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Magnetic Metamaterial Superlens for Increased Range Wireless Power Transfer

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The ability to wirelessly power electrical devices is becoming of greater urgency as a component of energy conservation and sustainability efforts. Due to health and safety concerns, most wireless power transfer (WPT) schemes utilize very low frequency, quasi-static, magnetic fields; power transfer occurs via magneto-inductive (MI) coupling between conducting loops serving as transmitter and receiver. At the “long range” regime – referring to distances larger than the diameter of the largest loop – WPT efficiency in free space falls off as $(1/d)^6$; power loss quickly approaches 100% and limits practical implementations of WPT to relatively tight distances between power source and device. A “superlens”, however, can concentrate the magnetic near fields of a source. Here, we demonstrate the impact of a magnetic metamaterial (MM) superlens on long-range near-field WPT, quantitatively confirming in simulation and measurement at 13–16 MHz the conditions under which the superlens can enhance power transfer efficiency compared to the lens-less free-space system.

The superlens, which can refocus not only propagating far-field waves but also non-propagating, near-field waves, has been one of the more provocative concepts to emerge from the field of metamaterials¹. A superlens comprises a medium whose electric permittivity ϵ and magnetic permeability μ both take on the value of -1 . The superlens structure offers a means of controlling and manipulating the near-fields that would otherwise decay rapidly away from a source. Initially, the superlens was proposed in the context of optics, where its use was suggested as a means of forming an image with resolution greater than that implied by the diffraction limit^{2,3}. The superlens functions via the excitation of magnetic and electric surface modes that couple to the near fields of an object placed on one side of the slab, subsequently bringing them to a focus on the opposite side. Since electricity and magnetism are nearly decoupled in the near field, it was realized early on that a superlens with either $\epsilon = -1$ or $\mu = -1$ could focus the near field of electric or magnetic sources, respectively. Imaging with a superlens has been demonstrated at visible and infrared wavelengths using thin layers of materials such as silver or silicon carbide whose dielectric functions take the value of $\epsilon = -1$ at particular wavelengths⁴.

At low frequencies, where magnetism is much more prevalent, superlenses based on structured metamaterials characterized as artificial magnetic permeability media have been pursued for a variety of applications, including as flux guides to enhance resolution in magnetic resonance imaging^{5,6}. More recently, as interest in WPT schemes has risen, the use of superlenses and other metamaterial-based components to enhance transfer efficiency has been suggested⁷. At the low frequencies typical of inductive WPT schemes, the excitation wavelength exceeds 10 m, whereas the dimension of the coils and loops is on the decimeter or centimeter scale. Thus, the loops can be initially approximated as magnetic dipoles as a route to gaining an intuitive understanding of the limits and behavior of the WPT system.

A general treatment of a magneto-inductive WPT system was carried out by Kurs et al., who made use of coupled-mode theory to calculate the expected efficiency of two self-resonant coils separated by a distance d in free space⁸. In that work and the subsequent analysis of Urzhumov et al.⁹, power transfer efficiency is defined as the power dissipated in a load placed on the receiver coil (R_x) divided by the total power dissipated in the transmitter (T_x) and receiver circuits, as well as in any intermediate “relay systems” (such as a repeater coil, lens or metamaterial layer):

$$\eta = \frac{W_{Rx}}{W_{Rx} + W_{Tx} + W_{Relay}} \quad (1)$$

Once the Rx and Tx circuits and an optional relay system are specified, power dissipation rates can be calculated using the coupled mode theory for arbitrary Rx and Tx configurations⁸, or the simplified coupled-dipole formalism for small resonant coils⁹. Coupled mode theory treats the Rx and Tx coils as resonators whose interaction is indicated by a mode coupling coefficient, κ , whereas the coupled-dipole theory uses the conventional notion of mutual inductance, L_{21} . Both theories predict the same long-range behavior for the WPT efficiency (1), namely, $\eta \sim d^{-6}$. The physical origin of this power law is due to the $1/d^3$ dependence of magnetic field in the near field of a magnetic dipole source. The overall system efficiency in magneto-inductive schemes is therefore inherently limited by the divergence of magnetic flux in free space, because power transfer is ultimately related to the amount of flux from the first coil that can be captured in the “aperture” of the second coil. Given that any coil or loop will behave roughly as a magnetic dipole, it is unlikely that any redesign or engineering of the coils can possibly enhance WPT efficiency of any system that is already optimally impedance-matched.

If the efficiency of a resonant WPT system is to be improved, a means must be found to recapture and refocus the otherwise divergent magnetic flux. Traditional lenses based on conventional materials only focus the far-fields, and therefore are irrelevant to this application. Near-field lenses of several configurations^{10–12} have been proposed; however those configurations provide partial field focusing with efficiency significantly lower than the perfect focusing promised by the superlens¹³.

The use of a near-field superlens in conjunction with resonant power transfer was first considered by Wang et al.¹⁴. Earlier, similar metamaterial lenses were proposed for magnetic resonance imaging applications^{15,16}. Examining both isotropic¹⁴ as well as anisotropic¹⁷ versions of the negative-permeability medium, these works provided significant numerical evidence, and some experimental evidence, of enhanced efficiency. Here, we address the question raised by the studies in Ref. 14,17, as to whether metamaterial superlenses can improve WPT efficiency (and conversely, reduce power loss) in the long-range near-field transfer regime.

Theoretically, a positive answer to this important question was given in Ref. 9. Figure 1 is based on the analytical solutions from Ref. 9, and it shows that a metamaterial with finite and realistic resistive/magnetic loss can help deliver magnetic flux and generate alternating current in a resonant Rx circuit, leading to overall improvement in WPT efficiency. This performance boost was predicted in the long-range, high-load transfer regime, where both the transfer distance d and the resistive load in the receive circuit exceed

Figure 1 | Wireless power transfer efficiency of a $D = 6$ cm MM superlens (a layer with isotropic $\mu = -1 - i\sigma$) calculated using the coupled-dipole theory⁹. The solid curve is efficiency in free space. Resistances $R_{Tx} = 0.01Z_0$ and $R_{Rx} = 0.1Z_0$.

Figure 2 | Magnetic metamaterial and superlens assembly. (A) Double-periodic array of resonators generating magnetic response in x and y directions. (B) Overall view of a triple-layer superlens with the top z-facing sheet removed. (C) One of the small non-resonant coils used in experiments.

certain thresholds. This Report presents experimental evidence that long-range WPT efficiency using a MM slab can exceed the maximum efficiency obtainable, *ceteris paribus*, in free space.

Results

Negative-permeability superlens design. Geometrically, the superlens is perhaps the simplest possible configuration for near-field focusing: it consists of a uniform layer of isotropic, negative permeability. This property simplifies the superlens design, which could be as simple as a double- or triple-periodic arrangement of identical unit cells. In addition, the superlens is translationally invariant, at least in the large aperture limit, which reduces the need for fine mechanical alignment of the WPT system relative to the lens. Figure 2 illustrates the geometry of our superlens implementation; the unit cell geometry, design, homogenization, and effective permeability are detailed in Methods. The major challenge for designing negative-permeability metamaterials at relatively low frequencies (MHz regime and lower) is the design of sufficiently low loss, strong magnetic dipole resonators of deeply sub-wavelength dimensions. Here, we have opted for unit cells of size ~ 2 cm, and achieved sufficiently large inductance by using multi-turn planar coils¹⁸.

Enhancement of Magneto-inductive coupling with finite aperture superlenses. Once a metamaterial layer with desired effective permeability is designed, we can characterize its effect on the coupling between two magnetic dipoles. We approximate a finite-aperture slab as a disk of the same diameter, which enables highly efficient axisymmetric description along the lines of Ref. 9,17 in a 2D rotationally-symmetric geometry modeled in COMSOL Multiphysics. We use the retrieved permeability components of the metamaterial slab, each fitted to a Lorentzian resonance shape, as the components of the slab diagonal permeability tensor $\mu = [\mu_T \mu_T]$

Figure 3 | Simulated (solid lines) and analytically calculated (dots) enhancement factor $G = T^{\text{slab}}/T^{\text{vac}}$ for transfer distance $d = 16$ cm and a slab with isotropic $\mu = [\mu_N \mu_N \mu_N]$, anisotropic $\mu = [\mu_T \mu_T \mu_N]$, and indefinite $\mu = [1 \ 1 \ \mu_N]$ and $\mu = [\mu_T \mu_T \ 1]$. Insets: $\text{Re}(H_2)$ for the isotropic slab, revealing anti-symmetric and symmetric modes excited at the lower and higher-frequency enhancement peaks.

Figure 4 | Simulated (A) and measured (B) transmission coefficient on dB scale, $10\log_{10}(T)$, of a single-layer triple-negative metamaterial (MM), indefinite MM, and freespace for coil-to-coil distances of 8 cm (blue curves), 16 cm (green curves), and 24 cm (red curves). Simulated (C) and measured (D) $10\log_{10}(T)$ of a 3-layer MM and freespace for the same distances.

μ_N] (assuming all off-diagonal elements are zero and relative permittivity is $\epsilon_r = +1$). The transmitting magnetic dipole is simulated as a current loop of radius $r = 1$ cm carrying a fixed current $I = 1$ A. We define the magnetic field transmission coefficient as $T = |H_{Rx}/H_{Tx}|^2$, where $H_{Tx} = I/2r$ is used to approximate the total field radiating from the Tx loop, and H_{Rx} is the field measured at a point on the axis-of-revolution a distance d away from the loop. It is convenient to define transmission enhancement factor due to the slab, using the ratio of transmission coefficients with and without the slab $G = T^{\text{slab}}/T^{\text{vac}}$.

Since the simulated coil is small relative to the slab and can be approximated as a dipole, we use the simulation results to validate the analytical solutions for the inductance between two dipoles with and without the MM slab (L_{21}^{slab} and L_{21}^{vac} , respectively) as expressed in Ref. 9. In Figure 3 we plot the simulated and analytical enhancement factors (the latter, defined as $G = |L_{21}^{\text{slab}}/L_{21}^{\text{vac}}|^2$, we evaluate numerically with Mathematica). Results indicate that the slab enhances the field transmission coefficient T by roughly a factor of five over an appreciable frequency region. In addition, we observe a striking agreement between simulation and analytical results as a function of frequency.

Measurements of enhancement with non-resonant coils. To experimentally verify the effect of the metamaterial “superlens” on WPT between two coils, we begin by constructing a slab from the fabricated MM. To assemble a 1-layer slab, we first designed the x - and y -oriented MM elements in rows with opposite-facing slits, which can be assembled into a wine-crate pattern, as shown in Figure 2A. The z -oriented resonators were fabricated across a single sheet, which was then placed perpendicular to the wine-crate and held together by additional slits cut around the wine-crate. In a similar fashion, we assembled a 3-layer MM slab (Figure 2B). To demonstrate a dipole-to-dipole WPT system, we used two small copper coils with cross-sectional wire diameter of 1.6 mm wound into a circular loop of radius 1 cm, aligned the coils coaxially and separated by distance d along their shared axis, and connected them to ports 1 and 2 of an Agilent Vector Network Analyzer (VNA). Since our coils are non-resonant, to compute the experimental WPT efficiency from the measured S-parameters we must first remove the losses resulting from the mismatch between the network analyzer and the coils. Calculations needed to account for these losses are detailed below in Methods.

Figure 4 shows the simulated and measured transmission coefficients for free space and in the presence of a 1- and 3-layer slab, across several coil-to-coil distances. In addition, for the 1-layer slab, we report the transmission coefficient of the two indefinite MM layers: one composed of only the z -facing MMs while the other consists of the xy -intersecting MMs.

Figure 5 | (A) Schematic of the metamaterial unit cell suitable for Printed Circuit Board fabrication process. The coils on the opposite sides of the substrate are rotated with respect to each other and connected by vias. (B) Each resonator has 17 turns on each side of a 10 mil substrate. Metal line widths are 200 microns, and the gap between neighboring cells is 1 millimeter. (C) The complete unit-cell consists of three mutually orthogonal resonators. (D) The 3-layer slab is composed of the unit-cells stacked along z .

Figure 6 | (A) Transverse component of the effective permeability for a 1-layer MM slab, calculated using the conventional S-parameter retrieval methods (circles) and the field averaging method (solid line). With the latter method, we can also calculate the normal component (crosses). Blue and orange represent the real and imaginary parts of μ , respectively. (B) The transverse and normal component of a 3-layer slab, retrieved using the Field Averaging method.

Discussion

Our central experimental results as shown in Fig. 4 are generally in very good agreement with numerical simulations, with the exception of the curves corresponding to power transfer distance $d = 8$ cm. The latter case needs additional discussion, considering that the distance from Tx and Rx coils to the surface of the metamaterial slab (of thickness $L = 6$ cm) is only $(d - L)/2 = 1$ cm, or roughly one half of the lateral unit cell dimension (array periodicity). In our numerical simulations (Fig. 4A,C), we first simulate a single period of the 2D array, and retrieve all three principal values of the effective permeability tensor. Then, we replace the slab with a layer of homogeneous magnetic medium having the same complex permeability components as retrieved. In doing so, near field effects not describable in terms of effective magnetic permeability are lost. The physical fields on the surface of an array can be Fourier transformed, and all waves with transverse wavenumbers $k > k_0 = \omega/c$ are necessarily evanescent. However, out of this infinite spectrum, the effective medium description is only adequate for components with $k < k_{\text{Bloch}} = \left(\frac{2\pi}{a}\right)$,

where a is the metamaterial lattice constant. The higher-order Fourier components with $k \geq k_{\text{Bloch}}$ decay rapidly away from the interface – as $\exp(-k_{\text{Bloch}}z)$ or faster. They can be picked up by a near field probe placed at $z = 1/k_{\text{Bloch}}$ (or closer), which corresponds to our measurements taken with $d = 8$ cm. However, these harmonics are negligibly small at distances $d > 15$ cm, which explains the excellent agreement between effective medium models and measurements in that regime (Fig. 4).

To summarize, we have demonstrated that a resonant array acting as an effective medium with negative-definite magnetic permeability enhances near-field transmission of quasi-static magnetic fields between non-resonant magnetic loop antennas. Significant enhancement is seen only at frequencies where at least one component of effective magnetic permeability has a negative real part. The enhancements due to different components of permeability tensor are

investigated (Fig. 3), and it is shown that the strongest effect is obtained when all three components of $\text{Re}(\mu)$ are negative (see Fig. 3, red and blue curves). We attribute the latter effect to the excitation of magneto-inductive surface waves existing in triple-negative permeability layers¹⁹. Enhancements in power transmission coefficient in the range of +15 to +30 dB are observed for all transfer distances from 8–24 cm; those transfer distances are 4–12 times greater than the diameter of both transmitter and receiver coils. Much higher enhancement is anticipated with larger-aperture super-lenses and multi-turn, self-resonant Tx/Rx coils.

Methods

Magnetic metamaterial design and fabrication. Our aim is to design and fabricate an isotropic metamaterial (MM) exhibiting $\text{Re}\{\mu\} < 0$ at 13.56 MHz with minimal losses. Assuming operational frequency close to 13.56 MHz, the free-space wavelength is $\lambda_0 \approx 22$ m; a conventional metamaterial whose elements are roughly $\lambda_0/10$ in size would be far too large for practical implementations. Instead, we must demonstrate the desired behavior with elements whose size is only several centimeters, on the order of $\lambda_0/1000$. To achieve this, we significantly increase the metamaterial unit cell inductance by utilizing the double-sided rotated coil design shown in Figure 5, which sandwiches a substrate between two via-connected multi-turn coils. The coils are rotated with respect to one another to form a composite circuit in which the inductances of two individual coils are added in series, resulting in the total inductance improved by a factor of four relative to the configuration with inductance in parallel.

We form the complete metamaterial unit cell by positioning three identical resonators perpendicular to each other, as shown in Figure 5C, and iteratively tweak the design in CST microwave studio using the standard S-parameters retrievals^{20,21} to obtain $\text{Re}\{\mu\} = -1$ in the desired ISM frequency band.

The figure of merit (FOM) for our design is the inverse loss-tangent ratio at the frequency where $\text{Re}\{\mu\} = -1$:

$$\left| \frac{\text{Re}(\mu)}{\text{Im}(\mu)} \right|_{\text{Re}(\mu) = -1} \approx \frac{1}{2} FQ \quad (2)$$

To minimize the loss tangent we choose a low-loss Rogers 4350 substrate and construct the metamaterial using a 1-ounce (34 μm thick) copper clad; the skin depth in Cu at 10 MHz is about 20 μm . The S-parameter retrieval method lets us compute the transverse permeability components μ_x and μ_y by setting periodic boundary

$$\Gamma_L^* = \frac{S_{22} - \Delta \Gamma_S}{1 - S_{11} \Gamma_S} \quad (11)$$

where $\Delta = S_{11}S_{22} - S_{12}S_{21}$. Substituting (10) into (9) and rearranging the terms results in the quadratic equation

$$\Gamma_S^2 (S_{11} - \Delta S_{22}^*) + \Gamma_S (|\Delta|^2 - |S_{11}|^2 + |S_{22}|^2 - 1) + (S_{11}^* - \Delta^* S_{22}) = 0 \quad (12)$$

yielding the solutions

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1} \quad (13)$$

$$\Gamma_L = \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2} \quad (14)$$

where $B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2$, $C_1 = S_{11} - \Delta S_{22}^*$, $B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2$, and $C_2 = S_{22} - \Delta S_{11}^*$. To convert the recorded S-parameters to $G_{T_{\text{max}}}$, then, one must first calculate (in order) Δ , C_1 , C_2 , B_1 , B_2 , Γ_L , Γ_S and Γ_{in} and use these parameters in (12).

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Author contributions

D.R.S. and Y.U. developed quantitative models for superlens-assisted power transfer and assisted in the analysis of simulations and experiments, Y.U., D.H. and K.S. developed the simulation algorithms, G.L. and K.S. performed numerical calculations, G.L. and P.S. designed PCB layouts, P.S., M.R. and J.E. constructed the metamaterial lens, M.R., J.E., P.S., T.N. and J.S.L. designed and conducted the experiments, and J.S.L. developed the project. All authors participated in discussing the results and writing the manuscript.

Additional information

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