Measurements of Metamaterial-Inspired, Electrically Small Antenna Systems†

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ABSTRACT: The paper discusses analysis and measurements of electrically small antennas. The antennas discussed here are based on antennas designed from metamaterial inspired concepts. An electromagnetic reverberation chamber is used for the tests of the antennas. A reverberation chamber is basically a shielded room (metallic wall) with an arbitrarily shaped metallic rotating paddle and is an ideal environment for measuring the total radiated power of an antenna. Simulations and measurements of various antennas will be presented.

INTRODUCTION

A variety of electrically small metamaterial-based and metamaterial-inspired antennas have been reported recently in [1] and [2]. It has been demonstrated that with the introduction of an electrically small metamaterial-inspired parasitic element in the very near field of an electrically small radiator, an electrically small antenna system can be made to be resonant (total input reactance equal to zero) and input resistance matched to the source (50 Ω) without the introduction of an external matching circuit. If a is the radius of the smallest enclosing sphere and $k = 2\pi / \lambda_0$, where λ_0 is the free space wavelength corresponding to the resonant frequency $f_0 = c / \lambda_o$, it has been demonstrated numerically that the overall efficiency of the antenna system is >90% when ka<0.5. While the overall efficiencies are large, the bandwidths remain small. In general, the Q values are just several times larger than the Chu limit.

These electrically small systems pose a number of interesting, yet difficult measurement challenges. The main points of interest in these designs were the facts that these electrically small antennas could be resonant and matched to the source without any external matching circuit, and that they could be very efficient. Consequently, measurements of the S-parameters and the overall efficiencies of these systems were desired to validate the simulation results.

Several of these antenna designs have been fabricated and tested from 300 MHz to 1.6 GHz. The S-parameter measurements were performed with standard vector network analyzer methods. The total radiated power results were obtained with reverberation chamber measurements. Both the measured S-parameter and overall efficiency results recover the simulated values very well. These simulations and measurements will be reviewed in detail in our presentation.

METAMATERIAL-INSPIRED 3D MAGNETIC-BASED EZ ANTENNA SYSTEMS

As discussed in [1] and [2], highly efficient electrically small antenna (ESA) systems can be obtained by properly matching resonant electrical negative (ENG) and magnetic negative (MNG) metamaterial shells, respectively, with driven electric and magnetic dipole antennas. As reported in [2], these shells act as highly resonant parasitic elements and are located in the very near field of the driven radiators. Moreover, structures that mimic the desired type of metamaterial, but are not themselves metamaterials, were also shown to lead to highly efficient ESA systems. One example is the coax-fed electric monopole 2D EZ antenna shown in Fig. 1a. The metamaterial-inspired meander-line parasitic structure (ENG type) in the very near field of the electric monopole provides the means for the antenna system

978-1-4244-4396-3/09/$25.00 ©2009 IEEE

to be resonant (reactive matching) and resistively matched to the source (50 Ω), without any external matching network. Another example is the coax-fed magnetic semi-loop driven, 3D EZ antenna shown in Fig. 1b. The metamaterial-inspired extruded capacitively loaded loop (CLL) structure (MNG type) in the very near field of the magnetic semi-loop provides the means for the antenna system to be resonant (reactive matching) and resistively matched to the source (50 Ω), without any external matching network. Both of these metamaterial-inspired antenna systems have been fabricated and tested. Their S-parameters have been measured with a standard vector network analyzer (VNA) and their total radiated powers have been measured in a reverberation chamber. The measured results are in very good agreement with the simulation results. Recent measurements by Dr. A. Erentok at the Antenna Measurement Facility at the Technical University of Denmark (DTU) have confirmed the radiation patterns predicted for both the 2D electric and magnetic EZ antennas at 1.6 GHz.

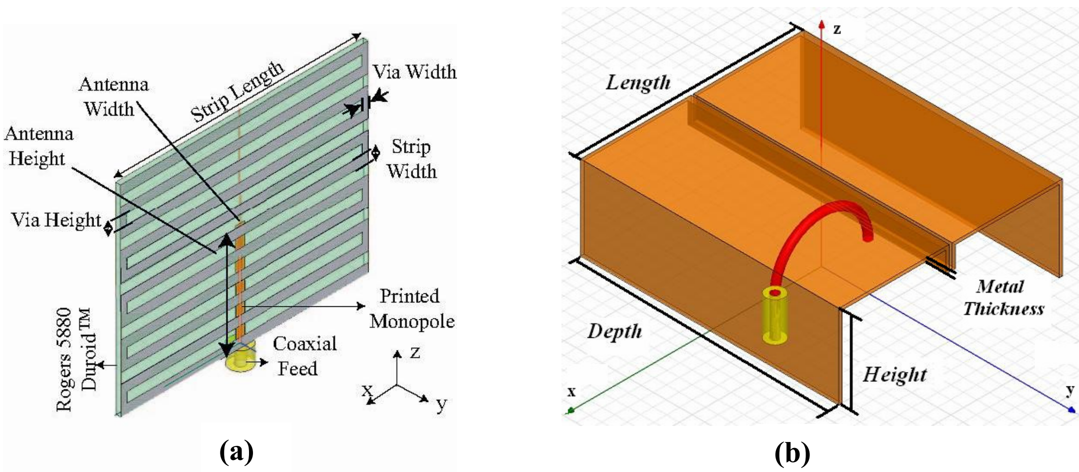

Figure 1. Metamaterial-inspired ESA designs: (a) 2D electric-based EZ antenna and , (b) 3D magnetic-based EZ antenna.

METAMATERIAL-INSPIRED Z ANTENNAS

With the desire to move these designs to lower VHF and UHF frequencies, the Z-antenna, shown in Fig. 2a, has been developed and is reported in [3]. It is a simplified version of the 2D EZ antenna shown in Fig. 1a. Using the concepts employed in [4], a lumped element inductor has replaced the majority of the meander lines. Like the meanderline, the Z-element is an integral part of the radiating structure. The dielectric substrate of the original EZ design was removed and the line thickness was increased (from the meanderline value to significantly larger than the skin depth at the lower frequencies of interest) to improve the overall radiation efficiency. The lumped element provides a means to mechanically or electronically change the resonance frequency, which is defined by the effective inductance and capacitance to be $\omega_0 = 1 \big/ \sqrt{L_{eff} C_{eff}}$. The variations in the performance of the Z-antenna, when its resonance frequency is varied from 60 MHz to 600 MHz, have been considered. While the inductor value was changed, the Z-element itself remained the same for all of those cases. It was found that only slight variations in the height of the monopole were needed to recover nearly complete resistive and reactive matching. Unfortunately, when this structure was fabricated by Boeing Phantom Works and shipped for testing at NIST, the weight of the suspended piece of the Z element caused a catastrophic failure at its joint with the inductor. A version of this antenna at 570 MHz was then designed and fabricated. The fabricated version of this antenna is shown in Fig. 2b. Experimental results will be shown in the presentation. Very good agreement between the simulation and measurement results were obtained.

REVERBERATION CHAMBER MEASUREMENTS OF ANTENNA EFFICIENCY

After fabrication, the antennas were measured at NIST using a reverberation test chamber, see Fig. 3a. We have chosen to use an electromagnetic reverberation chamber for the test of the antennas. A reverberation chamber is basically a shielded room (metallic walls) with an arbitrarily shaped metallic rotating paddle (stirrer or tuner) [5]. The rotating paddle creates a statistically uniform environment over throughout the working volume of the chamber [6]. Initially, reverberation chambers were used as high-field-amplitude test facilities for electromagnetic interference and compatibility (EMI and EMC). Reverberation chambers are currently used for a wide range of other measurement applications. Applications include, but are not limited to, determining: (1) radiated immunity of components and large systems, (2) radiated emissions, (3) shielding characterizations of cables, connectors, and materials, (4) antenna efficiency, (5) probe calibration, (6) characterization of material properties, (7) absorption and heating properties of materials, and (8) biological and biomedical effects. While most of the research and applications of reverberation chambers have been geared toward EMC/EMI, applications to antennas and wireless applications began to emerge over the past few years. These include total radiated power and antenna efficiency measurements [7, 8]. A summary of the literature for all these types the reverberation chamber measurements can be found in [9].

When a source (i.e., antennas under test) is placed in a reverberation chamber, the energy radiates from the antenna and interacts with (i.e. reflects off) the chamber walls and paddle. This energy is monitored at a receiving antenna in the chamber. Thus the total power received at the receiving antenna is the energy balance of the energy radiated for the source minus the energy lost into the chamber walls (and any cables and other objects inside the chamber). Reverberation chambers are an ideal environment for measurements of total radiated power and efficiency of antennas [7, 8]. However, in these types of measurements the losses in the chamber wall must be calibrated out. This is accomplished by using a known (well characterized) antenna as a *reference* source. In this approach, measurements at the received antenna are first obtained with the antenna under test (AUT) (see Fig. 1). Next, the measurements of the received antenna are then measured with the *reference* source (where the AUT in Fig. 1 is replaced with the reference antenna). The ratio of the received power of the AUT to the reference antenna gives a measure of the relative total radiated power and antenna efficiency (i.e., relative to the reference antenna). In these measurements we used a dual-ridged horn antenna for the reference antenna. Measurement uncertainties in reverberation chambers are below 1 dB. Fig. 3b shows the total radiated power (related to a horn antenna) for the antenna shown in Fig. 1b. From Fig. 3, we see that the metamaterial-inspired capacitively loaded the loop has a 30 dB improvement over the loop along. Also, we see the new antenna radiates a well as the reference horn, which has an efficiency of 92-94%. Measurements for other antennas will be discussed in our presentation.

CONCLUSIONS

In this paper we have discussed metamaterials-inspired, electrically small antennas. Simulations and measurements of various antennas were presented. We illustrate how the reverberation chamber is a fast an efficient test method for the test of antenna efficiency of these types of antennas. These simulations and measurements will be reviewed in detail in our presentation.

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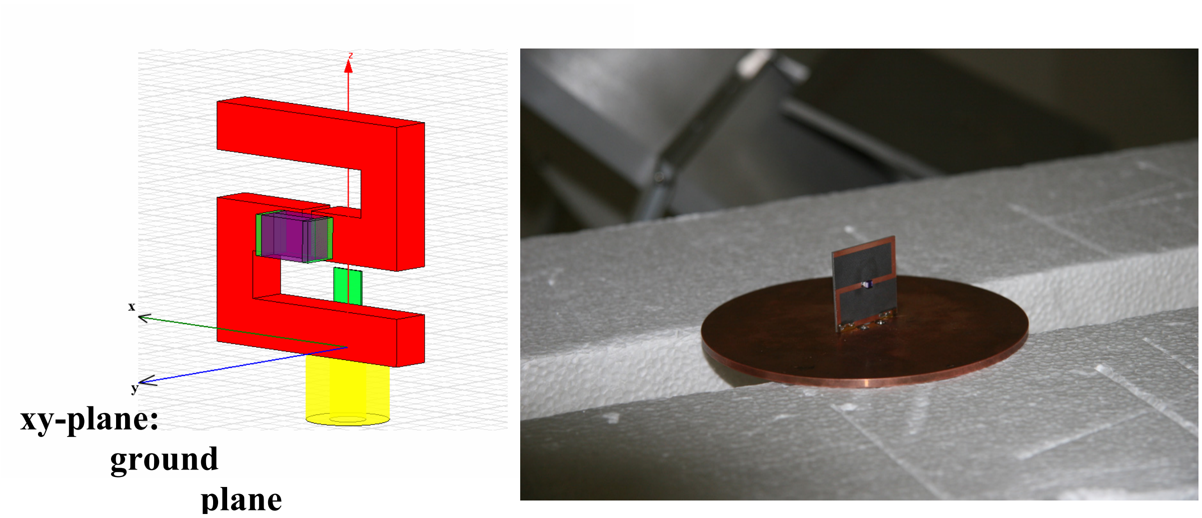
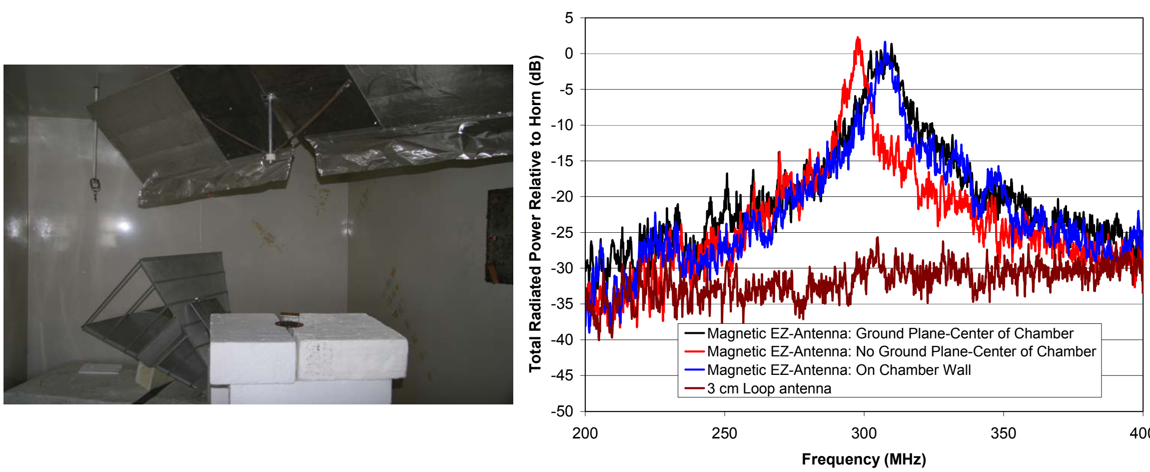


(a) (b)

Figure 2. Metamaterial-inspired Z antenna: (a) HFSS model and (b) Fabricated Duroid-based Z antenna.



a) b)

Figure 3. a) NIST reverberation chamber; b) Total radiated power of antenna shown in Fig. 1b for various configurations.