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Electromagnetic Antenna Cloaking with Metamaterial Structures

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Abstract- Electromagnetic (EM) cloaks, based on spatial transformations, can potentially be utilized as shielding devices for antennas in close proximity with multiple antenna arrangements as well as highly scattering environments. In these environments each antenna can be enclosed in a cloak that is designed to be shield at the transmitting frequencies of the neighboring antennas, but assumes free space values for the shielded antenna so it can radiate unimpeded. Perfect EM cloaking is, however, difficult owing to the anisotropic, inhomogeneous material parameters of the cloak. The physical embodiment of such structures, as well as numerical calculations, is exceedingly difficult, if not impossible, for realistic 3-D structures. To overcome these immense issues, this research utilizes dispersive media (Drude or Lorentz models) that can minimize some of the problems (anisotropic, inhomogeneous material parameters) associated with “true” cloaks, but can yield similar cloaking properties. The resulting cloak is frequency dependent which cloaks at a specific frequency and is transparent at other frequencies. The resulting medium is isotropic and homogeneous.

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Electromagnetic Antenna Cloaking with Metamaterial Structures

Ronald J. Spiegel [α] & Shengbing Shi [σ]

Abstract- Electromagnetic (EM) cloaks, based on spatial transformations, can potentially be utilized as shielding devices for antennas in close proximity with multiple antenna arrangements as well as highly scattering environments. In these environments each antenna can be enclosed in a cloak that is designed to be shield at the transmitting frequencies of the neighboring antennas, but assumes free space values for the shielded antenna so it can radiate unimpeded. Perfect EM cloaking is, however, difficult owing to the anisotropic, inhomogeneous material parameters of the cloak. The physical embodiment of such structures, as well as numerical calculations, is exceedingly difficult, if not impossible, for realistic 3-D structures. To overcome these immense issues, this research utilizes dispersive media (Drude or Lorentz models) that can minimize some of the problems (anisotropic, inhomogeneous material parameters) associated with "true" cloaks, but can yield similar cloaking properties. The resulting cloak is frequency dependent which cloaks at a specific frequency and is transparent at other frequencies. The resulting medium is isotropic and homogeneous.

I. INTRODUCTION

The operation of high power antennas in complicated environments, such as the presence of large mounting structures on ships or aircraft, where multiple antennas may exist in close proximity has been a serious issue for a long time. Near field EM coupling between antennas can severely distort radiation patterns as well as affect antenna electrical input parameters. Likewise EM scattering from near-by metal structures can also induce unwanted currents on the antenna elements which can produce adverse effects. Many attempts over the last several years have been utilized to reduce coupling and scattering effects, but, to date, there has been no "silver bullet" to completely eliminate the problem.

With the relatively recent advent of theoretical developments in EM cloaking,[1,2] a new approach is potentially available to solve antenna coupling issues in complex scattering environments. The approach, however, is not without difficult issues, especially in the physical implementation of such devices. One major problem is the complex media associated with cloaks is based on spatial transformations. The resulting media of the cloak is generally inhomogeneous and anisotropic with properties that do not exist normally in nature. To overcome the problem, metamaterial technology has been utilized in the GHz range.[3] While the resulting structure works in a laboratory setting, the transition to a more commercial venue poses problems because of the cumbersome physical features of the cloaking structure.

The problem that is addressed by this study is illustrated in Fig. 1 involving two antennas and two cloaks.[4] In Fig.1 (a.) antenna A_1, operating at frequency f_1, transmits and receives through cloak C1, A near-by antenna A_2 which is cloaked by C_2 and is designed to cloak EM fields at frequency f1. The roles are reversed in Fig. 1(b.). In general 3-D cloaks with inhomogeneous and anisotropic media cannot be modeled with commercially available computer codes (e.g. CST, COMSOL) owing to the complexity of the problem. For example, COMSOL can only handle 2-D objects with anisotropic media. Also, the physical embodiment of such structures is exceedingly difficult, if not impossible, for realistic 3-D cloak-based structures.

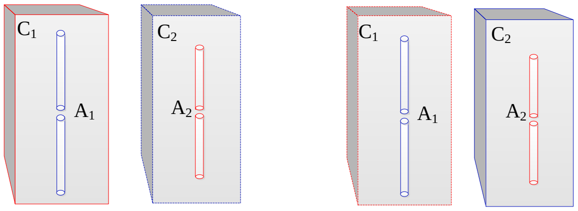

Fig. 1: Frequency configurations of antennas A_1, A_2 and cloaks C_1, C_2. (a.) A_1 radiating at f_1 and (b.) A_2 radiating at f_2. Solid boundaries for the cloaks indicate cloaking, while the dashed boundaries indicate the cloaks that are transparent

To overcome these immense issues, the cloaks developed in this study are not based on spatial transformations. Rather they are based on the dispersive properties of media, which will be shown to have similar cloaking properties as "true" cloaks for the antenna coupling problem. The resonance behavior of a material, such as a metamaterial, can be described with a bulk material model described by the Lorentz dispersion equation

$$\varepsilon_r = \varepsilon_\infty + \left[\left(\varepsilon_s - \varepsilon_\infty\right)\omega_0^2\right] / \left(\omega_0^2 + i\omega\delta - \omega^2\right) \qquad (1)$$

where ε_r is the relative dielectric constant; ω_0 is the resonance frequency; δ is the damping frequency; ε_s is

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the static dielectric constant; and ε_∞ is the dielectric value as the frequency becomes very large. To illustrate Eq. 1, numerical calculations presented below contain the following parameter values: $\omega_0 = 34.54 \times 10^9$ rad/s or $f_0 = 5.5$ GHz; $\delta = 0.628 \times 10^9$ rad/sec or 0.1 GHz; $\varepsilon_\infty = 1$; and $\varepsilon_s = 2$. Fig. 2 shows the real and imaginary parts of the dispersive relative dielectric constant, ε_r, for the listed parameter values.

There are some important features of these curves that should be emphasized. First, note that at the resonance frequency the real part of ε_r equals zero. The height and width of the imaginary component are controlled by the damping frequency. Above resonance, as the frequency becomes larger, the dielectric constant assumes the free space value. Below resonance frequency ε_r approaches 2. Note also that at f_0 the loss tangent of the material is infinity.

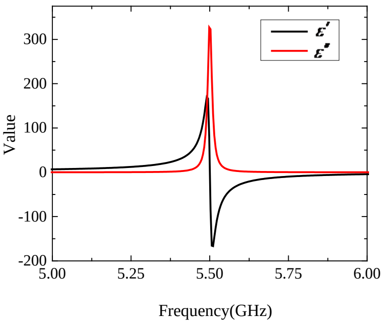

Fig. 2: Real and imaginary curves for ε_r

The complex wave number for the dispersive media can be expressed as $k = \omega k_0\sqrt{\mu_r \varepsilon_r}$ with $\mu_r = 1$

$$k = \omega k_0\sqrt{\varepsilon_r' + i\varepsilon_r''} \tag{2}$$

where ε_r' and ε_r'' are the real and imaginary components of ε_r, respectively, and k0 is the free space propagation constant. At the resonance frequency, $\varepsilon_r' = 0$ and k becomes imaginary so the wave in the media becomes strongly evanescent and virtually no EM fields exist in the material. In other words, the material acts almost like a perfect electric conductor (PEC). Thus, the two important features of this material are: (1) at the resonant frequency it acts almost like a perfect shield and (2) above and below the resonant frequency the material is almost transparent. If utilized in a manner depicted in Fig. 1, its properties can mimic a "true" cloak; hence the designation pseudo cloak. It should also be pointed out that the Lorentz model can be used for permeability. In Eq. (1) just replace ε with μ. Now at resonance the material acts like a perfect magnetic conductor (PMC).

To compare the properties of this cloak with those of a "true" cloak consider the following. An ideal cloak can only work for monochromatic (single frequency) EM waves. Generally, for an ideal cylindrical or spherical cloak, the radial constitutive parameters ε and μ are required to vanish (go to zero) at the inner boundary at the single frequency.[2] The singularity of the wave equation inside the cloak will form impenetrable PEC, PMC walls for EM waves. This is very similar to the condition of the pseudo cloak when ε_r or $\mu_r = 0$ at the resonance frequency forming a PEC or PMC like boundary. The difference, of course, is that for the pseudo cloak the entire layer acts like a shield whereas for an ideal cloak the barrier occurs at the inner boundary. This difference is essentially immaterial for cloaking antennas.

Finally, some difficulties of both cloaks should be pointed out. For non-monochromatic waves (all antennas have bandwidth) the shielding efficacy rapidly deteriorates away from the central frequency. The bandwidth limitations for an ideal cloak have been elaborated elsewhere.[5-7] It suffices to say that the main reason is based on group velocity delay. This delay is extenuated as the size of the shield gets larger, so that most ideal cloaks have to be small. For the pseudo cloak the reason is easy to see from Fig. 2 (a.). At resonance, when $\varepsilon_r = 0$, the slope of the response is very steep, resulting in a fairly narrow range of frequencies around the resonant frequency where ε_r values are close to zero. The saving grace is that most continuous wave communication antennas have very narrow bandwidths. However, some high peak power pulsed antennas may have wide bandwidths. Size limitations do not appear to be a problem for pseudo cloaks, except for the fact that large structures could influence the radiation patterns of nearby antennas.

Metamaterials (MMs) can produce EM phenomena that are not available in natural materials. Before construction of a prototype MM structure, numerical simulation can be used to design and analyze the MM structure as well as show that its properties are comparable to bulk properties of materials that are defined by ε and μ. For this study a split ring resonator (SRR) and a flat wire MM unit cell, as shown in Fig. 3, will be utilized. The split rings are comprised of a copper embedded on the top of a substrate and the flat copper strip id located on the back side of the substrate as shown in Fig. 3. The MM-based structure would consist of many of these small unit cells.

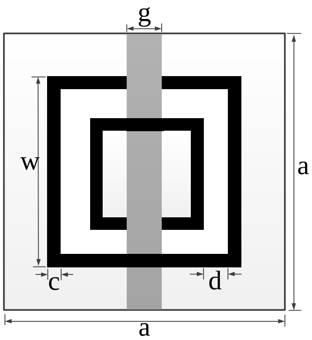

Fig. 3: SRR and flat strip MM unit cell (SRR on the front surface and the flat strip on the back side of the PCB board). Cell dimensions: gap and strip width g = 1.0 mm, a = 10 mm, w = 6 mm, d = 1.0 mm, c = 0.5 mm and substrate thickness = 0.5 mm. The substrate is comprised of a dielectric constant of 3.84 and a loss tangent of 0.018.

For a wave incident on SRR MM structure the S-parameters (S_{11} and S_{21}) for the structure are first calculated. The S parameters are related to the reflected, transmitted, and absorbed waves by the MM structure. The bulk properties (ε_{eff} and μ_{eff}) of the MM can then be calculated using either the Lorentz or Drude dispersive models. CST Studio can accomplish this by best fitting the parameters (ω_0, δ, ε_s and ε_s) associated with the Lorentz model (see Eq. 1) from the S-parameters associated with the MM structure. There are generally two approaches: parameter fitting of dispersion models and analytical extraction of medium parameters from S- parameters.[8]

The dispersion approach minimizes the difference between the S-parameters (scattering parameters) of the MM structure and a block of a homogeneous material with the same thickness as the MM unit cell. A Quasi-Newton optimization algorithm, which is built into CST's optimizer, is used to provide the best fit of the S-parameters of the dispersion model and the MM unit cell. The "goal" function in CST is to be minimized and for this case takes the form

$$Goal = \sum_n \begin{pmatrix} |S_{11} - S_{11ref}| + |S_{21} - S_{21ref}| \\ + |\angle S_{11} - \angle S_{11ref}| + |\angle S_{21} - \angle S_{21ref}| \end{pmatrix} \qquad (3)$$

where the equation includes both the magnitude and phase of the S-parameters and the summation is over all n frequency samples in the range of interest.

From CST's extraction procedure, the bulk properties of the associated with the SRR/flat plate structure were acquired. The extracted permittivity profile (not shown) was that of the Lorentz model and essentially the same as in Fig. 2, except the resonance frequency was approximately 4.49 GHz.

It is difficult to construct a spherical or a spheroidal antenna cloak out of MMs which are generally comprised of flat surfaces, a pseudo cloak was fashioned out of a rectangular box. The box structure contained the extracted permittivity profile for the SRR/flat plate structure. A view of the pseudo cloak is shown in Fig. 4, along with the dipole transmitter(1)/receiver(2) antennas. The dipole antennas were designed to operate at the Lorentz resonance frequency of the MM, approximately 5.5 GHz. To prove the effectiveness of the box to act as a cloak several different calculations were performed: e.g., S_{11}; S_{22}; S_{21}; a dipole operating inside and outside the cloak at both the resonance frequency and an off resonance frequency; and the radiating pattern of the transmitting dipole. However, space does not permit to show them all, but they all provided the necessary numerical proof that the concept was sound. To illustrate the point Fig. 5 contains the EM fields inside and outside the box produced by the transmitter antenna operating at the Lorentz resonance frequency. As observed the box provides very good shielding allowing very little energy to penetrate into interior of the box. In addition, the calculated induced current in the receiver antenna was approximately 9×10^{-4} with the box absent versus 2×10^{-10} with box present. These numerical data provide a good basis to proceed to the next step: construction of the pseudo cloak out of actual MM comprised of unit cells based on SRR/flat plate unit cell of Fig. 3.

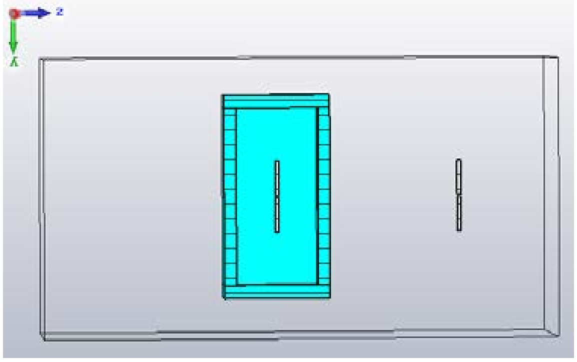

Fig. 4: Cross sectional view of a rectangular box shaped cloak, along with dipole antennas. Interior dimensions: sides 12 cm × 12 cm; top, bottom 6 cm × 6 cm; thickness 1.3 cm.

To verify the numerical results, MM boards with substrates comprised of woven E-glass and Epoxy were designed according to the specifications listed in Fig. 3 and fabricated (Better Boards, Inc., Cary, NC). Rectangular box structures of various sizes were assembled from the MM boards. The experimental set-up is shown in Fig. 6. Two monopoles were located over a ground plane and separated by 10 cm. Monopole 1 was primarily used as the transmit antenna and monopole 2 was utilized as the receiver antenna, although the roles of each antenna could be reversed. They were designed to operate at approximately the Lorentz resonance frequency of the MM structure (see

Fig. 2). Three different sized MM boxes were utilized in the study: sides of 3 × 3, 5 × 5, and 6 × 6 unit cells. The use of these MM structures allowed the determination whether the number of MM unit cells played a significant role in the cloaking features of the boxes. Measurements determined that all three boxes provided essentially the same cloaking performance, therefore, only the structure with sides containing 9 unit cells (3 × 3) and dimensions of 6 cm × 6 cm × 6 cm are presented here. This box is shown in Fig. 6. All the measurements were conducted using an Agilent Technologies (E8362B) 18 MHz – 20 GHz network analyzer.

Both monopoles were designed to operate at a resonance frequency of approximately 5.5 GHz. Fig. 7 contains the measured S11 and S21 profiles for the monopole antennas. As observed from Fig. 7 (a.) the lowest return loss for monopole 1 (similar for monopole 2) occurs at 5.26 GHz (approximately the Lorentz resonance frequency for the MM structure). From Fig. 7 (b.) note that S21 has a value of about -30 dB over most of the band covered (5 – 6 GHz).

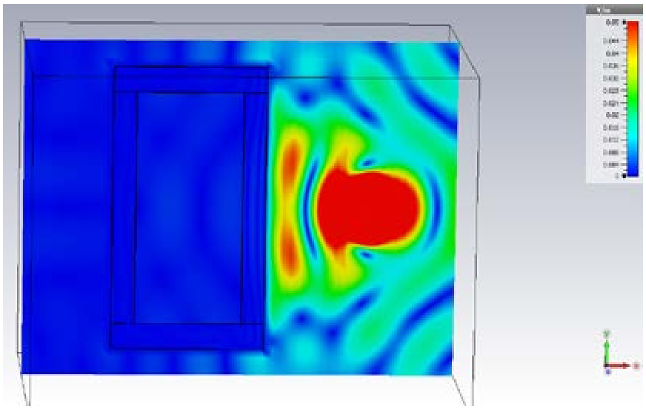

Fig. 5: EM fields inside and outside the box shaped cloak produced by an external 5.5 GHz dipole located 10 cm from the center of the box

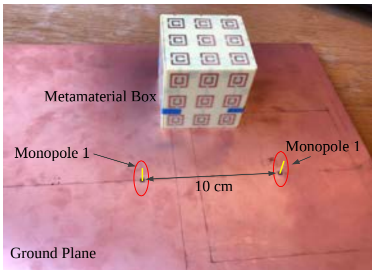

Fig. 6: A photograph of the experimental set-up

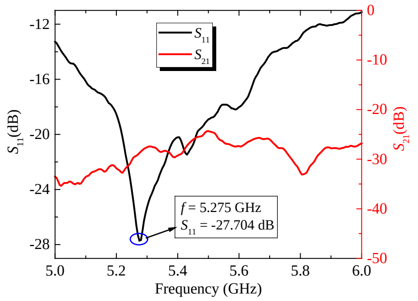

Fig. 7: S_{11} for monopole 1 and the coupling (S_{21}) between monopoles 1 and 2

Fig. 8 contains the results when the rectangular cloak is placed over either the transmit monopole or the receive monopole. When the MM box covers monopole2 (receive antenna), the S21 results are contained in Fig. 8 (a.). Observe that the cloak provide a very good shield (-85 dB) at a frequency of 5.59 GHz, which is very close to the extracted Lorentz frequency of 5.5 GHz. Fig 8 (b.) reveals similar results when monopole 1 (transmit antenna) is covered by the box, except the resonance frequency is slightly different (5.59 GHz versus 5. 62 GHz). It is likely that the small discrepancies in these measured resonance frequencies and calculated frequency (5.49 GHz) are due to small differences in the dielectric properties of the simulated and actual substrates.

Finally it is important to observe from the data in Fig. 8, for frequencies above and below the absorption band, the MM structure acts like it is essentially transparent to the incident fields. As shown the coupling values return to the levels measured when no box is shielding either antenna.

The experimental results verified the numerical predictions of the numerical simulations. MM cloaks at the resonant frequency almost act like a perfect shield and (2) above and below the resonant frequency the material is almost transparent. Its properties, for the antenna shielding problem, can mimic a "true" cloak with much less complexity in the properties of the MM structure. The measured shielding efficiency is over 99.9%.

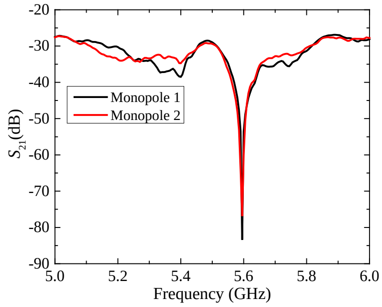

Fig. 8: Cloaking provided by the MM box.

Further work needs to be performed relative to the radiation patterns of two antennas in close proximity, when one or both antennas are covered by a MM box. Calculated results (not shown) have demonstrated that the radiation pattern may be slightly distorted by a rectangular MM box in close proximity to a radiating antenna. These numerical results, however, need to be verified by measured data. Radiation distortion may be improved by a smaller box or by a different structure with curved sides such as a sphere or spheroid. Of course, other antennas, such as a patch antenna, that radiate upwards rather than to the side as does a dipole-type antenna, help eliminate the problem.

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