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The efforts of this project considered two technological aspects of rectennas systems. One technology that was emphasized power-adaptive rectifying circuits (PARCs). If a rectenna system is to be integrated into an autonomous vehicle system and fed by a stationary microwave source, the electromagnetic power incident on the rectenna will vary with the distance between the source and the rectenna. Consequently, the output power from the rectenna could vary dramatically with small changes in the location of the rectenna system. To mitigate these input power effects, we considered a prototype PARC design at 1MHz and a corresponding RF PARC design at 2.45 GHz in the ISM band. As proposed, several power adaptive rectifying circuits were designed, built, and tested. Several metamaterial-based electrically small antennas were also considered during the project duration. These efforts included an integrated antenna-artificial magnetic conductor (AMC) system and a metamaterial-based efficient electrically small dipole antenna. An optimal design of a printed dipole antenna integrated with an AMC block having no ground plane was achieved. An efficient electrically small antenna was achieved by surrounding a center-fed dipole antenna with an ENG (epsilon negative) metamaterial spherical shell and a coax-fed monopole antenna with an ENG metamaterial hemispherical shell.					
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ONR Project: Metamaterial-based Patch Antennas and Adaptive Rectifying Circuits for High Power Rectenna Applications

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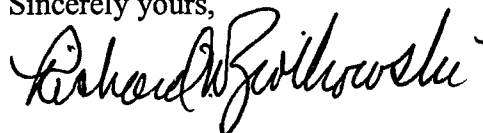
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As proposed, a power adaptive rectifying circuit was designed, built, and tested at 1MHz as a prototype for use in a metamaterial-based rectenna system in the ISM band at 2.45 GHz. Several metamaterial-based electrically small antennas were also considered during the project duration. Several of the highlights from this project, which will be submitted with this report, include:

- The report from a four person Fall-Spring 2003-2004 ECE Senior Capstone Project team that I oversaw which designed, fabricated and tested the power adaptive rectifying circuit.
- A paper and an IEEE AP-S presentation from my Ph. D. research assistant, Mr. Aycan Erentok, who worked directly on modeling the metamaterial-based efficient electrically small antennas for use in the rectenna systems. He was able to demonstrate that an efficient electrically small antenna could be realized by surrounding a dipole antenna with a resonant metamaterial shell.
- A MS thesis and an IEEE AP-S presentation from my MS student, Mr. Dongho Lee, who was a graduate student associated with this project. He continued our investigations into antennas in the presence of an artificial magnetic conductor (AMC) realized with metamaterial concepts. Because this AMC substrate had no ground plane, it reduces surface wave effects and should allow the integration of a dense array of rectennas.

This report concludes this one-year contract effort.

Sincerely yours,



Richard W. Ziolkowski
Kenneth Von Behren Chaired Professor

Our project efforts emphasized two technologies for wireless power transfer (WPT) applications. These applications included rectenna system concepts for ground-based and space-based wireless power transfer systems used to fuel autonomous vehicles or to provide emergency or boost power to mission critical platforms.

One technology that was emphasized in this project included the design, fabrication and testing of power-adaptive rectifying circuits (PARCs). If a rectenna system is to be integrated into an autonomous vehicle system and fed by a stationary microwave source, the electromagnetic power incident on the rectenna will vary with the distance between the source and the rectenna. Consequently, the output power from the rectenna could vary dramatically with small changes in the location of the rectenna system. To mitigate these input power effects, we considered the following: (1) a prototype PARC design that produced a constant output power level at 1MHz with a $5\pm 20\%$ dBm input power level, and (2) a PARC design that produced a constant output power level at 2.45 GHz with a $5\pm 20\%$ dBm input power level. Both designs were undertaken with the additional constraint that they produced the output power with a maximum RF-to-DC power conversion efficiency.

The original goal of the project was to design, fabricate and test a rectenna system that had a 20% input power bandwidth and operated in the 80-90% efficiency range in the ISM band at 2.45 GHz. Since a few patch antenna based rectenna systems reported to date have operated in this high efficiency range, but only at one input power level, this would be a significant advance in the rectenna state-of-the-art for autonomous vehicle applications. Unfortunately, because of the performance limitations in the components, particularly the diodes, used in our design, we could not achieve the high levels of efficiency that were targeted.

Another technology was the use of metamaterials to enhance the power-capture performance of the antennas in a rectenna system. This included an integrated antenna-artificial magnetic conductor (AMC) system and a metamaterial-based efficient electrically small dipole antenna. An optimal design of a printed dipole antenna integrated with an AMC block having no ground plane was achieved. An efficient electrically small antenna was achieved by surrounding a center-fed dipole antenna with an ENG (epsilon negative) metamaterial spherical shell and a coax-fed monopole antenna with an ENG metamaterial hemispherical shell.

The metamaterial results imply that superior microwave antenna systems could be achieved which could lead to smaller, lightweight, more robust and more efficient wireless power transfer (WPT) systems for both military and commercial applications. Electrically small antenna realizations of the rectenna systems can lead to efficient, small conformal power farms on mobile platforms. The integration of a power-adaptive rectifying circuit with the antenna will help maintain the conversion efficiency of the rectennas when the mission critical platforms are mobile. Dense arrays of radiating and rectifier-receiving elements could significantly benefit from the isolation properties afforded by these novel metamaterial designs.

The progress made in each of these research areas is summarized below.

1) Design, fabrication and testing of power-adaptive rectifying circuits that will enhance the conversion efficiency of rectennas in high power wireless power transfer systems.

The power conversion efficiency of a rectenna generally changes with the input. The terms V_j , V_{br} , and R_L are, respectively, the forward voltage drop (i.e., the junction voltage), the breakdown voltage of the diode, and the DC load resistance of the rectenna. The efficiency is generally small in the low power region of the incident power curve because the voltage swing at the diode is below or comparable with the forward voltage drop of the diode. The efficiency increases as the power increases and levels off with the generation of strong higher order harmonics. The efficiency sharply decreases when the voltage swing at the diode exceeds the breakdown voltage of the diode. The critical input power where the breakdown effect becomes dominant is expressed as $V_{br}^2/4R_L$. The three parameters that control the behavior of the diode, i.e., its breakdown voltage V_{br} , its zero-biased junction capacitance C_{j0} , and its internal series resistance R_s determine the power conversion efficiency of rectenna. The highest efficiency can be achieved with an ideal diode. This case has an infinite V_{br} and very small C_{j0} and R_s . These parameters are, however, related to each other through the diode's material properties. Consequently, we found it very important to have a good trade-off between the diode parameters in order to achieve high conversion efficiencies.

Because the operating point of the diodes and, hence, their conversion efficiency is greatly impacted by the power level input into the diodes, it is a major bottleneck in the performance of any rectenna system. Stabilization of the input power level would lead to stable rectenna conversion efficiencies. Since the power received by an antenna P_r with gain G_r at a distance r from a transmitting antenna that is radiating P_t watts with a gain G_t at the wavelength λ is

$$P_r = \frac{\lambda^2}{4\pi r^2} G_r G_t P_t$$

one finds immediately that the incident power to the antenna will vary as the distance between the source and the rectenna platform varies. Consequently, the power input to the rectifying circuit will have similar variations. We investigated the design of a power adaptive rectifying circuit (PARC) that could minimize the power output variations in the presence of these input power variations. By coupling an appropriately designed feedback network with variable components, the operating point of the diodes in the rectifying circuit can be optimally maintained. Thus the overall power transfer efficiency of a WPT system can be maintained. This is very important to mission critical platforms where 30-70% power variations are unacceptable.

At the 1MHz frequency, the PARCs considered were mainly lumped-element analog designs. After many iterations of design and testing that are summarized in the attached Capstone project

report, the optimal design shown Fig. 1 was found to have an adaptivity of 98% and a maximum power conversion efficiency of 34.6% at a voltage efficiency of 100%. This was true for an input power range of 4dBm-6dBm. Therefore, the final analog design met most of the original design specifications. In all the designs considered, the power conversion efficiency was low because there was a substantial amount of current lost from the input to the output due to the trade-off between adaptability, voltage maintenance, and power efficiency.

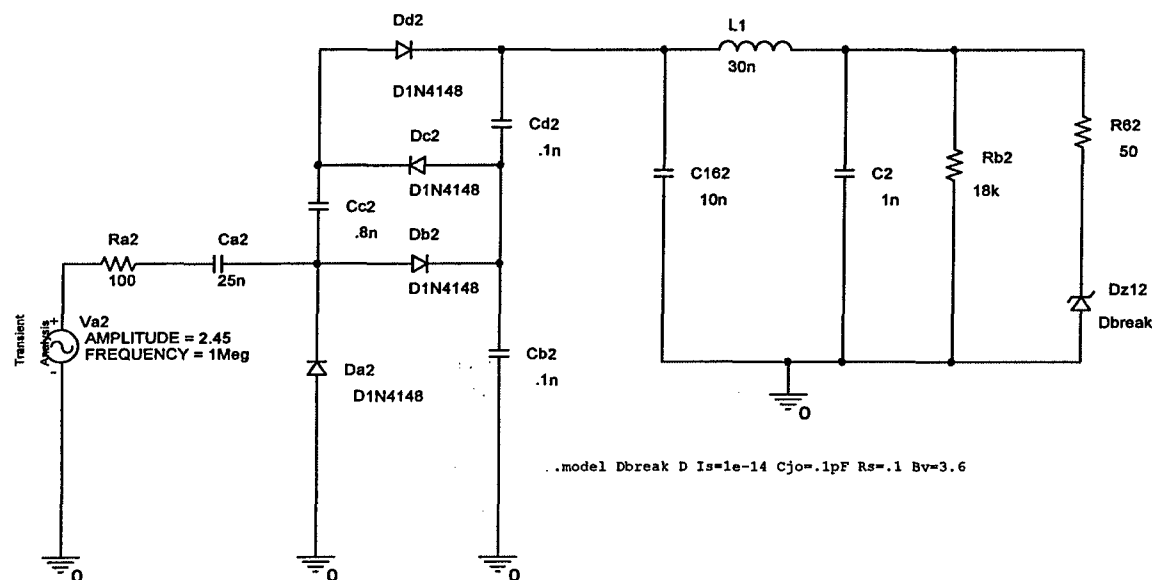


Fig. 1. Schematic of the prototype analog design that produced the maximum power conversion efficiency.

The analog designs were used as starting points for the RF designs at 2.45 GHz. The initial design was 100% adaptive, but had an extremely poor power conversion efficiency of 0.92%. The optimal design had a lower adaptability than the initial design (95% instead of 100%), however the power conversion efficiency was far superior yielding a value of 30.5% for input ranges within the proposed 4dBm-dBm range. Two approaches for the designed RF layout were analyzed. A multi-section transformer design yielded an S_{11} parameter of -1.25 dB at 2.45 GHz. The varied line length design produced an S_{11} parameter of -15 dB at 2.45 GHz and -22 dB at 2.44 GHz.

One purpose for designing the PARC at two different frequencies was to establish a benchmark which the RF design performance could be compared against. Based on the results mentioned above, the analog design was 98% adaptive and 34.6% efficient for the low input power level. The RF design was 94.93% adaptive and 30.5% efficient for the low input power level. This is only a 3% change in adaptivity and a 4.6% change in efficiency from the analog to the RF

design. Therefore, one can conclude that the analog design was an effective prototype for an RF circuit implementation.

During the development of the analog and high frequency circuit designs, several trade-offs were encountered. In order to achieve desired results and meet all specifications, multiple trials had to be completed to determine which contributing factors of the circuit were more advantageous than others. There were three major tradeoffs associated with the circuit design.

The first and most obvious tradeoff existed between the output voltage and the output current when the output power was fixed. More specifically, in order to obtain a higher output current, the output voltage decreased, and conversely, for a high output voltage, the output current decreased. This occurred when increasing and decreasing the impedance of the output stage. This relationship made optimization of the power conversion efficiencies difficult since an increase in the current efficiency meant a decrease in the voltage efficiency of the circuit. In addition, the relationship between the output current and the output voltage also affected the circuit's ability to adapt to input power variations. When designing the circuit to produce optimal power efficiency, the output current and output voltage needed to be as large as possible. However, the regulating stage for the RF and analog circuits used a zener diode that had a specific breakdown voltage. If the output current was increased too much to cause the output voltage to become considerably lower, the output voltage would not surpass the breakdown voltage of the zener diode. In that case, the functionality of the circuit would not be within the desired input range, and the circuit would not be adaptive.

A second trade-off existed between the overall power efficiency of the circuit, and the power adaptability of the output to a specified input range. This trade-off was significant since both of these parameters had to meet the given requirements. When designing the circuit, it was apparent that higher power conversion efficiency would come at the cost of adaptability. Specifically, designing the circuit such that it was adaptive to input power variations resulted in the power efficiency to decrease by 10% in several cases over the 4dBm-6dBm input range. However, this was not unexpected. After the input power reached the value that resulted in the output threshold power, any additional power was lost at nearly a one-to-one ratio. A decision had to be made as to what parameter was more important. It was decided that the circuit should be able to adapt to input power variations from 4dBm-6dBm to obtain a very constant and discrete DC output. Because of this, the circuit was made adaptive, consequently lowering the power efficiency of the circuit.

A third trade-off that existed in the circuit existed between the power efficiency or adaptability of the circuit and the output ripple. During simulations it was found that creating a minimum ripple at the output lowered the power efficiency of the circuit. Because of this, it had to be decided whether to leave a larger ripple on the output for higher power efficiency, or to reduce the amount of ripple therefore decreasing the power efficiency. After multiple comparisons were completed, it was decided that a smaller ripple was desirable as long as the power conversion efficiency was not reduced drastically. In addition, the ripple had a relationship with the circuit's ability to adapt to input power variations. When the ripple was large, the circuit was not able to

adapt to input power variations as well as when the ripple was small. This occurred because a larger ripple translated to larger variations in the output power. Consequently, since the output power variation was larger, the constant DC output value decreased.

In summary, we found that the tradeoffs between voltage and current, power efficiency and adaptability, and ripple and power efficiency and adaptability created problems during the design of the optimal circuit. For each tradeoff, comparisons were assessed to understand which parameter had a greater impact on the successful operation of the circuit; and the PARC components were adjusted accordingly.

As previously discussed, the main obstacle of the PARC designs was the tradeoff between efficiency and adaptivity. It was important to provide both efficiency and adaptivity for a practical design; however, the primary goal was to provide adaptivity to changes in the input power. If the design was highly efficient at one specific input but dropped exponentially as the signal decreased, the design would fail to meet its purpose. The final design at both the 1.0 MHz and 2.45 GHz target frequencies compromised power efficiency in favor of adaptivity. The objective of the design was to deliver as efficient an output over a range of inputs while maintaining a constant output signal. This objective was completed for the designs at both frequencies. Through multiple iterative simulations, the design was optimized to best deliver the specifications. The layout of the high frequency design was successful in minimizing the reflected signal at the input, producing an S_{11} of -15 dB at 2.45 GHz. Additionally, the analog prototype produced results comparable to the simulated results for the optimal design at 1 MHz. The analog design showed an efficiency range of 22.2% to 34.6% for an input range approximately 4 to 6 dBm while maintaining a power adaptivity of 98%. The RF design produced similar results to the analog design, with an adaptivity of 94% for an input range of approximately 9.5 to 12 dBm and a power efficiency range of 19.38% to 30.5%. While the power efficiency was between 20% and 35% for the tested inputs, the adaptivity of the PARC output power to changes in input power was greater than 90%. Despite the sub 50% power efficiencies, the voltage efficiencies of the designs were greater than 90% for most of the input ranges tested.

Several issues remain unresolved after the completion of the design and testing of the PARCs at both frequencies. The primary issue encountered yet again is the performance of the diodes in the system. Specifically, it was found that the performance of the zener diode included in the PARC designs severely limited the performance of the overall circuit. One possible solution to this problem would be to introduce a more complicated circuit that uses a series shunt regulator. The problem with this solution is that it requires the incorporation of a transistor, hence, external power sources into the design. Unfortunately, using transistors for regulation would not be the ideal solution because it lowers the power efficiency. However, if voltage efficiency is the primary concern, then this is a suitable approach. The ideal solution would be to find or fabricate, and use a zener diode with a suitable breakdown voltage as the only regulating component. This would decrease the amount of loading effects caused by additional components and help maintain higher efficiencies. Any future efforts associated with rectennas should emphasize a fundamental design of diodes made specifically for the proposed rectenna system.

The final RF PARC design also had some unresolved issues. The first issue was associated with the length of the microstrip layout. While the design was optimized for performance at 2.45 GHz, the amount of space needed for the layout was larger than originally anticipated. The goal was to have a design that could easily be integrated with a patch antenna and filter and fit on a 5 in. by 5 in. board. The length needed for the circuit alone was over 4.5 inches. The layout would need to be reduced by at least 2 inches in length before the design could be integrated as originally desired.

2) Design of metamaterial enhanced antenna designs for adaptation to rectenna systems.

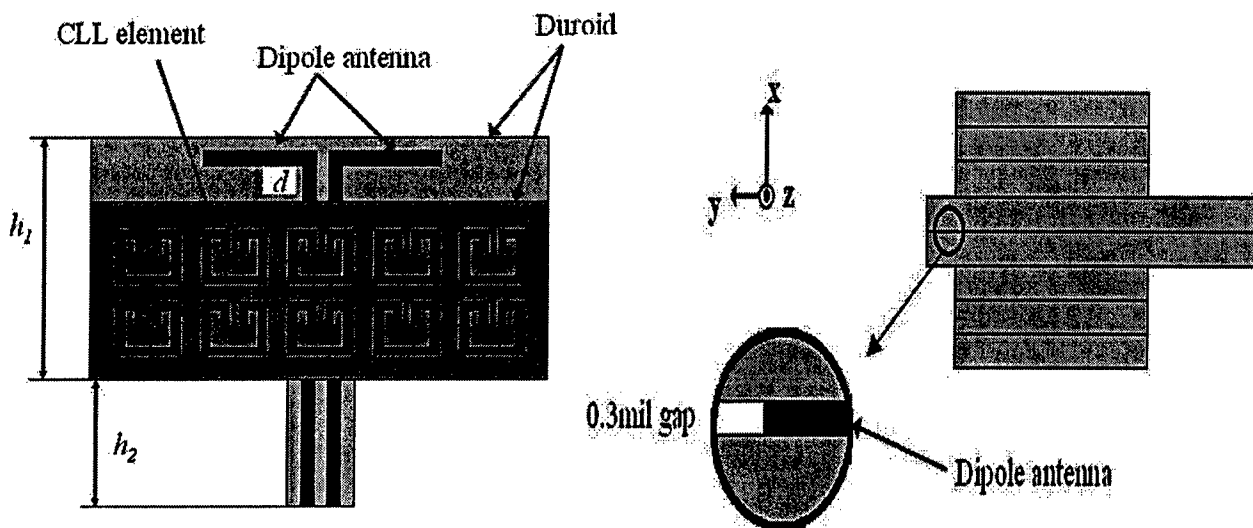
A rectenna generally consists of a receiving antenna, an impedance matching circuit with or without a built-in harmonic filter circuit, a rectifying circuit, and an output load. In our previous DARPA rectenna project, we developed a harmonic suppression microstrip patch antenna. While this antenna negated the need for the normally size intensive filter circuit, the overall board layout, including the rectifying circuit, was still larger than desirable. This was exacerbated by the realized sizes of our PARC designs. We have now realized that one really does want to have the rectifying circuits behind the antenna as seen by source and not in the same plane as we had with our previous patch antenna designs. Moreover, as shown previously, we have found that the more efficient the individual antennas are, the more efficient the overall rectenna array will be.

We continue to believe that one key factor to a successful rectenna array is the ability to increase the packing density of the antenna elements in the array. Since the total power output of the rectenna system is determined by the number of antennas in the array, one would like to have the individual antenna elements more closely spaced together. To achieve this, one must either decrease the coupling between these individual elements or make them electrically smaller while maintaining their overall efficiency.

To isolate the individual antenna elements associated with a rectenna array and to improve the efficiency of an individual electrically small antenna, we have considered incorporating metamaterials into the antenna systems. We have investigated two approaches. The first considered the integration of a resonant sized dipole antenna with the CLL-based AMC block developed in our previous DARPA rectenna project. The second considered improving the efficiency of an electrically small antenna by surrounding it with a resonant metamaterial shell. Both approaches were successful.

The printed dipole antenna was integrated into the capacitively loaded loop (CLL) based AMC block as shown in Fig. 2. The printed dipole was incorporated in one layer of the block; the distance between the antenna and the CLL elements was tuned to achieve the predicted resonant state. The resulting antenna patterns for a half-wavelength dipole antenna and a 0.325 wavelength dipole antenna are shown in Figs. 3 and 4. A greater than factor 2 enhancement of the electric field strength expected for an AMC surface was achieved because of the resonant nature of the system.

The first resonance occurred at 8.898GHz. When d was 52mils, the field strength ratio of the half wavelength dipole antenna with the AMC block to its value in free space alone was found to be 2.3137 and the corresponding front-to-back ratio was found to be 107.31. When d was 59mil, the field strength ratio of the 0.325λ dipole antenna with the AMC block and its value in free space was found to be 2.7257 and the corresponding front-to-back ratio was found to be 68.3 at 9.601GHz. We thus observed a more significant enhancement in the 0.325λ printed dipole antenna case's broadside ratio than in the half wavelength dipole antenna case in agreement with the ideal dipole results. The large front-to-back ratios indicate that a good isolation between the radiated fields and any circuits behind the overall system can be achieved.



**E-plane view of the integrated printed dipole
CLL-based AMC block structure**

**H-plane view of the integrated printed dipole
CLL-based AMC block structure**

Fig. 2. The distance d was varied to establish a resonance between the printed dipole antenna and the CLL-based AMC metmaterial block

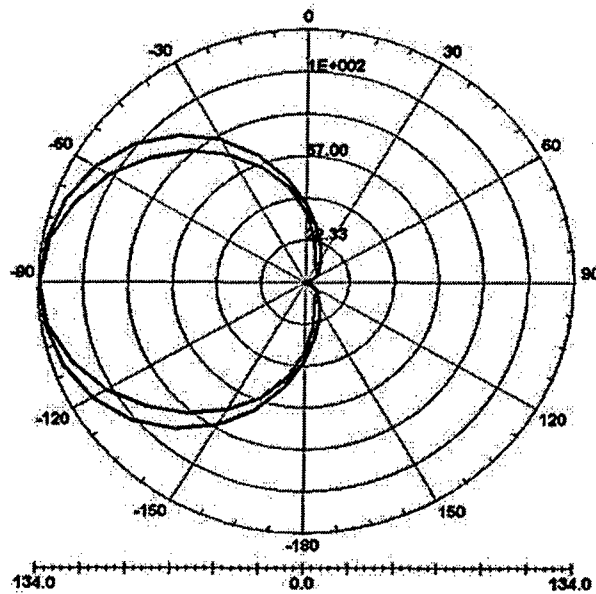


Fig.3. E- and H-plane radiation patterns for the 0.5 wavelength printed dipole antenna – CLL-based AMC block system. The E-field enhancement was 2.3137 and the corresponding front-to-back ratio was 107.31.

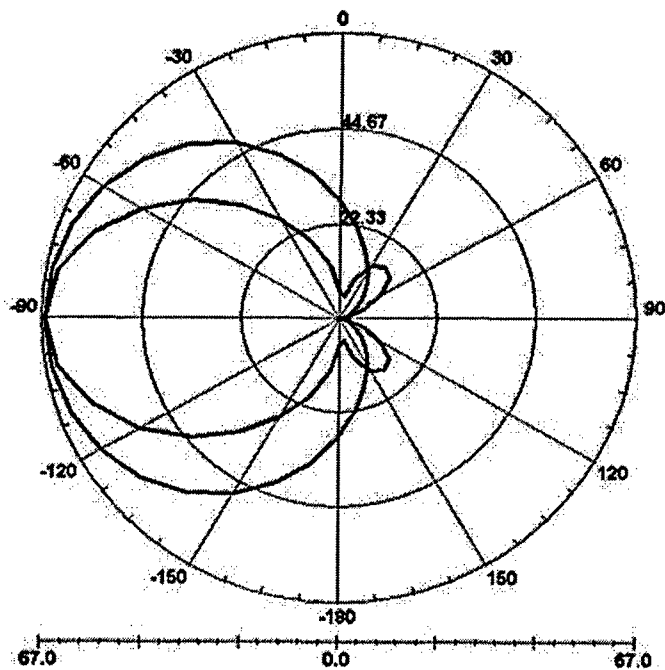


Fig.4. E- and H-plane radiation patterns for the 0.5 wavelength printed dipole antenna – CLL-based AMC block system. The E-field enhancement was 2.7259 and the corresponding front-to-back ratio was 68.3 at 9.601 GHz.

The design of an efficient electrically small antenna system was based on surrounding a dipole antenna with an ENG spherical shell. The geometry is shown in Fig. 5.

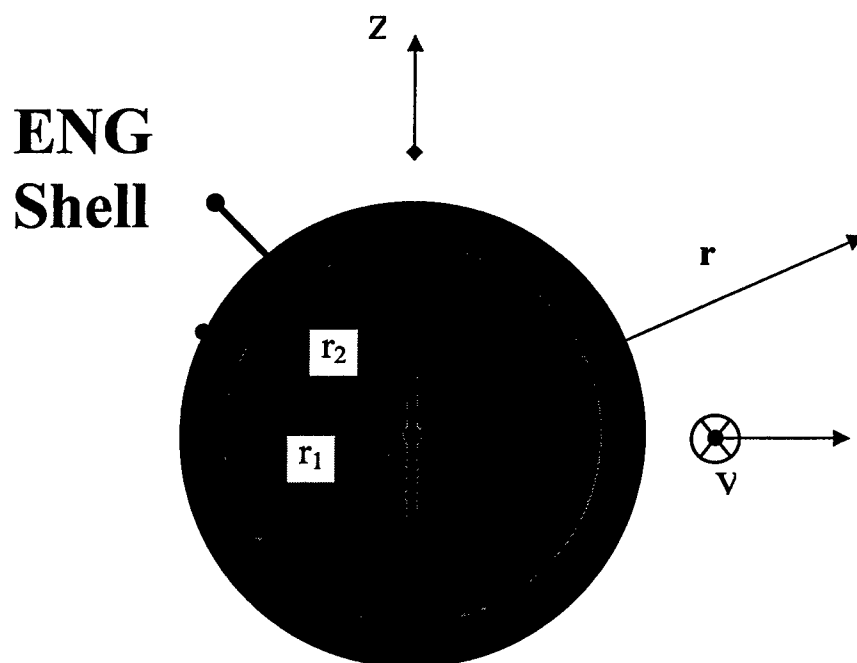


Fig. 5. Infinitesimal dipole-ENG shell system.

The electrically small dipole element is a highly capacitive element that has an extremely small radiation resistance. The electrically small shell also has a capacitive nature but with a permittivity filling that is negative, hence making the ENG shell an inductive distributed element. The combination can be designed to produce a resonance, despite the electrically small size of the system. The resonance is illustrated in Fig. 6. The gain over the corresponding free space dipole antenna was substantial, on the order of 63 dB.

We then considered more realistic dipole antennas including a center-fed dipole cylindrical wire antenna and a coax-fed monopole antenna. As shown in Fig. 7, we have demonstrated that the dipole enclosed in a properly designed resonant spherical ENG shell has a resonance that theoretically yields a 100% efficiency at the desired operating frequency. A similar result was demonstrated for the coaxially-fed monopole antenna enclosed in a resonant ENG hemispherical shell.

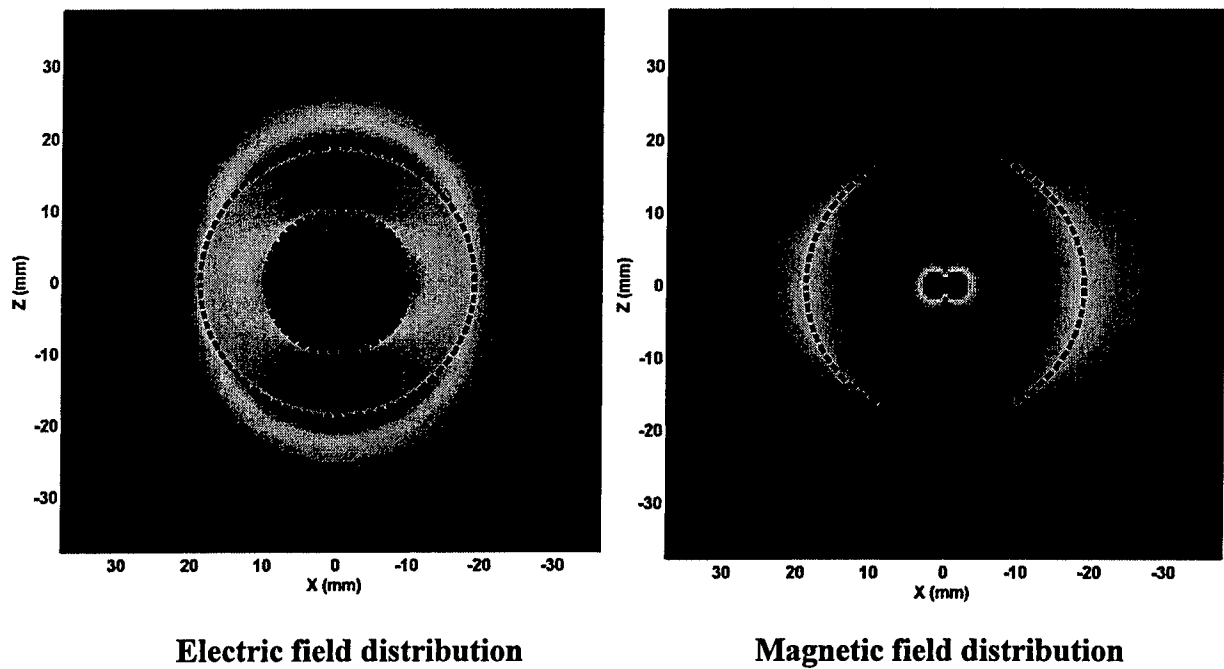


Fig. 6. Electric and magnetic field distributions for the resonant infinitesimal dipole antenna-ENG shell system.

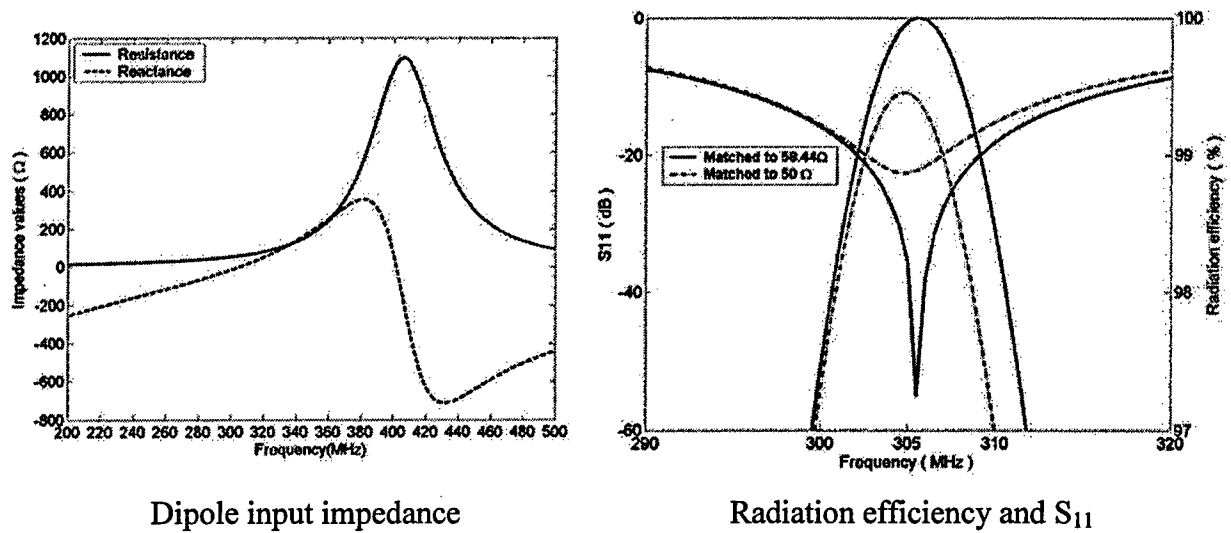


Fig. 7. Input impedance, radiation efficiency and S_{11} for the resonant center-fed cylindrical dipole antenna-ENG shell system.

The work performed in this project was reported in several forums including refereed journal papers, conference proceedings papers, and conference presentations at several professional society meetings including the IEEE AP-S and URSI. A list of these reports is below.

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