Improving Power Transfer Efficiency of a Short-Range Telemetry System Using Compact Metamaterials

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Abstract—Wireless power transfer using resonant inductive coupling has been employed in a number of applications, including wireless charging of electronic devices and powering of implanted biomedical devices. In these applications, power is transferred over short distances, which are much smaller (\( \sim \lambda/100 \)) than the wavelength of operation. In such systems, the power transfer efficiency of the link is inversely related to the range of operation. The power transfer efficiency is principally a function of the Q’s of the individual coils and the coupling between them. In this paper, we demonstrate improvements in power transfer efficiencies using negative permeability metamaterials by increasing the mutual coupling between coils. A metamaterial slab is designed for operation at 27 MHz and is compact in size. The power transfer efficiency of the telemetry system in free space is compared to that in the presence of the metamaterial placed near one of the coils. The efficiency of the system increased in the presence of the metamaterial even as the free-space separation was held constant. This shows that compact negative permeability metamaterials can be used to increase power transfer efficiency of short-range telemetry systems used in various applications.

Index Terms—Metamaterials, telemetry, wireless power.

I. INTRODUCTION

THE proliferation of wireless charging devices for consumer electronics and electric vehicles, as well as the widespread use of implantable biomedical devices for treatment and monitoring of various medical conditions has led to intense research and development in the field of wireless power transfer [1]–[3]. A typical power transfer system used in these devices consists of a series resonant transmitting coil that is connected to the power source and a parallel resonant receiving coil that is connected to the load. Power transfer occurs through inductive coupling between the coils. The power transfer efficiency of such a system is a function of the Q of the individual coils and the mutual coupling between them [4]. The Q can be improved by optimizing coil design [1]. However, even with a high Q, the coupling is severely limited by the distance between the coils. The power transfer efficiency of a telemetry system decreases with increasing separation of the coils. As the size of the coils is small, there can be a precipitous drop in efficiency over a short distance, which places a serious limitation on the operating range for telemetry systems. This paper presents a means to mitigate this problem using compact negative permeability metamaterials.

It was shown by Pendry [5] that, theoretically, a negative refractive index metamaterial lens focuses the propagating waves and enhances the near-field evanescent waves, thereby achieving perfect image reconstruction. The resolution of the image is only limited by losses in the metamaterial. For the past decade, research and development into realizing these metamaterials has accelerated. The practical realization of materials with negative refractive index [6] presents an interesting possibility for applications in telemetry systems. Since power transfer in telemetry systems is achieved by near-field inductive coupling and metamaterials enhance evanescent near fields, this gives rise to the possibility of improving coupling between coils using metamaterials. The enhancement of evanescent waves using negative permeability metamaterials was demonstrated in [7] and [8].

For an isotropic metamaterial lens, the perfect lens condition requires that the thickness of the slab be equal to the total free-space distance between the object and the image plane [5]. This implies that for small thicknesses of the slab, the coils will have to be very close to the material, and for large separation between the coils, the slab will have to be considerably thicker. However, since the aim of this research is near-field enhancement, as opposed to focusing propagating fields, the slab thickness dictated by the perfect lens condition is not necessarily optimal. A theoretical analysis using the point dipole approximation for resonating coils showed that power transfer efficiency increased when an anisotropic biaxial negative permeability material was placed between the primary and secondary coils [9]. In this case, the metamaterial slab was positioned between the transmitting and receiving coils and it was shown that there is an optimum coupling regime for a given power transfer system, which depends on material losses and resistances connected to the coils. However, in many cases the space between the coils may not be accessible to incorporate a metamaterial (e.g., in a bio-telemetry system where one of the coils is inside the body and placing a metamaterial slab inside the body...
may not be feasible). In such cases, the metamaterial can only be placed near the external coil. It is therefore important, especially for bio-telemetry, that the metamaterial improve performance even when it can be placed only in a very limited area. In this paper, we show that when a metamaterial is placed only in the space that is accessible to the external coil, efficiency increases are still possible. The increase in efficiency is mostly limited by the losses in the metamaterial. Moreover, the particular application being considered imposes its own limitations on the physical size of the metamaterial slab to be used. There is a tradeoff involved in designing a compact metamaterial slab that is also low loss. In this paper, we design a low-loss metamaterial that not only improves power transfer efficiencies, but is also compact enough to be useful in a variety of short-range applications.

A demonstration of the metamaterial coupling enhancement effect for high-power and long-range systems was given in [10]. In [10], a metamaterial was designed for an input power level of 80 W and a coil separation of 50 cm. The inductive coils were fed parasitically by a loop antenna, thereby removing the effect of the source and load resistances from the system while reducing the impact of the metamaterial on the coils. However, this increases the overall size of the system. In biomedical device applications, space is scarce and therefore solutions have to be efficient in utilizing the available real estate. In [10], the reported size of the unit cell was 6.5 cm, which achieves an effective medium ratio $\lambda/a$ ($a$ is the unit cell length) of 170 at the operating frequency of 27.12 MHz. This solution is not particularly feasible for small devices. A summary of recent progress in metamaterial enhanced wireless power transfer is given in [11]. In this paper, we take a practical approach in showing that a compact uniaxial metamaterial slab made up of double-sided spiral resonator (SR) unit cells improves the efficiency of a short-range wireless power transfer system that can find applications in wireless charging and implantable biomedical devices. In this system, the transmitting and receiving coils are fed directly as opposed to parasitic feeding. The distance considered for power transfer is 5 cm and the diameters of the coils (5 and 3.6 cm) are of the order of the distance between the coils. The individual unit cell of the metamaterial was miniaturized deep into the sub-wavelength region giving a unit cell size of $\lambda/744$. More importantly, we also demonstrate that increases in efficiency are achieved when the metamaterial is placed in proximity to the transmitting or receiving coil.

The remainder of this paper is organized as follows. In Section II, the design of the metamaterial is described and results for the effective permeability are presented. The experimental setup for the telemetry system is discussed in Section III and efficiency results are presented. The effects of coil offsets in the system is also discussed. The implications of the results pertaining to practical implementation as well as the limitations of the current system are discussed in Section IV. Conclusions are presented in Section V.

II. METAMATERIAL DESIGN

Negative refractive index materials, which are a particular class of metamaterials, have negative permittivity and negative permeability [5]. In the case of an isotropic perfect lens in free space, $\varepsilon = -1$ and $\mu = -1$. However, since wireless power transfer occurs through near-field magnetic coupling, we are interested in the evanescent magnetic field enhancement provided by a metamaterial. In the low-frequency quasi-static limit, electric and magnetic fields are mostly decoupled. Therefore, for the wireless power transfer application, only a negative permeability material is necessary.

Negative permeability materials are commonly realized using planar arrays of split-ring resonators (SRRs) or SRs [12], [13]. For the same unit cell size, SRRs have a lower resonant frequency than SRRs. In telemetry systems, frequencies commonly encountered are in the low-MHz range. In order to ensure that metamaterial size is compact, the unit cells have to be miniaturized deep into the sub-wavelength domain. The wavelengths at these frequencies are of the order of many meters and therefore the effective medium approximation can be easily applied to materials whose dimensions are of the order of a few centimeters. These materials can then be characterized and assigned effective medium parameters that describe the behavior of the material.

It was shown that double-sided printed SRs are capable of achieving lower resonant frequencies than single-sided spirals [14]. The important consideration in the design of the unit cell is a tradeoff between the frequency and $Q$ of the resonance. As the resonant frequency is lowered, the required number of turns for the SR increases, thereby increasing ohmic losses. This causes a deterioration of the $Q$. In the current work, a double-sided spiral unit cell was designed for a size of $1.7\text{ cm} \times 1.7\text{ cm}$ as a compromise between low-frequency operation and high $Q$. The spiral consists of 12 turns, giving a resonant frequency of 23.7 MHz. The spiral on the bottom side is rotated with respect to the spiral on the top side, as shown in Fig. 1. The width of the traces was 100 $\mu$m and the spacing between them was 0.5 mm. The substrate chosen was Rogers RO3010, which has a dielectric constant of 10.2 to increase effective capacitance between the two layers of the spiral and thereby lower the resonant frequency.

The complete details of the geometry are shown in Fig. 1. The design was first simulated in CST Microwave Studio using unit cell boundary conditions. A $4 \times 4$ planar array of these spirals was subjected to an incident plane wave with the magnetic field perpendicular to the plane of the spirals. The magnitude of the transmission coefficient determined from simulation is shown in Fig. 2. The material parameters were extracted from the $S$-parameters of the simulation according to the procedure outlined in [15]. Fig. 3 shows the permeability values extracted from simulated transmission coefficients. A permeability value of $-1$ was obtained at 26.8 MHz. At this frequency, the imaginary part of $\mu$ had a value of 0.07 giving an effective loss tangent ($\tan(\delta)$) of 0.07 at 26.8 MHz. This is with infinite unit cell boundary conditions. In practice, since only a finite slab of material can be fabricated, there might be some deviation from these values. The near-field enhancement produced by negative permeability metamaterials is severely limited by the losses in the material. Therefore, it is necessary to design a metamaterial with a sufficiently low loss to observe a tangible increase in the magnitude of the near field within the constraints of the application. The length of one spiral is 1.6 cm in the direction of propagation while the resonant frequency of the spiral
Fig. 1. Geometry of the metamaterial unit cell. (a) Top view. (b) Bottom view.

Fig. 2. Simulated transmission coefficient of the metamaterial unit cell as a function of frequency showing resonance at 23.7 MHz.

The array of spirals was fabricated on a single substrate layer and ten layers were stacked back to back with an inter layer spacing of 2 mm. A sufficient number of layers is needed for the bulk effective medium properties to be descriptive of the behavior. However, as more layers are added, the thickness of the slab increases and the losses also increase. We chose ten layers as a compromise between these objectives. This constituted a uniaxial anisotropic metamaterial. Such a material has also been referred to as an indefinite permeability lens [16]. Since these lenses have negative $\mu$ along only one Cartesian axis, their construction is simplified and their thickness can be minimized according to the requirements of the application. The dimension of each layer in the current design was 6.9 cm × 6.9 cm and the thickness of the fabricated metamaterial with ten layers was 1.9 cm. Thus, the metamaterial slab was kept to a compact and manageable size with approximate lateral dimensions of the order of the coils in the telemetry system.

III. Experimental Setup and Measurements

A. Telemetry System

Wireless power transfer over short distances is achieved by inductive coupling between resonant coils. In this work, the telemetry system consists of a transmitting coil of diameter 5 cm and a receiving coil of diameter 3.6 cm. These dimensions are representative of coils that could be used for powering an implanted device. The coils used in the current work are printed spiral inductors etched on a substrate, as shown in Fig. 4. The self resonant frequency of each coil as reported in Table I was well above the desired operating frequency. The coils are tuned using variable capacitors to 26.8 MHz. The transmitting coil is a part of a series resonant circuit, whereas the receiving coil is part of a parallel resonant circuit. The resistance connected to the transmitting coil is 5 $\Omega$, which represents a typical value for the output impedance of the circuitry (most commonly a power amplifier) connected to the coil. A load resistance of 3.9 k$\Omega$ was connected across the terminals of the receiving coil. The data for the two coils used in the experiments are given in Table I.

B. Measurements

The coils were placed facing each other in free space separated by a distance of 5 cm, which is a nominal distance one would encounter in a short-range power transfer system. The

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Fig. 3. Extracted permeability of the metamaterial from simulation using the procedure given in [15].
transmitting and receiving coils were connected to the two ports of a network analyzer and the S-parameters were measured. A photograph of the experimental setup is shown in Fig. 5. A wireless power transfer system operating by resonant near-field inductive coupling can be modeled as a two-port network, as shown in Fig. 6. The efficiency of a wireless power transfer system when modeled as a two-port network with impedance parameters is given by the following formula [17]:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{|Z_{21}|^2}{R_L Z_{11}}.
\]

The Z-parameters were obtained from the S-parameters, and using the above formula, the efficiency of the system was calculated. The self impedance curves of the transmitting and receiving coils separated by 5 cm in free space are shown in Fig. 7. We assume that this is the closest distance at which the transmitting coil can be placed relative to the receiving coil (to obtain the best possible efficiency) and it cannot be moved any closer due to the physical constraints imposed by the application. If the transmitting coil cannot be moved any closer, it stands to reason that a metamaterial slab cannot be placed in the space between the coils as well. In implantable devices for example, due to the presence of a physical boundary such as the skin, the closest position for the placement of external coil is typically the surface of the body. Consequently, it would also be difficult or impossible to place the metamaterial slab inside the body and therefore the closest position for the placement of the metamaterial slab also lies on the body surface. Therefore, to justify the use of the metamaterial, it should be capable of increasing the efficiency of the power telemetry system when it can only be placed where the transmitting coil can also be placed. The metamaterial is now placed at the position of the transmitting coil and the coil itself is moved further away by a distance \(d\). The S-parameters are measured and the power transfer efficiency is calculated once again. The maximum efficiency was obtained at 26.65 MHz. Therefore, the transmitting and receiving coils were retuned closer to 26.65 MHz. The two scenarios without and with the metamaterial are shown in Fig. 8(a) and (b), respectively (\(T_x\) refers to the transmitting coil and \(R_x\) refers to the receiving coil). We refer to this instance where the slab is closer to the transmitting coil as Case I.

Fig. 9 shows the variation of power transfer efficiency for four different positions of the transmitting coil in Case I. When the transmitting coil is placed at distances of \(d = 1, 2, 3\) cm from the metamaterial slab, the power transfer efficiencies in all three cases are greater in the presence of the metamaterial even though the absolute distance between the coils has increased. The free-space efficiency was 11.3% and the maximum efficiency obtained in the presence of the metamaterial
was 18.23% at a distance $d = 1$ cm. As the distance is further increased, the efficiency is equal to the free-space value at $d = 4$ cm. Beyond this distance, the efficiency falls below the free-space value because the metamaterial cannot improve the efficiency sufficiently to compensate for the coil separation. Therefore, there is a region next to the metamaterial slab in which placing the transmitting coil gives better power transfer efficiency than the free-space case. The efficiency of a two-coil power transfer system is also given by [18]

$$\eta = \frac{k^2 Q_t Q_r}{1 + k^2 Q_t Q_r}$$

(2)

where $k$ is the mutual coupling and $Q_t$ and $Q_r$ are the loaded $Q$ factors of the transmitting and receiving coil, respectively. The efficiencies obtained from direct measurements and mutual coupling values calculated from the above equation are given in Table II. A plot of the coupling values as a function of distance between the transmitting coil and metamaterial along with the free-space coupling is given in Fig. 10.

The experiment is repeated with the metamaterial slab now placed near the receiving coil [see Fig. 8(c)]. This is referred to as Case II. The distance between the slab and the transmitting coil is now 5 cm and the receiving coil is placed near the metamaterial slab. The efficiency is shown in Fig. 11 for three different positions of the receiving coil with $d = 2.5$ cm, 3 cm, and 3.5 cm. When the receiving coil is very close to the metamaterial slab, the induced effect of the slab on the coil is severe and the efficiency decreases. Therefore, placing the receiving coil adjacent to the metamaterial does not lead to increased efficiency. However, as the receiving coil is moved away, this effect is mitigated and the efficiency exceeds the free-space case. As can be seen, when the receiving coil is placed at distances of 3 and 3.5 cm from the metamaterial slab, the efficiency is improved. At a distance of 4 cm, the efficiencies are almost equal and for further separations the efficiency decreases. Therefore, the range of distances where increased efficiency is obtained is more limited in Case II and the increase in efficiency is minimal.
Fig. 9. Measured efficiency plots with the metamaterial slab close to the transmitting coil (Case I) for different positions of the transmitting coil. Efficiency increases are seen for $d = 1$ cm, $2$ cm, and $3$ cm compared to the free-space case, while the efficiency is the same as the free-space case for $d = 4$ cm. Peak efficiencies at each distance are given in Table II.

<table>
<thead>
<tr>
<th>Distance of $T_x$ Coil from the slab (cm)</th>
<th>Efficiency $\eta$ (%)</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.2</td>
<td>0.0197</td>
</tr>
<tr>
<td>1.5</td>
<td>18.23</td>
<td>0.0197</td>
</tr>
<tr>
<td>2</td>
<td>17.74</td>
<td>0.0194</td>
</tr>
<tr>
<td>2.5</td>
<td>16.92</td>
<td>0.0188</td>
</tr>
<tr>
<td>3</td>
<td>16.12</td>
<td>0.0183</td>
</tr>
<tr>
<td>3.5</td>
<td>14.8</td>
<td>0.0174</td>
</tr>
<tr>
<td>4</td>
<td>13.19</td>
<td>0.0163</td>
</tr>
<tr>
<td>Free Space with 5 cm separation</td>
<td>11.3</td>
<td>0.0151</td>
</tr>
</tbody>
</table>

### C. System Simulation

A power transfer system with the same specifications as described above was simulated in CST Microwave Studio. The parameters were adjusted to ensure that the self impedances of the transmitting and receiving coils were the same as observed in the experiment. The efficiency was determined in free space at a separation of $5$ cm using (1). A homogeneous metamaterial slab of thickness $2$ cm was then added near the transmitting coil at a distance of $1$ cm. The lateral dimension of the slab was $7$ cm $\times$ $7$ cm. The distance between the slab and the receiving coil was maintained at $5$ cm, as explained in Section III-B.

This slab was assigned an effective negative permeability along the axis passing through the slab and the centers of the coils. The relative permeability in other directions was $1$ and the relative permittivity was $1$ in all directions constituting an indefinite permeability lens [16]. The accurate measurement and characterization of material properties of compact metamaterials at low frequencies is a subject of active investigation. In simulating the metamaterial, a Lorentzian dispersion relation was used as shown in Fig. 12 and the efficiency was determined with this metamaterial slab in place. Similarly, the metamaterial was also positioned $3$ cm from the receiver coil and the efficiency was determined.

Only two representative cases, as described above, were used to show that the experimental results were in reasonable agreement with simulated results from a field solver. The maximum coupling was obtained for $\mu = -1/2$ and the loss tangent at that point was $0.07$. The plots of simulated efficiencies are shown in Fig. 13, while in Table III, the efficiencies obtained from simulation of the metamaterial close to the transmitting coil (Case I) and close to the receiving coil (Case II) are shown. The results are in reasonable agreement with experiment (Table IV) with differences that can be attributed to variations in the properties of the fabricated metamaterial from the simulated predictions, fabrication tolerances, and exact placement and alignment of the telemetry coils. As can be seen, the efficiency is greater in the presence of the metamaterial slab close to the transmitting coil, even though the absolute separation between the coils has increased. The gains obtained from placing the slab in proximity to the receiving coil are negligible, which corresponds to experimental observations. In [16], it is shown by numerical
modeling that an indefinite permeability lens can achieve better coupling than anisotropic and isotropic lenses. Depending on the lateral dimensions of the lens, its thickness, the distance between the coils, and individual coil parameters, the system with an indefinite permeability lens could be optimized for coupling and power transfer efficiency. In this paper, we show one such system in which increases in power transfer efficiency are possible when the metamaterial slab is placed close to the transmitting or receiving coils.

D. Offset in Coil Positions

One commonly encountered problem that is specific to bio-telemetry systems is the offset between the implanted coil and the external coil. More often than not, the centers of the external and internal coil are not aligned along the same axis leading to a drop in efficiency. This is generally attributed to a slight displacement of the implanted device in the patient’s body. The metamaterial slab can be helpful in mitigating the effect of offset coils. We only consider linear translation in the offset because it is encountered most often in practice. The receiving coil is now offset by 0.7 cm along the diameter so that the centers of the two coils are offset and a point on their outer circumference now lies on a common tangent. This is shown in Fig. 14. The metamaterial is placed close to the transmitting coil, the same position as before, and the power transfer efficiency is measured once again. We consider only the case where the metamaterial is close to the transmitting coil because this gives us the best performance. Fig. 15 shows the efficiencies in the presence of offset coils. In this case, the coils are of comparable diameter. Therefore, the drop in efficiency due to a small offset in the alignment is not severe. However, the presence of the metamaterial still produces an increase in efficiency compared to the free-space case and also to the free-space case when the coils are aligned correctly. The maximum efficiency obtained with the metamaterial is 15.14% when the transmitting coil is at a distance of 1 cm from the slab as opposed to 11.3% in free space with no offset and 10.4% with offset. In order to mitigate the effects of
greater offsets, the size of the metamaterial slab and its orientation may have to be changed.

IV. DISCUSSION

While increased efficiencies are obtained in both Case I as well as Case II, the optimum position for the metamaterial slab is in close proximity to the transmitting coil. In most implementations of bio-telemetry systems, the power transmitting circuitry is positioned outside the body with the receiving coil situated on the implanted device. In wireless charging, the charging station is connected to the main power supply and is stationary. Therefore, in most applications of short-range power telemetry, the metamaterial slab can be integrated with the power transmitting coil and can offer substantial improvements in efficiency, as demonstrated here. The increase in efficiency was also obtained for different positions of the transmitting coil relative to the metamaterial slab. This provides additional degrees of freedom for implementation in any practical device and the optimal location can be chosen based on physical constraints and the best efficiency obtained. In [19], a simulated study is carried out of a two metamaterial slab system for wireless power transfer. However, both the metamaterial slabs consist of only one layer of unit cells (usually called a metasurface) and are placed in the space between the coils. The dimension of a single unit cell is 7.8 cm × 7.8 cm. In this paper, we have demonstrated that a compact metamaterial slab consisting of layers unit cells (each unit cell of dimension 1.7 cm × 1.7 cm) improves the efficiency of a short-range wireless power transfer system. It can also be observed that despite the increased separation between the coils as compared to the reference configuration, the metamaterial is able to increase the efficiency of the system in both Case I and Case II. In the current work, the maximum efficiency obtained and its comparison with free-space efficiency for both cases is given in Table IV.

If the metamaterial is positioned further away from each coil, toward the halfway point between the two coils, the induced effect of the metamaterial on the self impedance each coil is mitigated and further increases in efficiency are possible. However, in many practical scenarios that space might not be accessible. In this work, we have shown that the metamaterial can produce increases in efficiency even when constraints allow its placement only in a very limited space. This result is of tremendous significance in powering of implantable devices and wireless charging. Thus, devices can be powered more efficiently or the range of operation of an existing power transfer system can be increased. The most significant limitation of this method stems from the losses in the metamaterial. There is a tradeoff between building compact metamaterials and reducing their losses. Thus, for each application, the optimum size and lowest loss metamaterial can be designed to increase the efficiency.

V. CONCLUSIONS

With more devices using short-range wireless power transfer, it has become critical to design systems with high efficiencies. In this paper, a uniaxial metamaterial was designed for short-range systems. The metamaterial unit cell was miniaturized deep into the sub-wavelength range and a compact material consisting of these unit cells was constructed. Experiments with a realistic two coil power transfer system showed that efficiency increases were achievable even when the absolute separation between the coils was greater and the metamaterial was placed close to the transmitting or receiving coil. This gives considerable latitude in the design of short-range wireless power transfer systems and allows optimum solutions to be found within the constraints of specific applications. It was also shown that using a metamaterial slab could potentially alleviate the effects of coil offsets on system efficiency. Thus, using a compact metamaterial slab is a viable solution to increase the efficiency of a wireless power transfer system and can be helpful in applications like wireless charging and powering implantable biomedical devices.

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REFERENCES


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Dr. Lazzi was the chair of Commission K (Electromagnetics in Biology and Medicine) (2006–2008) and a member-at-large (2009–2011) of the U.S. National Committee, International Union of Radio Science (URSI). He has been an associate editor for the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (2001–2007) and was a guest editor for the “Special Issue on Biological Effects and Medical Applications of RF/Microwaves” of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in 2004. In 2009, he was the Technical Program Committee chair of the IEEE Antennas and Propagation International Symposium and URSI meeting, Charleston, SC, USA. He is currently a member of the Editorial Board of the PROCEEDINGS OF the IEEE and the chair of the IEEE Sensors Council Technical Achievement Award Committee. He has been the editor-in-chief of the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (2008–2013). He was the recipient of the 1996 Curtis Carl Johnson Memorial Award for the best student paper presented at the 18th Annual Technical Meeting of the Bioelectromagnetics Society (BEMS), a 1996 International Union of Radio Science (URSI) Young Scientist Award, a 2001 Whittaker Foundation Biomedical Engineering Grant for Young Investigators, a 2001 National Science Foundation (NSF) CAREER Award, a 2003 NCSU Outstanding Teacher Award, the 2003 NCSU Alumni Outstanding Teacher Award, the 2003 ALCOA Foundation Engineering Research Award, the 2006 H. A. Wheeler Award of the IEEE Antennas and Propagation Society for the best application paper published in IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 2005, a 2008 Best Paper Award of the IEEE conference Globecom, the 2009 ALCOA Foundation Distinguished Engineering Research Award, a 2009 R&D100 Award, and the 2009 Editors Choice Award from R&D Magazine for the Artificial Retina Project.