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Metamaterial-based and Metamaterial-inspired Efficient Electrically Small Antennas: Designs, Simulations and Experiments

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1. Introduction

The size reduction of state-of-the-art electronic circuits, as well as recent technological advances in fabrication processes, has changed the expectations of antenna designs and their performance in wireless communication and sensor network applications. An inexpensive, easy to build, efficient and electrically-small antenna system would be an ideal fit for many new generation communication and sensor systems.

Metamaterials, in general, are artificially fabricated media based on resonant or non-resonant inclusions that can be engineered to obtain unusual electromagnetic (EM) behaviours that can not be readily found in nature. The renewed activity in such artificial materials has attracted interest from different research disciplines and has produced many designs in a wide frequency spectrum including examples from microwave to millimetre-wave to optical structures. The proposed metamaterial based EM applications include subwavelength imaging at microwave and optical frequencies; phase compensated microwave circuit designs; efficient electrically small antennas (EESAs); leaky wave and low-profile antennas; scattering enhancements and mitigation (cloaking); etc. [1-3].

Metamaterials (MTMs) provide one with a design approach to tailor the permittivity and permeability properties of a medium to both positive and negative values for a variety of applications. We have been studying, e.g., [4, 5], the use of MTMs to achieve EESAs We have designed several metamaterial-based antenna systems in which specific metamaterial shells have been used to achieve distributed matching elements that provide a natural reactive *and* resistive matching. We have also designed MTM-inspired antenna systems [6-8], both planar (2D) and volumetric (3D) and both electric- and magnetic-based, of which some have been fabricated and tested. A comparison of our predictions and the corresponding experimental results for these MTM-inspired systems are in very good agreement.

We define an electrically small antenna in free space by the constraint that $kr_e \leq 1.0$, where r_e is the radius of the smallest sphere that surrounds the antenna system; and an electrically small antenna fed coaxially through a ground plane by the constraint $kr_e \leq 0.5$. The electrically-small limit for a coaxially-fed antenna through a ground plane is then $r_e \leq 0.08\lambda_0$.

2. Metamaterial-based EESAs

We have suggested the use of metamaterial shells as distributed matching elements that can lead to an EESA. An electrically-small electric (magnetic) dipole acts as a capacitive (inductive) element. We have demonstrated that an electric or a magnetic dipole antenna can be naturally matched to a 50Ω source by introducing an appropriately designed electrically-small epsilon-negative (ENG) or mu-negative or MNG shell, as well as with double-negative (DNG) shells in either case. These metamaterial-based antenna systems have been modelled with ANSOFT's HFSS and COMSOL's Multiphysics simulation packages. Both approaches provided the desired simulation of the input impedance of these antenna systems. The ANSOFT HFSS model was restricted to ideal, frequency independent metamaterial shells; the COMSOL Multiphysics models

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provided us the means to include dispersive effects into the metamaterial shells. For instance, as shown in [5], the COMSOL Multiphysics simulation of a coax-fed monopole enclosed in an ENG shell was first designed with the non-dispersive ENG shells to achieve the desired resonant system. In particular, an input impedance $Z_{input} = 49.90 - 3.48\times10^{-4}\,\mathrm{j}\ \Omega$ was obtained at a resonance frequency of $f_{res} = 299.99$ MHz for the 50 Ω source with the parameters: coax inner conductor radius $a = 1.2\,mm$; coax outer conductor radius $b = 2.301\times a = 2.7612\,mm$; monopole length $\ell = 4.0823\,mm$; and ENG shell inner radius r_1 = 8mm; and outer radius r_2 = 15.502mm with $\varepsilon_r\left(f_{res}\right) = -3.0$. The predicted overall efficiency was 99.99%. These values give $ka = 0.0973$ and $Q_{\mathrm{Chu}} = 1/ka + 1/\left(ka\right)^3 = 1094.6$ at the resonance frequency. The quality factor obtained from the predicted resistance and reactance curves with Yaghjian and Best's formula, $Q_{\mathrm{YB}} = \left[f_0/2R_{input}\left(f_0\right)\right]\left|\left(\partial_f Z_{input}\right)\left(f_0\right)\right|$, was $Q_{\mathrm{YB}} \approx 12.02 = 0.011Q_{\mathrm{Chu}}$ in very good agreement with the corresponding analytical results. The COMSOL Multiphysics predicted electric field intensity distribution and the input resistance and reactance values are shown in Fig. 1.

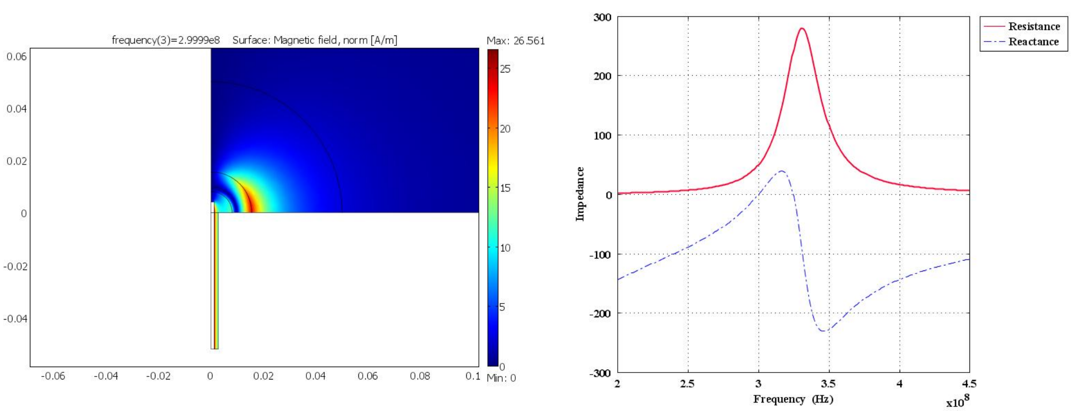

Figure 1. COMSOL model of the electrically-small coax-fed monopole-ENG shell antenna system: (a) predicted electric field intensity distribution, (b) Input resistance and reactance.

The dispersive ENG shells, specified by different limit models of the quantity $\partial_\omega\left(\omega\varepsilon_r\right)$, were then simulated with this COMSOL Multiphysics model. Because the permittivity value is identical by design for each model at the resonance frequency, the overall efficiency of the antenna system, even with dispersion being present, remains 99.99%. On the other hand, because the slope of the resistance and reactance curves will change with each dispersion model, the resulting Q values will be different for each of them. The predicted values of $Q_{\mathrm{YB}}/Q_{\mathrm{Chu}}$ for several passive dispersion models and one active (gain) dispersion model are given in Table I. One finds that a smaller $\partial_\omega\left(\omega\varepsilon_r\right)$ value, leads to smaller Q values and, hence, to larger fractional bandwidths. The results from the corresponding analytical resonant infinitesimal dipole-ENG shell systems are also given. The agreement between the analytical and numerical results is very good. As noted in [4, 5], all of the dispersion limit models, except the Drude (Yaghjian-Best) version, have Q_{YB} values below the corresponding Chu limit value. Results for similar metamaterial-based antenna systems that are matched to a 75Ω source are also provided to illustrate that the metamaterial shells can be designed to match an electrically-small antenna to a specified source. Numerical results such as these give us confidence that the analytically predicted Q values for idealized antenna systems are very good indicators of the performance of the corresponding more realistic systems.

The design of metamaterials to achieve these various dispersion models is currently in progress. At the present time, it has been demonstrated experimentally that one can achieve a lumped-element-based DNG metamaterial with a unit cell size that is $\lambda_0/75$ at 400 MHz with losses on the order of 1.0dB/cm. Further experimental realizations with even smaller unit cells and with controllable dispersion properties would allow the experimental determination of which model gives the ultimate physical limitation on the *Q* values on the metamaterial-based antenna systems.

Table 1. COMSOL predicted values of Q_{YB}/Q_{Chu} for various dispersion-limit models

Source	Drude	Landau-Lifschitz	Entropy	Lorentz-Lorentz Gain	Nondispersive
Analytical	1.59	0.80	0.60	0.010	0.010
50 W Coax	1.68	0.84	0.64	0.011	0.011
75 W Coax	1.38	0.70	0.53	0.015	0.015

3. Metamaterial-inspired EESAs

An electrically-small magnetic dipole (loop) antenna is known to be a very inefficient radiator, i.e., because it has a very small radiation resistance while simultaneously having a very small inductive reactance, a large impedance mismatch to any realistic power source exists. We have demonstrated [6] that a 3D, extruded capacitively loaded loop (CLL) element can be used as a natural matching element to an electrically-small loop antenna to achieve an antenna system with a high overall efficiency. We have also demonstrated [7] that an interdigitated 2D version of this antenna can also attain similar high overall efficiencies. We have fabricated and tested versions of these 2D magnetic-based EZ antennas. The geometry and a comparison of the predicted and measured S_{11} values are shown in Fig. 2. We have found that these 3D and 2D designs can be achieved for a broad range of frequencies. Designs at 300 MHz, 430 MHz and 1580 MHz will be presented.

An electrically-small electric dipole antenna is also known to be a very inefficient radiator, i.e., because it has a very small radiation resistance while simultaneously having a very large capacitive reactance, a large impedance mismatch to any realistic power source exists. We have demonstrated [8] that like the magnetic-based EZ antennas, we can achieve 2D and 3D electric-based EZ antennas that have high overall efficiencies. We have fabricated and tested a 2D version of these electric-based EZ antennas. We have found that these 3D and 2D designs can also be achieved for a broad range of frequencies. Designs at 430 MHz and 1300 MHz will be presented. The geometry and a comparison of the predicted and measured S_{11} values for one such 2D electric-based EZ antenna at 1373 MHz having $ka=0.497$ are given in Fig. 3. The corresponding radiated power has been measured in the reverberation chamber at NIST in Boulder, CO. There is very good agreement between our predictions and the measured results. In particular, the experimental results confirm the predictions of about a 90% overall efficiency.

4. Conclusions

Metamaterial-based efficient electrically-small antennas have been designed and simulated. Efficient electric- and magnetic-based 2D and 3D electrically-small metamaterial-inspired antennas have also been designed, fabricated and tested. The measured and predicted results are in very good agreement.

Acknowledgments

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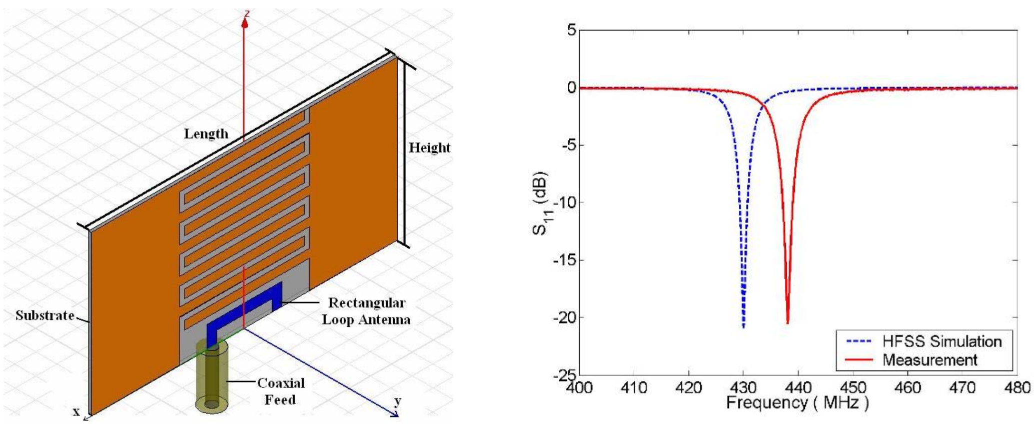

Figure 2. The 2D magnetic-based EZ antenna geometry and a comparison of the predicted and measured S_{11} values for an electrically-small limit case at 430 MHz.

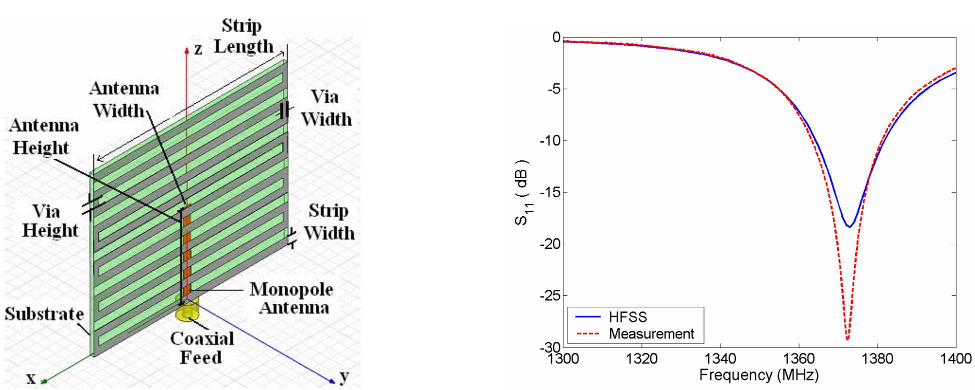

Figure 3. The 2D electric-based EZ antenna geometry and a comparison of the HFSS predicted and measured S_{11} values for an electrically-small limit case at 1373 MHz.