Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method

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ADVANCES IN

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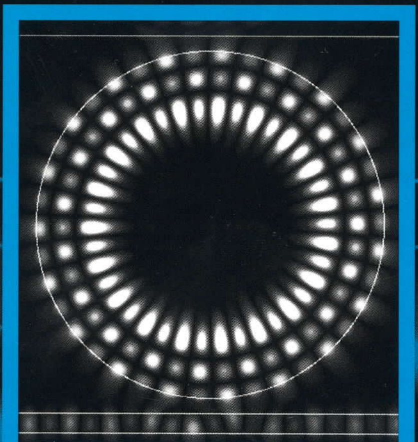
The Finite-Difference Time-Domain Method



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EDITOR

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Preface

The predecessor of this book, *Computational Electrodynamics: The Finite Difference Time Domain Method*, appeared in summer, 1995. I am gratified with its high level of use by both the university and industrial research communities. It is frequently cited in refereed journal papers as the primary background reference for FDTD methods and applications.

Since the publication of the 1995 book, there has been much progress in this field. When the publisher contacted me regarding a possible updating and expansion of the original work, I responded with a proposal for an entirely new book that would instead complement the original tutorial material. The basic ideas behind this book are:

- Provide a convenient single-source reference on the state of the FDTD art for university graduate students and faculty and professional engineers and scientists involved in electromagnetics technology;
- Build upon the strong base in FDTD theory presented in the 1995 book, while minimizing the duplication of content;
- Select the most important advances made in FDTD theory and applications since 1995;
- Present the absolute latest research results possible, organized into major themes that are mutually reinforcing;
- Engage experts in each topic area to write invited chapters that provide in-depth coverage;
- Encourage the chapter authors to provide ample and well-explained tutorial material in sufficient depth to permit the readers to replicate their results;
- Conduct a very active editorial role so that the final chapter manuscripts have a uniform style, read with a common "voice," and have common symbols and notation. That is, the book should read like a *book*, and not a disjointed collection of material cobbled together.

Chapter 1 is intended to provide an annotated FDTD literature review that is so comprehensive that it alone merits constant usage of the book. In this chapter, Dr. Shlager and Prof. Schneider substantially expand and update the review that they recently published in *IEEE Antennas and Propagation Magazine*. While their new review lays out the literature background for all of the material in the chapters that follow, it is noteworthy that these authors had no knowledge of the identities of the other contributors to this book. This was a strategy that Shlager and Schneider proposed to ensure complete impartiality in their review.

The theme of Chapters 2 and 3 involves new techniques aimed at reducing numerical dispersion and computer resources in FDTD approaches. In Chapter 2, Prof. Turkel reports recent progress in compact fourth-order spatial-differencing methods. The Ty(2,4) and Ty(4,4) algorithms investigated in this chapter permit 8:1 reductions in gridding density in each Cartesian direction relative to the classic Yee algorithm for comparable solution accuracy. Ty(2,4) is especially intriguing since it can be directly and easily overlaid on existing Yee grids, and uses Yee's leapfrog time stepping. Prof. Turkel further demonstrates how abrupt material boundaries can be treated in a manner that preserves the fourth-order accuracy of the basic numerical method. This approach has significant promise for incorporation in many existing FDTD codes.

In Chapter 3, Prof. Katehi, Dr. Harvey, and Prof. Tentzeris review their recent pioneering work in applying wavelet technology to FDTD methods. Their multiresolution time-domain technique permits an unprecedented control of the distance and time scales of the electromagnetic phenomena to be modeled, and yields significant reductions in numerical dispersion and computer burdens. Unique to this method is its ability to automatically adapt to changing needs for local space-time resolution as the various wave species being modeled propagate through the mesh.

The theme of Chapters 4, 5, and 6 involves recent advances in fundamental aspects of grid-based time-domain Maxwell's equations algorithms: (1) generalized meshes; (2) perfectly matched layer absorbing boundary conditions; and (3) periodic structures. In Chapter 4, a multi-disciplinary group of authors having university, national laboratory, and aerospace industry backgrounds (Prof. Gedney, Dr. Roden, Dr. Madsen, Dr. Mohammadian, Dr. Hall, and Dr. Shankar, and Mr. Rowell) combine forces to provide a comprehensive discussion of finite-difference and finite-volume time-domain techniques implemented on generalized meshes, including those that are unstructured. Their discussion extends over 100 pages and is intended to be both broad and deep. The authors' careful and detailed exposition of the theory is supported by computed examples for electromagnetic wave interactions with a variety of three-dimensional structures.

In Chapter 5, Prof. Gedney thoroughly discusses recent advances in PML absorbing boundary conditions, including means to terminate lossy and dispersive media. He details the most recent understanding of the nature and mutual relationships of the Berenger, stretched-coordinate, and uniaxial PML formulations. Comprehensive parametric studies are reported to allow the reader to optimally choose the PML parameters for best efficiency under a variety of practical modeling circumstances.

In Chapter 6, Dr. Maloney and Dr. Kesler review in detail their promising new work in modeling periodic structures within the confines of finite-sized FDTD space lattices. Several potential approaches are examined with regard to numerical stability, dispersion, accuracy, and efficiency. Practical examples involving a microwave photonic bandgap structure, a frequency selective surface, and an antenna array are discussed. This work opens new possibilities for FDTD modeling of an entire class of structures that previously could be investigated only by applying frequency-domain mode-matching or moment-method techniques.

The theme of Chapters 7 through 11 involves recent progress in FDTD modeling of specific, high-interest engineering applications in microwaves, millimeter waves, and optics technology. In Chapter 7, Dr. Maloney and Prof. Smith provide a detailed tutorial discussion of the key aspects of FDTD modeling of antennas. They then report a detailed benchmark FDTD study of a standard-gain microwave horn antenna used for transmitting and receiving, and demonstrate that superb correspondence can be obtained with high-quality measurements when the FDTD modeling is done with care and proper attention to details. The chapter concludes with examples of emerging FDTD modeling applications involving microwave photonic bandgap structures, ground-penetrating radar, and antenna-radome interaction.

In Chapter 8, Dr. Houshmand, Prof. Itoh, and Prof. Piket-May show how FDTD methods can be efficiently and systematically applied to model high-speed electronic circuits of all types, whether microwave amplifiers or digital circuits. On the microwave side, a key theoretical advance involves the development of simple (yet robust) Norton's and Thevenin's equivalent circuits "looking into" the FDTD space lattice. These equivalent-circuit connections into the FDTD solver permits its direct interfacing with the popular SPICE circuit-analysis software or with special-purpose state-variable circuit algorithms. On the digital-circuit side, specific FDTD techniques are presented to calculate the effective inductance of complicated, multiplane, power-distribution systems for multichip modules. In addition, an engineering case history is reviewed involving the use of FDTD in designing an ultrahigh-speed, 2.5-GHz clock-distribution scheme for a multichip module employing low-impedance Josephson-junction logic. Design trades-off are discussed.

In Chapter 9, Prof. El-Ghazaly reviews his pioneering work in combining FDTD electromagnetic wave modeling with the physics of charge transport within millimeter-wave MESFETs. Such a first-principles model is especially useful at frequencies in the many tens or even hundreds of gigahertz, where the lumped-circuit transistor models used in Chapter 8 (to link with Norton's or Thevenin's equivalent circuits of the FDTD grid) may lose accuracy. In this elevated-frequency regime, the simultaneous motion of semiconductor charges and electromagnetic fields across the transistor leads to mutual charge-field interactions that require a self-consistent model. After discussing the algorithmic aspects of the combined charge and electromagnetic wave simulator, the author goes into considerable detail regarding examples of full-physics MESFET design. A global design process is detailed wherein the MESFET physics is modeled while accounting for the input and output matching networks using a convolutional approach.

In Chapter 10, Prof. Hagness discusses recent applications of FDTD modeling to micron-scale optical resonators useful for low-threshold, high-speed lasers and practical optical signal processors. A variety of such structures are reviewed, including vertical-cavity surface-emitting lasers, photonic-bandgap structures, and strongly confined, waveguide-coupled, microrings and microdisks. The microrings and microdisks are particularly challenging for FDTD simulations since: the waveguide coupling is via the evanescent field (causing the sensitivity to gap dimensions to be high); resonator Q factors range up to 10,000; multimoding in the disk occurs due to various radial whispering-galley modes; and resonance splitting can occur due to nuances of surface roughness. The key aspects of these modeling challenges are thoroughly discussed, and engineering tradeoff studies of important design parameters are conducted.

In Chapter 11, Prof. Gandhi reviews his pioneering work in using FDTD to evaluate the dosimetry and engineering aspects of human exposure to a wide variety of electromagnetic fields including those generated by 60 Hz power lines, VHF plane waves, ultrawideband electromagnetic pulses, and handheld wireless personal communications devices. Rigorous analytical, numerical, and experimental validations of the FDTD modeling approach are provided for canonical antennas adjacent to brain-equivalent phantoms. Experimental validations are also provided for FDTD predictions of far-field radiation patterns and near-field absorption within skull and brain tissues when actual cellular telephones are positioned adjacent to the human head. Here, highly detailed anatomical models derived from MRI scans are used in the FDTD investigations.

The twelfth and final chapter (by Prof. Chew) has its own theme: to provide an excellent, highly detailed tutorial discussion of imaging and inverse problems in electromagnetics. In addition to the widely used frequency-domain forward-scattering techniques used for this purpose, this chapter shows how FDTD modeling can be advantageously applied. Numerous examples of two- and three-dimensional reconstructions are provided to indicate both the potential and limitations of existing inverse-scattering methods and algorithms.

In assembling this book, I gratefully acknowledge the chapter contributors. Each one devoted considerable time wrenched from their busy schedules to create detailed and expert scholarly works, always under deadline pressure. Their biographical sketches appear at the end of the book. Also acknowledged are the helpful contributions of my graduate students, especially Milica Popovic, who assisted mightily in dealing with a variety of electronic downloads. I bid a fond farewell to Susan Hagness who now goes on to have graduate students of her own as a professor.

Finally, I acknowledge my wife, Sylvia, and younger son, Nate, now completing his sophomore year at New Trier High School. Quoting in part from the preface of the 1995 book, they "somehow were able to keep their composure while sharing a home with a very driven person..." In this case, it meant having to deal with a husband / dad who slaved on the computer for months on end until the wee hours every night, and generally wasn't much fun at all. (My older son, Mike, missed his Dad's isolation and grumpiness. He has been away from home as a freshman at the University of Iowa during most of the editing of this book. Lucky!)

The FDTD story is continuing. As indicated by the scope of the experts' contributions in this book, the electromagnetics engineering community is indeed rapidly moving "to develop detailed FDTD models of microchips, microlasers, and microcells, and bring the power of Maxwell's equations to bear upon society's needs in ultrahigh-speed communications technology." More so than ever before, I believe that electromagnetics engineers have a special responsibility to utilize their technical knowledge to enable people to freely communicate. We can best understand each other when we talk to each other. This is what our human society is all about.

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