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

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SUMMARY There have been significant advances in computational electromagnetics (CEM) in the last decade for a variety of antennas and propagation problems. Improvements in single frequency techniques including the finite element method (FEM), the fast mulitipole moment (FMM) method, and the method of moments (MoM) have led to significant simulation capabilities on basic computing platforms. Similar advances have occurred with time domain methods including finite difference time domain (FDTD) methods, 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. Many commercial products have been made available through the efforts of many individuals. 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.

key words: *computational electromagnetics, method of moments, finite element method, finite difference time domain, metamaterials*

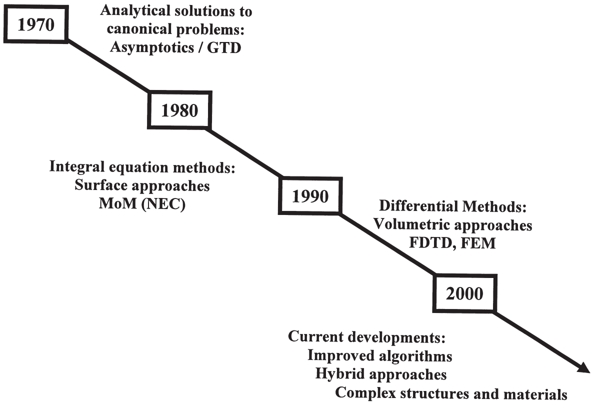

Fig. 1 Historical trends in computational electromagnetics (CEM) approaches.

1. Introduction

Consider the time line shown in Fig. 1. Many of the beginnings of computational electromagnetics (CEM) can be traced to scattering and diffraction algorithms based on asymptotic techniques such as geometrical optics and the geometrical theory of diffraction (GTD). Integral equation methods, such as the method of moments (MOM), provided some of the first CEM tools to generate self-consistent calculations of the behaviors of wire antennas (sources). The evolution of discrete differential equation based CEM tools, such as the finite element method (FEM) and the finite difference time domain (FDTD) method, followed and provided a means to simulate the behaviors of very general, complex electromagnetic (EM) environments.

The frequency domain integral equation approaches, for example, the standard MoM techniques such as those used in the Numerical Electromagnetics Code (NEC), are based on formulations derived from applications of the boundary conditions associated with Maxwell's equations. They require Green's functions to propagate either the electric (EFIE) or the magnetic (MFIE) fields from the sources to observation points where the appropriate EM 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 these equations is then obtained by projecting them 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 resulting equations onto the testing functions, as well as the desired speed and accuracy 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 complex 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 [1], [2]; fast schemes based on the fast multipole method (FMM) [3], [4]; and the characteristic basis function method (CBFM) [5]–[7]; with domain decompositions [8]–[10]; hybrid schemes, e.g., finite element-boundary integral (FE-BI) approaches [10]–[14]; and parallel computing schemes [15].

The frequency domain differential equation approaches, such as the FEM technique, are based on first

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decomposing the problem space into a set of geometrical building blocks (a mesh formed usually by triangles in 2D and tetrahedrons in 3D). A set of basis functions are created to match those 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 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 reduce the number of calculations has been recognized. Significant progress for antenna and scattering problems has been achieved, for example, with higher order basis elements [16]–[19]; with hybrid approaches [20]; with domain decompositions and reduced order models [20], [21] multi-level techniques [22]; and parallel computing schemes [23].

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 forward in time. The Yee algorithm, which uses staggered grids for the electric and magnetic field components and a leap-frog 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 the FDTD approach 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. Numerical dispersion can cause phase errors when large problems involving precise phase information are considered. 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 [24]–[26]; higher order and more general discretization schemes [27], [28]; local grid refinement methods [29]; reduced order models [31], [32]; multi-resolution methods [33]–[37]; implicit schemes [38]; and the J.-P. Berenger inspired PML schemes [39], [40], their Maxwellian counterparts [41]–[45], and recent ABC advances [46]. Time domain finite integration technique (FIT) [47], [48]; transmission line matrix [49]; IE [50]; and finite element [51], [52] methods provide alternate approaches.

While the frequency domain methods provide accurate solutions at one frequency, their solution at many frequencies is required for ultrawide bandwidth (UWB) 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 well suited to such problems. A large variety of lossy dispersive material models have been incorporated in the approach. It can handle, for example, single frequency or broad bandwidth antenna structures coated with inhomogeneous dispersive dielectrics.

Intimately coupled with methods and algorithmic developments have been the advances in computer technology. A historical view of the general classes of the platforms used for CEM tools is shown in Fig. 2. While the beginnings of CEM occurred on large centralized serial processor mainframes in the 1970's and 1980's, it began to move to distributed serial processor workstation environments and centralized parallel processor mainframes in the 1990's. More recently, parallel processor and even more powerful distributed serial processor workstation environments have been realized. The use of PC-class processors

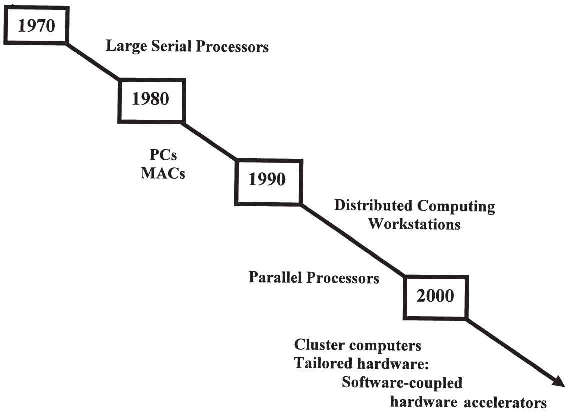

Fig. 2 Historical trends of hardware used to support computational electromagnetics (CEM) tools.

in massively centralized or distributed clusters has continued to increase our capabilities to model ever more complex, grand challenge classes of EM problems.

Despite the ever increasing quality and quantity of compute-resources, the demands for accuracy and speed for EM design applications continue to drive CEM research into novel domains. More robust and accurate CEM algorithms continue to be developed. More clever and efficient utilization of any given software yield desired answers in less time. More often than not, however, the user must still tailor his/her CEM algorithm for the specific computing platform to maximize its performance.

2. Recent 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.

One major direction for CEM algorithms is to continue to employ and refine hybrid strategies. More often than not, one method has appealing characteristics in certain regions of a problem while another is superior in the remaining regions. Hybridization of these approaches yields more efficient and accurate simulators. Another interesting trend is the use of hardware tailored to the CEM algorithm and to the EM problem under consideration. Yet another appealing research direction deals with combining together enhanced versions of standard CEM approaches with physics intensive packages appropriate for the description of the phenomena under investigation. This approach allows one to model more effectively the EM responses of large complex structures with more detailed and complete physics descriptions.

J. Volakis and his research team, for instance, have been very successful with hybrid finite element approaches [10], [11]. This includes the finite element-boundary integral (FE-BI) method, in which the FEM is used to model the volume fields while integral equations model the equivalent currents to enforce the EM boundary conditions at the boundary of the volume and the radiation conditions external to the volume, and the array decomposition method. The hybrid FEM approach has been used successfully to simulate printed antennas integrated with FSSs, large finite arrays, reconfigurable and multifunctional RF antenna apertures, antennas integrated with metamaterials and biological effects associated with antennas. Similarly, E. Yilmaz, H. Bagci, A. Cangellaris, J.-M. Jin, and E. Michielssen (UIUC) have combined together several solvers to achieve a hybrid EM/Circuit formulation that has proven to be very effective in modeling complex systems and environments [53]–[58]. Their hybrid approach includes time domain integral equation EM field solvers accelerated with FFT- and PWTD-methods and parallelized algorithms; linear and nonlinear lumped elements circuit solvers; macro models defined with state space descriptors and treated with recursive convolution; and transmission line (cable) model solvers based on a one-dimensional FDTD method. It has been used to simulate several interesting applications such as on-chip power grids, reflection grid amplifiers, and high-intensity radio-frequency (HIRF) susceptibilities of connected PCs and antenna arrays with a mixed signal PCB in cockpit environments.

The use of hardware accelerators has been very successful in many areas of electrical engineering, particularly with signal and image processing applications. Recent advances in this accelerator hardware have made it attractive to consider for CEM applications. For instance, it has been shown by M. Okoniewski and his research team [59] that the FDTD mesh can be represented as an LC network, each LC pair being represented as an integrator. Realizing these LC integrators in digital circuit form using bit serial representations, they have teamed with Acceleware, Inc., to produce an FDTD accelerator that can deal with 125 Mega-cells per second, more than five times faster than a conventional high performance PC platform. Analogous considerations in [60] have demonstrated similar enhancements.

A. Taflove and his research team, for instance, have combined the FDTD method with several classes of physics models. They have used the resulting FDTD simulators to model extremely low-frequency propagation within the Earth-ionosphere waveguide to identify potential precursors of earthquakes and to prospect for deep underground oil and ore deposits [61]; to model ultrahigh-speed wireless digital interconnects to investigate chip-to-chip data transfers at rates > 400 Gbits/sec [62]; to model optical ultramicroscopy; and to model bio-photonics to investigate the early-stage detection of epithelial cancers such as those found in the colon [63]. His team has also considered using rate equation models of multi-level atoms to achieve a self-consistent modeling of optical interactions with gain media in complex/random structures [64]. Similarly, R. Ziolkowski, G. Slavcheva, and J. Arnold [65]–[68] have combined FDTD solvers directly with semi-classical models of multi-level atoms to simulate a variety of optical phenomena including ultrafast pulse propagation under self-induced transparency (SIT) conditions and nonlinear gain dynamics in active optical waveguides and semiconductor microcavities.

The ability to predict the propagation of EM waves through and the scattering of EM waves from theoretical materials with unusual EM responses and to model directly these behaviors in the presence of their complex composite material realizations has allowed Ziolkowski [69]–[79], as well as a number other researchers, to investigate the behavior of metamaterials and nanostructures, and their use for a variety of EM applications. These CEM capabilities have allowed researchers to characterize the fundamental properties of metamaterials with numerical experiments, to design their physical realizations, to define protocols for experimental confirmation of their properties, and to guide understanding of the actual experimental results.

3. Metamaterials

Artificial dielectrics were explored, for example, in the 1950's and 1960's for light-weight microwave antenna lenses. Artificial chiral materials were investigated in the 1980's and 1990's for microwave radar absorber applications. In the past few years, there has 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. 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 approximately 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 conductor (AMC), double negative (DNG), single negative (SNG), 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.

An example of the use of CEM tools to simulate accurately the unusual behavior of an EM wave propagating in a DNG metamaterial, i.e., a medium with both $\varepsilon(\omega) < 0$ and $\mu(\omega) < 0$, is shown in Fig. 3. The FDTD approach is used to model the propagation of a Gaussian beam through a pair of DNG slabs [74], [75], [79]. The beam is launched two free-space wavelengths from the DNG slab pair with a half-wavelength waist. The DNG media are modeled by incorporating a low loss Drude material that is matched to free space, i.e., the relative permittivity and permeability are modeled as $\varepsilon_r(\omega) = \mu_r(\omega) = [1 - \omega_p^2/(\omega^2 - j\omega\Gamma)]$, where the angular frequency of interest ω_0 and the plasma frequency ω_p are related as $\omega_p^2 = \xi\omega_0^2$ and the loss parameter $\Gamma \ll \omega_0$. The first DNG slab has $\xi = 2$ so that $n_{real}(\omega_0) = \sqrt{\varepsilon_r(\omega_0)}\sqrt{\mu_r(\omega_0)} \cong -1$ and the second DNG slab has $\xi = 4$ so that $n_{real}(\omega_0) \cong -3$. The DNG slab pair is surrounded by free space; the depth of each slab is two free-space wavelengths. The beam is normally incident on the slabs; the interface of the first slab is in the far field of the beam. Thus the beam is diverging when it begins to interact with the first DNG medium. At the interface between a douple positive (DPS) and a DNG medium, Snell's Law gives a negative angle of refraction, i.e., $\theta_{refraction} = -\sin^{-1}(\theta_{incident}/|n_{DNG}|)$. Thus the first slab will convert the diverging beam into a focusing beam, the initial waist being recovered by design at the interface between the two slabs. Because of the larger magnitude of the index of refraction in the second slab, the angle of refraction is very small and the slab channels the beam energy through it, the wings of the beam feeding its center. The field level at the output face of the second DNG slab is approximately the same as its value at the input face. The beam expands at the free-space rate once it emerges from the second slab. The snapshots in time of the electric field intensity predicted by the FDTD simulator in Fig. 3 illustrate this behavior. The electric field intensity is shown for: (a) $t = 0$, (b) $t = 1200\,\Delta t$, (c) $t = 2100\,\Delta t$, and (d) $t = 6000\,\Delta t$. These CEM results confirm the ability of a flat DNG slab to focus a diverging beam and the possibility of channeling a beam through a flat DNG slab.

Another example of the ability of the FDTD approach to model unusual metamaterial behavior is given in Fig. 4. A line source is located in the center of a slab of matched zero-index metamaterial, i.e., $\varepsilon_{real}(\omega_0) \cong 0$ and $\mu_{real}(\omega_0) \cong 0$ so that $n_{real}(\omega_0) \cong 0$ [77]. The metamaterial is modeled as a low loss Drude material with $\xi = 1$. The slab is $\lambda_0/10$ thick and is backed with a perfect magnetic conductor (PMC)

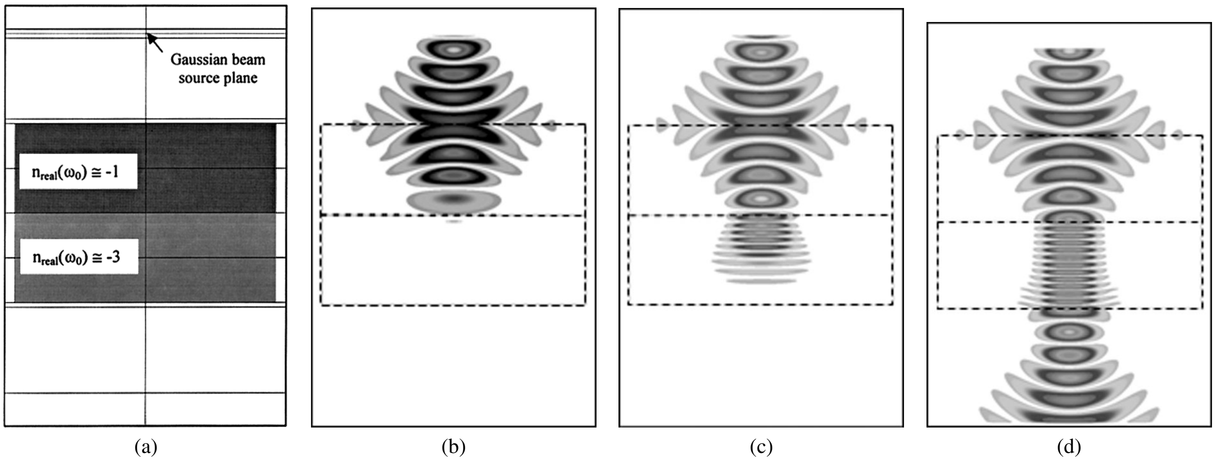

Fig. 3 A diverging Gaussian beam is focused by a $n_{real}(\omega_0) \cong -1$ flat DNG slab and then channeled by a $n_{real}(\omega_0) \cong -3$ flat DNG slab before being re-emitted as a diverging Gaussian beam. The electric field intensity is shown for: (a) $t = 0$, (b) $t = 1200\,\Delta t$, (c) $t = 2100\,\Delta t$, and (d) $t = 6000\,\Delta t$.

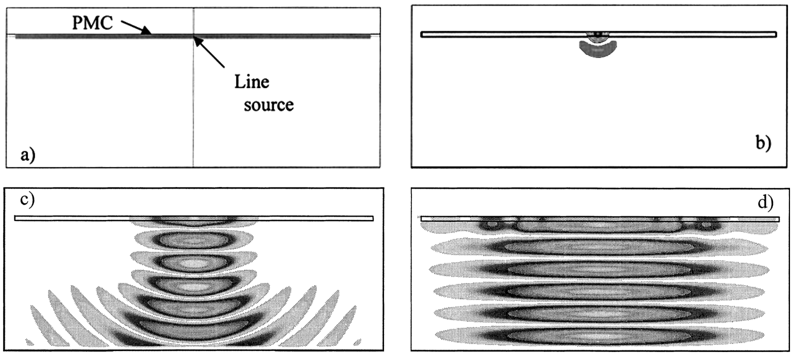

Fig. 4 The electric field intensity radiated by a line source centered in a $\lambda_0/10$ thick zero-index slab that is terminated in a PMC sheet: a) $t = 0$, b) $t = 167\,\Delta t$, c) $t = 1000\,\Delta t$, and d) $t = 4833\,\Delta t$.

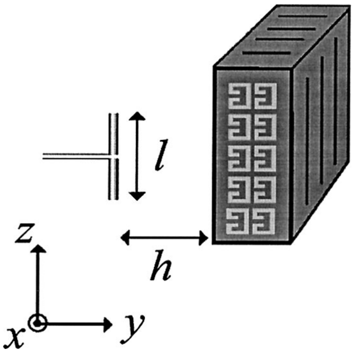

Fig. 5 HFSS geometry to simulate the resonant interactions of a dipole antenna with a finite AMC metamaterial block.

ground plane. As shown by the FDTD predicted snapshots in time of the electric field intensity in Fig. 4, the cylindrical wavefronts emitted by the line source are quickly converted into planar wavefronts. The zero-index slab causes the entire output face of the slab to have the same phase, thus resulting in a highly directive output beam.

The main CEM approaches used (to date) to simulate the behavior of metamaterials and their applications have been the FDTD and FEM techniques. The FEM approach has been used, for example, by Ziolkowski's research team to design and model physical realizations of DNG and AMC metamaterials [70], [78], [79]. An example of one such geometry is shown in Fig. 5 [78], [79]. Ansoft's High Frequency Structure Simulator (HFSS) has been used to model 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. More than the expected factor of two enhancement of the electric field in the broadside direction, as well as a front-to-back ratio of approximately 44.2 dB (162), has been predicted when the resonant interaction occurs. Such HFSS simulations are being used currently to design an experimental realization of this configuration.

4. Nano-Antennas

Another forward looking application of CEM techniques is their use for modeling nanotechnology structures. There has been much recent interest in a variety of nanostructures such as nanoantennas and plasmonic nanostructues [80]–[87]; nanowaveguides [88]; and EBG structures at optical frequencies [89]–[103]. Physical effects of interest include waveguiding via defects; NIR properties; plasmons; surface plasmon polaritrons; resonant dipole, quadrapole, and octopole coupling; nanocavity lasering; and other subwavelength scattering and propagation phenomena. This nanotechnology area is a challenging CEM environment that requires novel incorporations of complex material models with Maxwell's equations. Simulations of nanostructures will again provide a means to understand their basic physics, to help with their designs, to aid in testing their potential applications, and to act as guides for experiments.

5. Conclusion

There remain many challenges for using CEM tools to improve our understanding of metamaterials and to advance their usage in antenna and propagation applications. This includes phenomena in the microwave, millimeter wave, terahertz, and optical regions of the frequency spectrum. The CEM tools have proven extremely valuable in aiding the development of current technologies; they will continue to play a major role in all future EM applications.

Interested readers can consult a variety of general references for recent CEM advances including, for instance, [104]–[106] for FEM techniques, and [106]–[109] for FDTD techniques. Collections of articles on very recent research on metamaterials can be obtained in [79], [110], and [111].

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. Finally, in such a brief review of such a very active research area, someone's efforts will have been inadvertently neglected. For all whose names or relevant work that I may have failed to note herein, I sincerely apologize.

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