Antennas and Propagation in the Presence of Metamaterials and Other Complex Media: Computational Electromagnetic Advances and Challenges

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1. Introduction

There have been significant advances in computational electromagnetics (CEM) in the last decade for a variety of antenna, propagation, and other classes of problems. Improvements in single frequency techniques including the finite element method (FEM), the fast multipole moment (FMM) method, and the method of moments (MoM) have led to significant simulation capabilities on basic computing platforms. Many commercial products have been made available through the efforts of many individuals. Similar advances have occurred with time domain methods including the finite difference time domain (FDTD) method, time domain integral equation (TDIE) methods, and time domain finite element (TD-FEM) methods. Very complex radiating and scattering structures in the presence of complex materials have been modeled with many of these approaches. The CEM simulators have enabled virtual EM test ranges that have led to dramatic improvements in our understanding of antennas and propagation in complex environments and to the realization of many of their important applications.

2. General CEM Trends

The main computational engine of most frequency domain methods (EFIE, MFIE, FEM, FDFD) deals with matrix inversions. Solutions to larger problems require larger matrix solvers, hence, either clever algorithms or faster computers with larger in-core memory sizes. The main computational engine of most time domain methods (FDTD, TD-FEM, FVTD, TDIE) is based on a marching in time solution of a state-space system of either differential equations or integral equations. Solutions again require either clever algorithms or faster computers with larger in-core memory sizes.

The frequency domain integral equation approaches, for example MoM techniques, are based on formulations derived from applications of the boundary conditions associated with Maxwell’s equations. They require Green’s functions to propagate the fields from the sources to the observation points where the boundary conditions are then enforced. The integral equations are solved by first representing the fields in terms of a set of basis functions; a matrix equivalent of the equations is then obtained by projecting the equations onto a set of testing functions. The choice of both testing and basis functions depends on the desired accuracy of the representation of the derivative and integral operations associated with the projections of the fields onto the basis functions, the applications of Maxwell’s equations (Green’s function and boundary conditions), and the projections of the equations onto the testing functions, as well as the desired speed of the computations. Because the propagation of field information is being described by Green’s functions, the source and observation points can be distantly separated. This non-local formulation has the advantage that one does not have to discretize the entire problem space; its disadvantage is that it leads to full matrices. Knowing the need to reduce the matrix fill times and the matrix solve times has led to several alternate approaches. Significant progress for antenna and scattering problems has been achieved, for example, with higher order schemes (Gedney, U. Kentucky; Peterson, Georgia Tech.); fast schemes based on the FMM approach (W. Chew, UIUC) and the
The frequency domain differential equation approaches, for example FEM techniques, are based on first decomposing the problem space into a set of geometrical building blocks (a mesh formed by usually triangles in 2D and tetrahedrons in 3D). A set of basis functions are created to match these elements. A weak form of the Helmholtz equation (second order differential equation obtained from Maxwell’s equations) for (usually) the electric field is then derived by projecting the equation and the boundary conditions onto these basis elements. A matrix equation relating the fields to the sources is obtained. However, in contrast to the IE methods, the resulting FEM matrix is sparse because the basis elements and the differential operations acting on them are very localized in space. This leads to faster matrix solutions of larger matrices, hence, the ability to handle a larger number of unknowns. Nonetheless, the FEM approach requires the discretization of everything in the problem space. However, it is very advantageous because the elements can be made to conform to the local features of the scatterers or antennas. The number of unknowns can be extremely large depending on the smallest feature to be resolved and the numerical accuracy desired. It also requires the introduction of absorbing boundary conditions (ABCs) to truncate the FEM mesh. Radiation conditions and variants of the perfect matched layer (PML) are commonly used. Because of the enormous number of unknowns required for accurate solutions to practical antenna and scattering problems, the need for clever approaches to reducing the number of calculations has been recognized. Significant progress for antenna and scattering problems has been achieved, for example, with higher order basis elements (A. Cangellaris, UIUC; R. D. Graglia, Torino; J.-M. Jin, UIUC; J.-F. Lee, OSU; D. White, LLNL); with domain decompositions and reduced order models (Cangellaris, UIUC); multi-level techniques (Z. Cendes, ANSOFT); and parallel computing schemes (T. Cwik, JPL).

In the time domain, the FDTD method has become one of the most common approaches for modeling antennas and propagation. The problem space is discretized in terms of “legos”, usually squares in 2D and cubes in 3D. Maxwell’s equations are discretized directly onto this regular mesh. The resulting state-space equation system is marched on in time. The Yee algorithm, which uses staggered grids for the electric and magnetic field components and a leapfrog time advance to achieve second order accuracy in space and time, is the most common. The advantage of the FDTD approach is complete flexibility in the types and arrangements of the structures and materials that can be modeled. The main cost of this flexibility is that it can be very compute intensive. There are other disadvantages too. In particular, because the FDTD grid can only stair-step a curved boundary, very fine discretization is necessary to yield accurate results for large dynamic range scattering (e.g., RCS) problems. Moreover, to ensure stability, the Courant condition leads to time steps restricted by the smallest feature to be resolved. There is also the need for accurate absorbing boundary conditions to truncate the mesh, particularly for highly resonant systems that require long simulation times to achieve steady state conditions. Again, however, these needs have led to several variants including conformal FDTD methods (A. Taflove, Northwestern; R. Mittra, PSU); higher order and more general discretization schemes (Petropoulos, NJIT; F. Teixeira, OSU); local grid refinement methods (R. Lee, OSU); reduced order models (Cangellaris, UIUC); multi-resolution methods using wavelets (M. Tentzeris, Georgia Tech.; L. Carin, Duke); accelerated algorithms through tailored VSLI (M. Okoniewski, U. Calgary); implicit schemes (O. Ramahi, U. Maryland); and the J.-P. Berenger (C.E.A., France) inspired PML schemes and their Maxwellian counterparts (S. Gedney, U. Kentucky; R. Ziolkowski, U. Arizona). Time domain finite volume (T. Weiland, Darstadt); transmission line matrix (W. Hoefer, Victoria); and IE methods (Michielssen, UIUC) provide alternate approaches.

While the frequency domain methods provide accurate solutions at one frequency, their solution at many frequencies is required for ultrawide bandwidth excitations. In contrast, the time domain solutions
naturally yield solutions for pulsed excitations, but require long run times to achieve steady state conditions. Both are very flexible for modeling complex structures. However, the frequency domain solutions have not been generally applied to complex media problems. For instance, it is difficult to introduce complex materials into IE formulations because the Green’s function in the presence of these materials must be known. Nonlinear materials are more naturally modeled in the time domain. On the other hand, the FDTD approach is suited to such problems. A large variety of lossy dispersion models have been incorporated in the approach. It can handle, for example, single frequency or broad bandwidth antenna structures coated with inhomogeneous dispersive dielectrics.

3. Metamaterials

In the past few years, there has also been a renewed interest in using structures to develop materials that mimic known material responses or that qualitatively have new response functions that do not occur in nature. Artificial dielectrics were explored, for example, in the 1950's and 1960's for lightweight microwave antenna lenses. Artificial chiral materials were investigated in the 1980's and 1990's for microwave radar absorber applications. Recent examples of these artificial material or metamaterial activities include electromagnetic band gap (EBG) structured materials in which the effects are associated with Bragg scattering resulting from periodic inclusions separated by a half-wavelength or more, and effective media generated by artificially fabricated, extrinsic, low dimensional inhomogeneities in a host substrate whose size and separation are much smaller than a wavelength. These metamaterials have led to a number of very interesting electromagnetic response functions including artificial magnetic conductors (AMCs), double negative (DNG), and negative index of refraction (NIR) behaviors. These engineered response functions are being used to modify the performance of a number of antenna systems and the environments in which their signals propagate and to realize a number of novel applications.

In my presentation I will highlight several of the recent advances in the general CEM area. I will then emphasize the importance of metamaterials to the general areas of antennas and propagation. I will then discuss how the CEM advances have led to our understanding of how metamaterials work themselves and in conjunction with radiating systems. The main approaches (to date) to simulating the behavior of metamaterials and their applications have been the FEM and FDTD techniques. I will also describe what I consider to be the CEM Challenges to improve our understanding and to advance the applications of antennas and propagation in the presence of engineered material environments such as DNG, NIR, and EBG materials. Example simulations include FDTD modeling of the negative refraction of a Gaussian beam, Fig. 1, and of the focusing of a Gaussian beam, Fig. 2, in a lossy, dispersive DNG metamaterial having an index of refraction \( n_{\text{real}}(\omega_h) = -1 \) at the driving frequency \( f_0 = \omega / 2 \pi \). Another FDTD simulation example in Fig. 3 represents a line source in a matched zero-index slab to achieve a highly directive output beam. A FEM simulator, represented by Fig. 4, modeled the results the resonant interaction of a dipole antenna and an AMC that consists of a finite metamaterial block formed with capacitively loaded loops embedded in a dielectric substrate in the absence of a ground plane.

4. Nano-Antennas

Another forward looking application of CEM techniques is their use for modeling nanotechnology structures such as nanoantennas (R. Ziolkowski), nanowaveguides (M. Tanaka and K. Tanaka, Gifu), EBG structures at optical frequencies (S. Noda, Kyoto; A. Scherer, Cal Tech; S. Fan, Stanford; R. W. Ziolkowski, U. Arizona); and multi-level atoms integrated with Maxwell’s equations (A. Taflove, Northwestern; G. Slavcheva, J. Arnold, Glasgow, and R. Ziolkowski, U. Arizona). This is a challenging CEM environment that requires novel incorporations of complex material models with Maxwell’s equations. Simulations of several of these phenomena will be included if time permits.
Acknowledgments: I would like to thank the ISAP organizers for giving me the opportunity to highlight many of the recent exciting CEM activities in the antennas and propagation community.

1. Negative refraction of a Gaussian beam in a DNG metamaterial slab.

2. Focusing of an expanding Gaussian beam by a DNG metamaterial slab.

3. Electric field radiated by a line source in a matched zero-index metamaterial slab.

4. Resonant interactions of a dipole antenna with a finite AMC metamaterial block.