A PATH TO AN EFFICIENT ELECTRICALLY SMALL ANTENNA: A DIPOLE ANTENNA ENCLOSED IN A DOUBLE NEGATIVE (DNG) OR A SINGLE-NEGATIVE (SNG) METAMATERIAL SPHERICAL SHELL

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INTRODUCTION

Metamaterials are engineered media whose electromagnetic responses are different from those of their constituent components. They are often generated by incorporating in a periodic manner various types of artificially fabricated, extrinsic, low dimensional inhomogeneities in some background substrate. Metamaterials that mimic known material responses or that qualitatively have new response functions that do not occur in nature have been realized.

There are several classifications of metamaterials. We choose to name them based on their fundamental properties, i.e., by the signs of their permittivity and permeability. The double positive (DPS) metamaterials have both the permittivity and permeability positive, i.e., $\varepsilon > 0, \mu > 0$. The epsilon-negative (ENG) metamaterials have the permittivity less than zero, i.e., $\varepsilon < 0, \mu > 0$. The mu-negative (MNG) metamaterials have the permeability less than zero, i.e., $\varepsilon > 0, \mu < 0$. The double negative (DNG) metamaterials have both the permittivity and permeability negative, i.e., $\varepsilon < 0, \mu < 0$. This classification is depicted in Fig. 1. There have been a variety of antenna applications conceived and realized with these various types of metamaterials. We will focus our discussion on the possible realization of an efficient, electrically small antenna using metamaterials to modify the very near field of an electrically small dipole antenna to overcome its usual mismatch to free space. Special emphasis will be given here to an ENG shell surrounding such a dipole antenna.

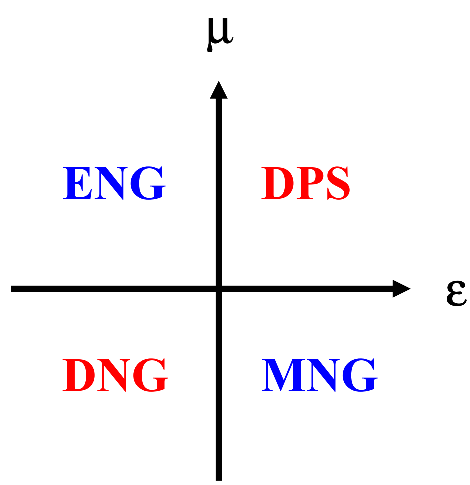

Fig. 1. Metamaterial classifications

ENG SHELL-DIPOLE ANTENNA SYSTEM

We have investigated previously the possibility of matching an electrically small electric dipole antenna to free space by surrounding it with a DNG spherical shell [1]. The three-region (two nested sphere) geometry used in the majority of our investigations is shown in Fig. 2. The inner radius of the DNG sphere is r_1, the outer radius is r_2. Relations for the electric and magnetic vector potentials, and for

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the resulting electric and magnetic fields, are obtained in a straightforward manner for each region. The unknown coefficients in those relations are found by applying the appropriate electromagnetic boundary conditions, that is, by making the tangential fields, E_θ and H_ϕ, continuous across each shell interface. The resulting equations are straightforward to obtain and solve. It was demonstrated in [1] that an electrically small dipole antenna surrounded by an electrically small DNG shell can be designed to achieve a resonant configuration that significantly increases the power radiated by the dipole antenna in comparison to its behavior in free space.

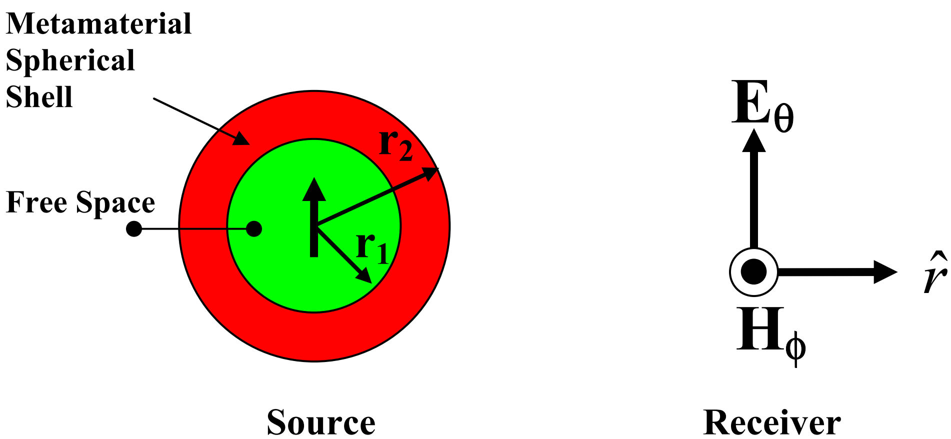

Fig. 2. Dipole antenna surrounded by a metamaterial shell.

Encouraged by the recognition of resonant scattering from metamaterial coated, electrically small spheres [2], [3], and confirmation of reciprocity between these source and scattering problems [3], [4], we began investigating the dipole-ENG shell configuration. The solution to the dipole-ENG shell system is a straightforward extension of the work in [1]. Because an electrically small ENG shell driven by an electromagnetic field will act as a dipole itself, hence, as an inductive element (i.e., as a capacitor loaded with a negative permittivity), it can be designed to produce the inductance needed to match it with the capacitance of the dipole antenna to form a resonant LC circuit. This concept is shown in Fig. 3. The possibility of matching an electrically small antenna with an ENG material alone rather than with a DNG shell is especially appealing, since ENG materials are found in nature or can be manufactured much more readily. For example, consider at 300 MHz an electrically small electric dipole with length $\ell = 10\,\text{mm} = \lambda_0/100$ embedded in a small sphere of DPS, free space material whose radius $r_1 = 10\,\text{mm}$, which is in turn surrounded by a ENG whose outer radius is r_2 and whose permittivity and permeability values are $(\varepsilon, \mu) = (-3\varepsilon_0, +\mu_0)$, where ε_0 and μ_0 are, respectively, the free space permittivity and permeability values. The external region, $r > r_2$, is assumed to be free space. Losses in the ENG medium have been introduced by setting $\varepsilon_2 = \varepsilon_{2re} - j\,\varepsilon_{im}$, where the loss tangents $L.T. = \varepsilon_{im}/\varepsilon_{2re}$ were set to the fixed values $0.0, 0.0001,$ and 0.001. The radiated power gain, i.e., the power radiated by the dipole-ENG shell system normalized by the power radiated by the same dipole in free space, both ideal dipoles being driven with the same 1.0 A current across their terminals, was obtained. The maximum radiated power gain of the analytical solution occurred at $r_{2,\max} = 18.79\,\text{mm}$. The losses simply reduced the peak of the response and caused a broadening of the resonance region. They do not make the effect disappear.

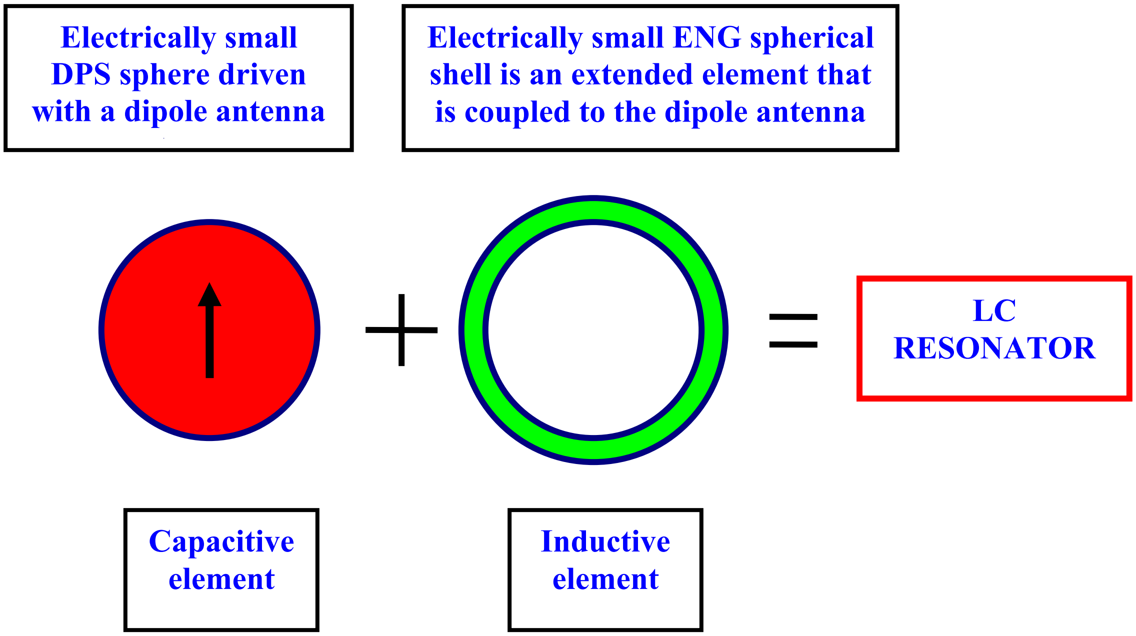

Fig. 3. An ENG shell combined with a dipole antenna can lead to a resonant system.

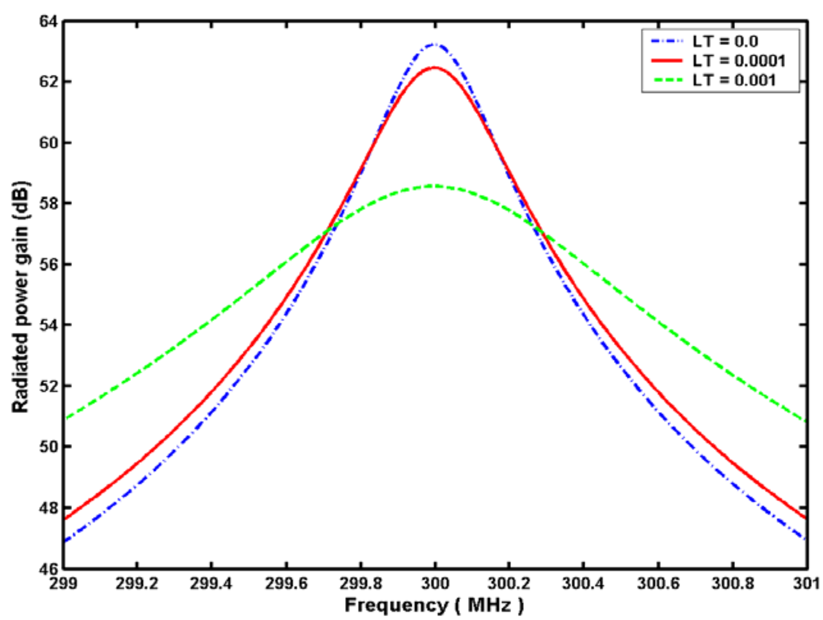

Fig. 4. Resonant radiated power gain of an electrically small dipole antenna surrounded by a matched electrically small ENG shell as a function of the driving frequency.

For the resonant ENG shell size, $r_1 = 10\,\text{mm}$ and $r_{2,\max} = 18.79\,\text{mm}$, the frequency response of the dipole-ENG shell system was then obtained. It is shown in Fig. 4. Clearly, there is a resonant enhancement of the radiated power for the specified choice of the ENG shell. The 3dB bandwidth of the radiated power gain for the lossless system is 13.3%, yielding a quality factor $Q = f_0 / \Delta f = 7.52$. In comparison, with the minimum enclosing sphere radius $a = r_{2,\max}$ at 300MHz giving $ka = 0.118$, the standard prediction of Q for an electrically small antenna (the Chu value) is $Q_{Chu,\, free\, space} = \left[1+2(ka)^2\right] \Big/ \left\{(ka)^3 \left[1+(ka)^2\right]\right\} \approx 616$. The ideal dipole-ENG shell system is thus found to yield a quality factor that is significantly smaller than the Chu limit.

HFSS MODELING OF A DIPOLE ANTENNA IN THE PRESENCE OF AN ENG SHELL

It must be realized that the dipole antennas in these analytical solutions are ideal and infinitesimal. We wanted to know how the dipole, if the actual size of the dipole with a realistic fed point was taken into account, and non-perfect spheres would − if at all − affect the enhanced gain predictions. We selected ANSOFT's High Frequency Structure Simulator (HFSS) as the computational electromagnetic (CEM) modeling tool for this investigation. Because of its resonant nature the dipole-ENG shell configuration proved to be a very difficult problem for HFSS. A large number of HFSS simulations were tested to obtain a valid dipole – ENG shell system model. Our antenna was modeled as a cylindrical dipole of length $\ell = 10\,\text{mm}$ that had a current gap feed of length $0.2\,\text{mm}$. The radii of the dipole and feed were both $0.1\,\text{mm}$. Thus there was a large aspect ratio that had to be handled by the mesh; this consequently led to very large simulation sizes and, hence, run times. We introduced E- and H-symmetry planes to reduce the size of the HFSS simulation space, i.e., to one octant. The inner radius of the ENG sphere was set to be $10\,\text{mm}$. The outer sphere radius was first varied to find the optimum size. Then the shell size was fixed at the optimum value and the frequency was varied. While there is a slight shift in the resonant shell radius and corresponding resonant frequency, comparisons of the results obtained with the analytical model and the HFSS simulations for the fields, the radiated power gains, and the frequency bandwidth of the system show very good agreement. Comparisons between the analytical and HFSS results will be presented. We are currently investigating how the presence of a feeding network will impact these results, i.e., we are now modeling the radiation efficiency and radiated power gains for specified input powers. We are also currently using HFSS to design a metamaterial that exhibits the desired ENG properties and that could be integrated into a spherical geometry. These additional studies will also be presented. They are giving us insight into how a realistic electrically small efficient antenna (EESA) might be achieved.

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