterial thickness and are thus the frequencies for optimal transmission through air (MM lens could not fit). The red curve is the frequencies which were measured in the presence of the metamaterial.

This experiment shows that the metamaterial has an impact even when the entire 9x9x2 lens (side length ~20cm) is almost the same size as the coils used. Unfortunately, the large increase in coil diameter with no increase in coil length meant that the efficiency vs. distance measurements could not scale and thus the efficiency falls off as fast as for smaller coils. This could be attributed to the fact that the large ratio between coil radius and length requires increasing use of the thin current loop approximation for magnetic fields as opposed to an infinite solenoid approximation, which would state that the total flux inside the loop would increase with area. Although the area does increase as the square of the radius, the flux per unit of area decreases as the square of the radius as well and thus no large gains in total flux produced can be made. Therefore, the larger coils behave similarly to the smaller ones.

CONSLUSION

These experiments demonstrate the large potential of the metamaterial concept for increasing wireless power efficiency through air or free space. Although the gains seen in these experiments are small for distances relatively far from the metamaterial, they are significant enough to warrant further study of the concept. It is possible that the metamaterial provides large gains over distances much larger than those measured here but in order to detect those gains more sensitive and noise-immune measurement equipment must be used. The noise asymptote is around 160mV in all the experiments – this means that it is impossible to detect the true level of MM-less transfer for levels below this with the simple oscilloscope method used here. More sensitive equipment, such as a lock-in amplifier, would have to be used for more accurate results.

The results of these tests can also be used to devise some future approaches. One interesting further experiment would be to see how well the gains from the MM lens can be combined with the natural resonant frequency of the MM-less setup. For example, the natural frequency of the two 15cm coils spaced a few centimeters apart is in the 2MHz range – building a MM lens with its resonant frequency in this range as well could potentially yield a larger boost. In general, further experiments should be oriented toward decreasing the resonant frequency of the metamaterial resonator to levels for which there is already sufficiently developed hardware for practical wireless power transmission. Overall this is a promising technology which can be exploited in many creative ways for large improvements in wireless power transfer.