Reinventing Electromagnetics:

Emerging Applications for FD-TD Computation

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Computed solutions to Maxwell's equations continue to lead to engineering advances of immense importance to society. The finite-difference time-domain method opens up a wide range of applications, traditional as well as novel.

MAXWELL'S PARTIAL DIFFERENTIAL EQUATIONS OF ELECTRODYNAMICS, formulated about 130 years ago, combined the then-separate concepts of electric and magnetic fields into a unified theory of electromagnetic wave phenomena. Nobel laureate Richard Feynman has called this theory the most outstanding achievement of 19th-century science. Now, engineers worldwide solve Maxwell's equations with computers ranging from simple desktop machines to massively parallel supercomputing arrays to investigate electromagnetic wave guiding, radiation, and scattering. As we approach the 21st century, it may seem a little odd to devote so much effort to solving the 19th century's best equations. Thus, I pose the question: Of what relevance are Maxwell's equations to modern society?

Until 1990, the answer to this question would almost certainly have related to the perceived need for a strong military defense. Solutions of Maxwell's equations for wave phenomena in this era were driven primarily by defense requirements for aerospace vehicles having low radar cross sections. The primary computational approach for detailed modeling of electromagnetic wave scattering involved setting up and solving frequency-domain *integral equations* for sinusoidal currents that had been induced on the surfaces of airplanes and missiles by an impinging radar beam. The integral equations were derived from Maxwell's equations by defining appropriate vector and scalar potentials and Green's functions. From a computing perspective, this *method of moments* procedure meant setting up and solving dense, complex-valued systems of thousands or even tens of thousands of linear equations using direct or iterative techniques.

Since 1990, interest in an alternative class of potential-free solutions of Maxwell's equations has exploded in the electromagnetic engineering community. These are solutions of four coupled *partial differential equations* (the two Maxwell's curl equations and the two Gauss's Law divergence equations)

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on space grids, in either the time or frequency domain. There are four primary reasons for this explosion of interest:

(1) Partial differential equation (PDE) solvers yield either sparse matrices (derived from finite-element frequency-domain formulations) or no matrices at all (finite-difference or finite-volume time-domain methods). The limitations of the existing dense-matrix linear algebra technology required for solving frequency-domain integral equations are thereby avoided.
(2) PDE solutions present a systematic approach to dealing with complex material properties and inhomogeneities important in the electromagnetic response of a structure. Here, specifying a new structure to be modeled is reduced to a problem of mesh generation rather than the potentially much more complicated problem of reformulating the underlying integral equation.
(3) Individual users' computer resources (whether at the desktop or available from a remote supercomputer facility) have expanded to the point where PDE solutions have become practical. 1980s-vintage supercomputing in the range of 10 Mflops to 1 Gflops is migrating to the desktop, while 1990s supercomputer capability is expanding from 10 Gflops to 1 Tflops.
(4) Combined with modern software and techniques for color graphics, visualization, and animation, PDE solvers yield detailed results for three-dimensional field distributions that can provide much insight into the physical mechanisms of electromagnetic wave interactions.

The level of interest in PDE solvers for Maxwell's equations has greatly expanded, as indicated by the more than 100 papers in this area presented at the IEEE Antennas and Propagation Society's international symposia in each of the past three years. This represents an order-of-magnitude increase since the mid-1980s. A similar evolution is happening in the symposia and journals of the IEEE Microwave Theory and Techniques Society.

However, the impact of emerging PDE Maxwell's equation solvers will not end with the traditional electromagnetic-wave-based IEEE societies. Such solvers, especially those formulated in the time domain to incorporate lumped or distributed nonlinear effects over extremely large instantaneous bandwidths, will have strong positive impact in two core areas of electrical engineering, electronic circuits and optics, which have not traditionally been associated with "exact" solutions of Maxwell's equations. Simply speaking, Maxwell's equations (with nonlinearities and dispersions properly modeled) provide an overarching framework for the physics of electromagnetic wave transport phenomena, and *all* high-speed devices of interest to modern society have such wave transport behavior as a critical operating factor.

Application areas

To pursue this theme, I will highlight several areas where PDE Maxwell's equations solutions are being applied, ranging from a traditional electromagnetic modeling problem involving scattering and radar cross section to a notably novel one involving interaction of subpicosecond optical pulses. In particular, the results discussed here were obtained using a space-grid time-domain approach for Maxwell's equations that I have pursued since 1972: the finite-difference time-domain method. (See the sidebar on p. 26 for a conceptual explanation of how the FD-TD and the related finite-volume time-domain (FV-TD) methods work, as well as for a list of additional references.) FD-TD has become extremely popular since 1990, with literally hundreds of papers published in the worldwide literature each year. The models discussed here, developed in my laboratory, represent a cross section of the wide-ranging applications of FD-TD computational electromagnetics. These include

- radar scattering by a jet fighter up to 1 GHz;
- radiation by wideband antennas and phased arrays;
- UHF, microwave, and optical interactions with human tissues for planning heat treatment of cancer and for studying how the retina works;
- crosstalk and ground-loop coupling in complex, multilayer circuit boards and connectors;
- analog and digital operation of transistor and logic circuits operating well above 250 MHz; and
- subpicosecond optical switches based on nonlinear interactions of self-focussed laser beams.

We ran the FD-TD models on Cray C-90 supercomputers, solving them for up to 180 million vector-field unknowns in three dimensions. (The software was subsequently ported to the Cray T3D, which allowed a nearly linear expansion of problem size with the number of processing elements.)

Radar cross-section modeling

It is feasible to embed an entire jet aircraft within an FD-TD space grid to compute its

FD-TD and FV-TD Methods for Maxwell's Equations

The problems involved in applying frequency-domain integral-equation, dense-matrix, method-of-moments (MM) technology to large-scale computational electromagnetics modeling have recently expanded interest in an alternative class of *nonmatrix* approaches: direct space-grid, time-domain solvers for Maxwell's time-dependent curl equations. These finite-difference time-domain (FD-TD) and finite-volume time-domain (FV-TD) approaches appear to be as robust and accurate as MM, but have dimensionally reduced computational burdens. They are analogous to well-known mesh-based solutions of fluid flow problems in that the numerical model is based on a direct time-domain solution of the governing partial differential equation. Yet, they are very nontraditional approaches for electromagnetic engineering applications, where frequency-domain methods (primarily MM) have dominated.

FD-TD and FV-TD are direct marching-in-time solution methods for Maxwell's curl equations that simulate the actual continuous electromagnetic waves by sampled-data numerical analogs propagating in a computer data space. These methods employ no potentials or Green's functions. Rather, they are based on volumetric sampling of the unknown electric and magnetic fields within and surrounding the structure of interest, and over a period of time. The sampling in space is on a predefined mesh at a resolution set by the user to properly sample (in the Nyquist sense) the highest near-field spatial frequencies thought to be important in the physics of the problem. Typically, 10 to 20 samples per wavelength are needed. The sampling in time is selected to ensure the algorithm's numerical stability.

Time-stepping continues as the numerical wave analogs propagate in the space grid to causally connect the physics of all regions of the target. Phenomena such as induction of surface currents, scattering and multiple scattering, aperture penetration, and cavity excitation are modeled time step by time step by the action of the curl equations analog. Self-consistency of these modeled phenomena is generally assured when their spatial and temporal variations are well resolved by the sampling process, and the time-stepping is continued until all causality criteria are met.

The primary FD-TD and FV-TD algorithms used today are fully explicit second-order-accurate grid-based solvers employing highly vectorizable and concurrent schemes for time-marching the six vector components of the field at each of the volume cells. The recently published Berenger perfectly matched layer theory[1] has been widely adopted to simulate the extension of the mesh to infinity by absorbing outgoing numerical wave modes at the mesh's outer boundary.

At present, the optimal choice of FD-TD or FV-TD computational algorithm and mesh is not settled. There is substantial effort by groups worldwide to evaluate and improve existing meshes;[2] to develop automated mesh generators suitable for specifying tens or hundreds of millions of grid cells in three dimensions;[3] and to develop efficient software for massively parallel supercomputers employing as many as 2,000 processors.[4]

Probing further

The classic papers describing the basic FD-TD algorithm and the first effective absorbing boundary condition for FD-TD were published, respectively, by K.S. Yee[5] in 1966 and by G. Mur[6] in 1981. In 1975, Morris Brodwin and I published the first FD-TD electromagnetic wave interaction models that could compute sinusoidal steady-state fields for 2D and 3D structures,[7,8] and in 1980 I coined the FD-TD acronym.[9] Two good collections of papers by active researchers in this field include the January–June 1990 combined issue of *Electromagnetics*; and Volume 2 of the Progress in Electromagnetics Research book series, *Finite Element and Finite Difference Methods in Electromagnetic Scattering* (Elsevier, New York, 1990). The first textbook and research reference focusing on FD-TD methods, *The Finite Difference Time Domain Method for Electromagnetics*, was written in 1993 by K.S. Kunz and R.J. Luebbers (CRC Press, Boca Raton, Fla.). Finally, Shlager and Schneider have recently established an online database for FD-TD literature.[10,11]

References

1. J.-P. Berenger, "A Perfectly Matched Layer for the Absorption of Electromagnetic Waves," *J. Computational Physics*, Vol. 114, No. 4, 1994, pp. 185–200.
2. N.K. Madsen, "Divergence Preserving Discrete Surface Integral Methods for Maxwell's Curl Equations Using Non-Orthogonal Unstructured Grids," *J. Computational Physics*, Vol. 119, 1995, pp. 34–45.
3. V. Shankar, A.H. Mohammadian, and W.F. Hall, "A Time-Domain Finite-Volume Treatment for the Maxwell Equations," *Electromagnetics*, Vol. 10, Jan.–June 1990, pp. 127–145.
4. S.D. Gedney and S. Barnard, "Efficient FD-TD Algorithms for Vector and Multiprocessor Computers," in *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, A. Taflove, ed., Artech House, Norwood, Mass., 1995, pp. 545–584.
5. K.S. Yee, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media," *IEEE Trans. Antennas and Propagation*, Vol. 14, No. 4, 1966, pp. 302–307.
6. G. Mur, "Absorbing Boundary Conditions for the Finite-Difference Approximation of the Time-Domain Electromagnetic Field Equations," *IEEE Trans. Electromagnetic Compatibility*, Vol. 23, No. 4, 1981, pp. 377–382.
7. A. Taflove and M.E. Brodwin, "Numerical Solution of Steady-State Electromagnetic Scattering Problems Using the Time-Dependent Maxwell's Equations," *IEEE Trans. Microwave Theory and Techniques*, Vol. 23, No. 8, 1975, pp. 623–630.
8. A. Taflove and M.E. Brodwin, "Computation of the Electromagnetic Fields and Induced Temperatures within a Model of the Microwave-Irradiated Human Eye," *IEEE Trans. Microwave Theory and Techniques*, Vol. 23, No. 11, 1975, pp. 888–896.
9. A. Taflove, "Application of the Finite-Difference Time-Domain Method to Sinusoidal Steady-State Electromagnetic Penetration Problems," *IEEE Trans. Electromagnetic Compatibility*, Vol. 22, No. 2, 1980, pp. 191–202.
10. K.L. Shlager and J.B. Schneider, "A Selective Survey of the Finite-Difference Time-Domain Literature," *IEEE Antennas and Propagation Magazine*, Vol. 37, No. 4, Aug. 1995, pp. 39–57.
11. URL http://www.eecs.wsu.edu/~schneidj/fdtd-bib.html.

induced surface electric currents and scattering cross section at radar frequencies up to at least 1 GHz. An example of this is shown in Figure 1, which depicts a snapshot of the induced surface electric current on the VFY-218 prototype Lockheed fighter plane at 1 GHz for nose-on incidence.[1] This model was implemented using EMDS, the Cray Research proprietary FD-TD software. EMDS incorporates Lockheed's computer-aided design software, ACAD, which enables engineers to construct complex aerospace structures. Then EMDS automatically generates a body-conforming electromagnetic wave model of the structure. Cray's MPGS software, which is integrated into EMDS, provides color visualization of the computed surface currents.

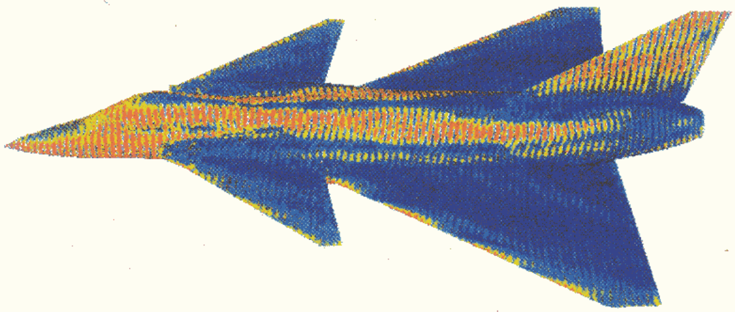

Figure 1. Distribution of electric current on the surface of a full-size Lockheed VFY-218 prototype fighter aircraft, computed by the FD-TD method with the EMDS software package from Cray Research. A 1-GHz plane wave is hitting the aircraft nose first. Modern supercomputing is permitting the detailed analysis and design of stealthy aircraft at microwave frequencies, by applying differential-equation–based Maxwell's equations solvers.

Antenna design

This area includes the design of UHF and microwave data links for worldwide personal wireless telephony, cellular communications, remote computing, and advanced automotive electronics (particularly car location and navigation). Here, FD-TD solvers for Maxwell's equations enable us to model complicated antennas, especially those having finite ground planes that cannot be analyzed using conventional frequency-domain methods (which are based on the Green's function).

In perhaps the most complex antenna modeling by any computational method so far (up to 60 million vector-field unknowns), Eric Thiele and I built FD-TD models for phased arrays of up to eight elements of Vivaldi tapered-slot antennas operating at 6 to 18 GHz.[2] (Vivaldi antennas are broadband printed-circuit structures, normally used in phased arrays to permit electronic beam steering. Past applications have included electronic counter measures on defense systems.) We obtained results for radiation pattern and input impedance, taking into account the complex interactions between the array's elements. Figure 2 shows the geometry of the quad Vivaldi antenna element and the eight-element phased array; it also shows the computed radiation patterns in the plane of the radiated electric field for the array at 12, 15, and 18 GHz.[2] This illustrates the evolution of strong, undesired radiation pattern lobes as the excitation frequency increases. Additional FD-TD studies have shown subtle ripples in the copolarized pattern and a large sensitivity of the cross-polarized fields to slight alignment errors and feed asymmetries arising during construction. Here, FD-TD computational modeling provides a means to prototype a complex antenna design on the computer and spot troublesome problems before any metal is bent.

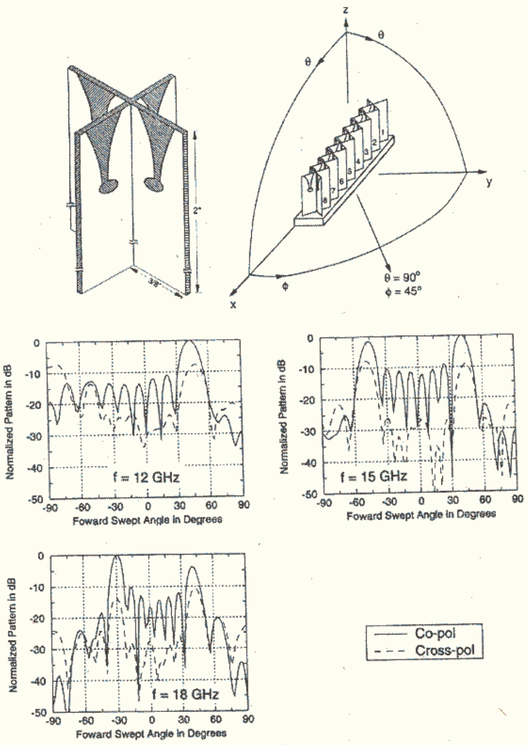

Figure 2. Top: geometry of a quad Vivaldi antenna element and an eight-element array. The graphs below illustrate the FD-TD–computed radiation patterns for the eight-element array assuming a 45° nominal beam steer. Note the evolution of undesired radiation pattern lobes as frequency increases. Large-scale Maxwell's equations solvers are now permitting the analysis and design of complex antenna arrays suitable for defense applications and wireless communications.

Hyperthermia treatment of cancer

FD-TD Maxwell's equation solvers are now being applied in clinical settings to design electromagnetic hyperthermia treatment. [The article by David Colton and Peter Monk on p. 46 in this issue discusses related work, the detection of disease via electromagnetic waves. —*Ed.*] This medical technology uses electromagnetic wave absorption at radio, UHF, or microwave frequencies to heat cancerous tumors inside the human body, thereby rendering the tumors more vulnerable to ionizing radiation or chemotherapy. Because FD-TD can construct enormously detailed models of inhomogeneous dielectric structures, the physician can tailor the electromagnetic hyperthermia protocol to individual patients by using computed tomography (CT) imaging. The user builds a database for the FD-TD solver representing a 3D dielectric medium that is unique to each patient's tissue structure. This enables the user to model the field physics unique to the patient's tissue geometry and then to select electromagnetic applicators. An example of this work is shown in Figure 3, which depicts the FD-TD–computed distribution of absorbed microwave power and induced temperatures in a CT-generated model of a particular patient's thigh. The waveguide hyperthermia applicator was modeled at 918 MHz.[3]

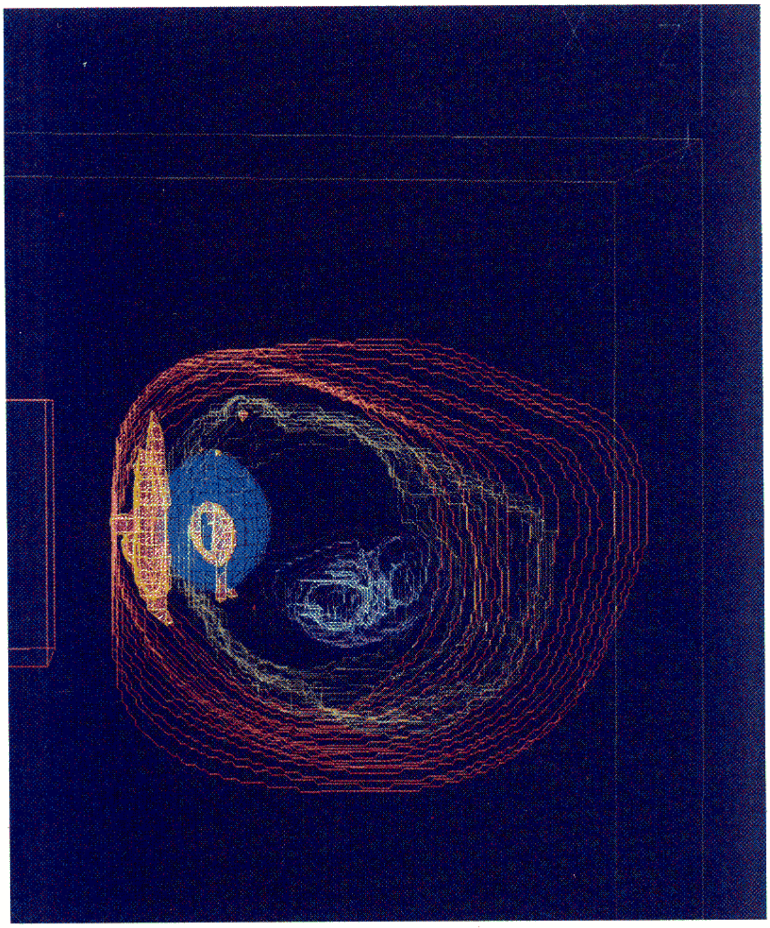

Figure 3. Model of a patient's thigh exposed to a waveguide hyperthermia applicator. The CT-generated planes are shown stacked one above the other from the top looking down. Yellow and magenta denote surfaces that absorb heat at a constant rate equal to 25 percent of peak; blue denotes surfaces at a constant induced temperature of 42° C. This temperature is the desired threshold for cancer cell destruction. The visualization helps the physician to see if the proposed treatment fully encompasses the tumor in the hot spot, and yet does not make the hot spot so large that good tissue is destroyed.

This work is leading to more effective clinical usage of electromagnetic hyperthermia for cancer treatment. Further, FD-TD computational technology may help researchers understand electromagnetic wave dosimetry in humans relevant to potential hazards such as cellular radio emissions. Ironically, this may aid us in understanding the flip-side question of cancer *formation* due to living in a world awash with electromagnetic energy.

Physics of human vision

In a similar bioelectromagnetics genre (but at much higher wave frequencies), it is possible to study the optical interactions of photoreceptors within the human retina from a fundamental electrodynamics perspective. My colleagues Melinda Piket-May and John Troy and I began the following project with the hypothesis that the detailed physical structure of a photoreceptor affects the physics of its optical absorption and, thereby, vision.

Figure 4 presents a visualization of the FD-TD–computed magnitude of the standing wave of the optical electric field within an idealized (but highly detailed) 2D rectangular model of an isolated human retinal rod of dimensions $2 \times 20\ \mu$m.[4] Plane-wave axial illumination with transverse magnetic polarization is assumed at the incident wavelengths 475 nm (blue light), 505 nm (green), and 714 nm (red). Using a very fine 5-nm uniform spatial resolution, it is possible to model in detail the rod's 15-nm-thick outer-wall membrane and its 15-nm-thick internal disk membranes. We assumed that there are 799 of these disks distributed uniformly along the length of the rod, separated from each other by 10 nm of fluid and separated from the outer-wall membrane by 5 nm of fluid. The index of refraction for the disk/wall membrane is taken as 1.43, and the index of refraction for the fluid is taken as 1.36, in accordance with generally accepted physiological data.

The FD-TD studies indicate that the bulk structure of the retinal rod exhibits the physics of

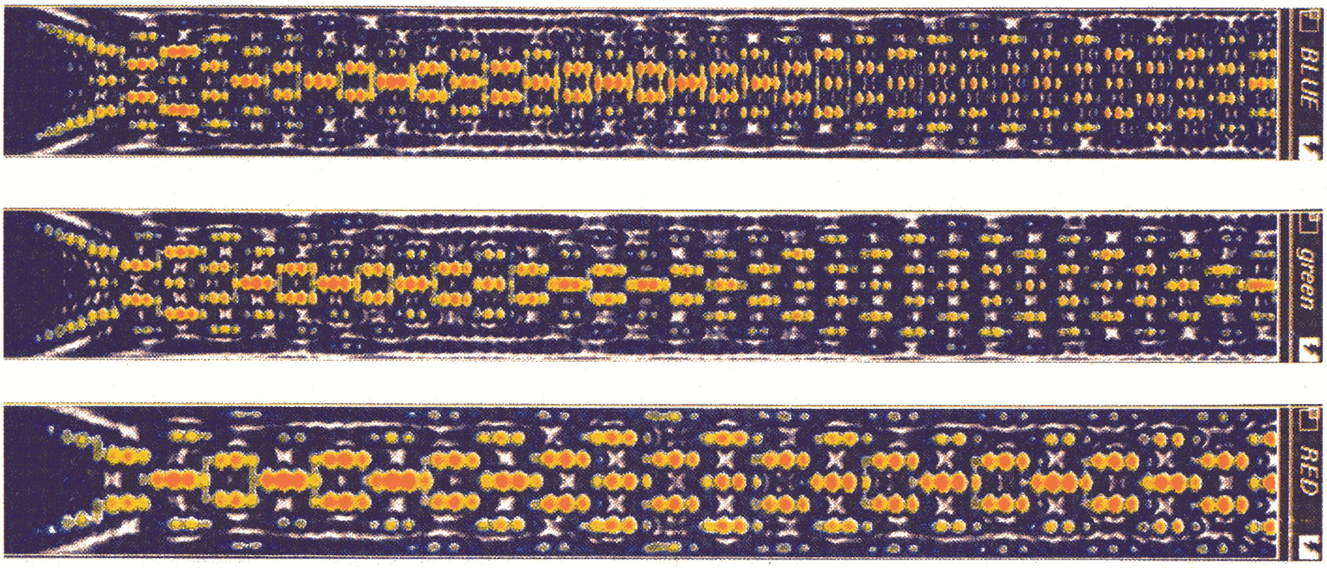

Figure 4. This standing wave of the optical electric field in the human retinal rod was computed using the FD-TD method at incident wavelengths of 475 nm, 505 nm, and 714 nm (top to bottom). The retinal rod seems to exhibit a type of frequency-independent electrodynamic behavior, a discovery that could lead to new structures for optical signal processing. FD-TD is the *one* method that permits the tissue complexity and size of this biological structure to be modeled for electromagnetic wave interactions. In this visualization, red represents the maximum intensity, yellow is above the incident intensity level, green is near incident, blue is low, and white areas are intensity minima.

an optical waveguide, while the internal disk-stack periodic structure adds the physics of an optical interferometer. As seen in Figure 4, these effects combine to generate a complex optical standing wave within the rod. To assist in understanding the physics of the retinal rod as a complex optical waveguiding structure, the 2D standing-wave data were reduced. First, at each illumination wavelength, the 2D field distribution was collapsed to a 1D distribution over the axial coordinate simply by summing the standing-wave values at each transverse plane in the rod. Then, a discrete spatial Fourier transform of the 1D distribution was taken over the axial coordinate. We found that, with the exception of isolated peaks unique to each wavelength, the spatial frequency spectra of the 1D distributions for each polarization are essentially *independent* of the illumination wavelength. The retinal rod thus appears to exhibit a type of frequency-independent electrodynamic behavior.

From an electrical engineering standpoint, frequency-independent structures have found major usages in broadband transmission and reception of radio frequency and microwave signals. There is a limited set of such structures, and it is always exciting to find a new one. In this case, my colleagues and I believe that we have pinpointed a frequency-independent biological cell structure that has been constructed by nature in each of our eyes. We speculate that frequency-independent retinal-rod–like structures may eventually be engineered and used for optical signal processing.

Digital circuit packaging and interconnects

Engineering problems in the propagation, crosstalk, and radiation of electronic digital pulses have important implications in the design of multilayer circuit boards and multichip modules, widely used in modern digital technology. Most existing computer-aided circuit design tools (Spice is one example) are inadequate when digital clock speeds exceed about 300 MHz. These tools cannot deal with the physics of UHF and microwave electromagnetic wave energy transport along metal surfaces like ground planes, or in the air away from metal paths, which predominate above this frequency. Electronic digital systems develop substantial analog wave effects when clock rates are high enough, and full-vector (full-wave) Maxwell's equation solvers become necessary for understanding them.

In what may be the most complex 3D modeling of these effects so far, Melinda Piket-May and I used FD-TD to simulate subnanosecond digital pulse propagation and crosstalk behavior in a real-world computer module. The system consisted of a stack of four multilayer circuit boards (each with more than 10 metal-dielectric-metal layers) linked by three connectors having scores of via pins.[5] We modeled the entire module—*each layer and via* of each circuit board and each connector—at a uniform resolution of 0.004 inch. Up to 6×10^7 electromagnetic-field-vector unknowns were solved per modeling run, a factor about 100 times larger than the capacity of the largest Spice or finite-element computer-aided design tool available.

Figure 5, top, shows a radially outward-propagating electromagnetic wave within the top circuit board of the stack; this wave was generated by a subnanosecond pulse passing down the via pin. Although the relatively intense magnetic field adjacent to the excited via was quite localized, moderate-level magnetic fields emanated throughout the entire transverse cross section of the board and linked all of the adjacent via pins. In fact, the video of the dynamics of this phenomenon showed repeated bursts of outward propagating waves linking all points within transverse cross sections of the board as the pulse passed vertically through the multiple circuit board layers. The resulting pin-to-pin crosstalk is vividly illustrated in Figure 5, bottom, which depicts the early-time coupling of magnetic fields from the excited via pin to the adjacent unexcited via pins, as seen in a vertical cut through the top multilayer board and interboard connector of the stack.

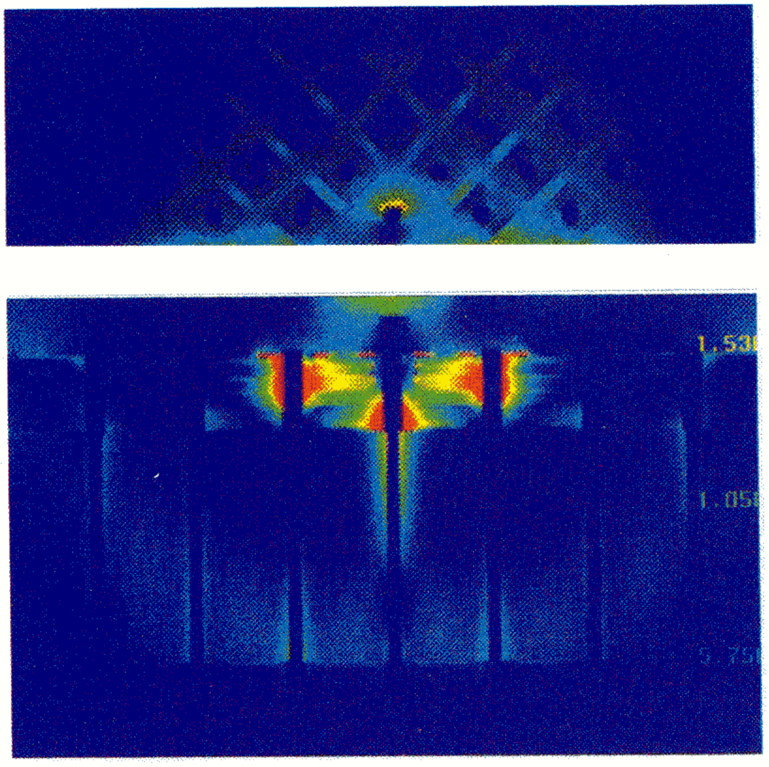

Figure 5. The FD-TD method applied to digital circuit packaging. In this visualization, the magnetic field is coupling from one via pin (excited by a subnanosecond pulse) to adjacent (unexcited) pins. The numerical model shows that the energy in a digital pulse may be guided only *loosely* by a metal path, and can readily couple to adjacent metal paths—thus possibly jamming the operation of the circuits connected to these paths. *Top*: A plan view, showing a cylindrical wave propagating radially outward in the top multilayer circuit board of the stack from the excited via pin. *Bottom*: A vertical cut through the top multilayer circuit board and interboard connector. Red is maximum magnetic field intensity; yellow is moderate; green is low-level; dark blue is negligible.

Figure 6 shows the magnitude and direction of the late-time currents flowing along the vertical cross section of the complete four-board/three-connector stack. A subnanosecond digital pulse was assumed to have excited a single vertical via pin in the top multilayer board. The currents were calculated in a postprocessing step by numerically evaluating the curl of the magnetic field obtained from the three-dimensional FD-TD model. At the time of this visualization, current had proceeded down the excited via through all four boards and all three connectors. However, upward-directed current is seen to flow on the adjacent vias. In effect, ground return current from the excited via jumped onto the signal pins of adjacent unrelated digital circuits. This represents an undesired ground-loop coupling which can jam the digital circuits using these vias.

Incorporating models of active circuit devices

It is an important and nontrivial conceptual leap to go from modeling only passive device packaging and interconnects, as discussed above, to including the physics of nonlinear active circuit devices (diodes, transistors, and logic gates) in the electromagnetics model. The lumped-circuit behavior of linear and nonlinear active devices can be directly incorporated into a generalized FD-TD Maxwell's equations solution, a solution that can model structures as complex as that of Figure 6. As before, the FD-TD simulation automatically and self-consistently takes into account the full-wave effects of distributed electromagnetic wave coupling, radiation, ground loops, and ground bounce.

The key to this process is linking circuit theory with field theory. In undergraduate electrical engineering programs, professors often tell students that circuit theory is a subset of field theory, but then promptly drop the connection because it is more convenient to proceed with analyzing the lumped devices of circuits rather than the distributed fields within those devices. However, as indicated by Figure 6, it is becoming apparent that the circuits/fields connection is not simply of academic interest, and may be readily implemented for substantial practical gain. (In fact, ignoring the circuits/fields connection can lead to a disaster caused by self-jamming of high-speed circuits.)

To explore this connection, it is useful to remember how circuit quantities (voltage, current, and impedance) relate to electric and magnetic fields. For simplicity, consider a microstrip line parallel to a conducting ground plane. If the microstrip is modeled in an FD-TD grid, we can excite it by specifying a Gaussian pulse time history for the collinear electric-field components that bridge the gap between the ground plane and the strip conductor at the desired source location. Then, by Faraday's Law, the line voltage V at any point along the line at any time step can be obtained by implementing a path integral of the FD-TD–computed electric field along a contour extending from the ground plane to the microstrip. Further, by Ampere's Law, the current I can be obtained at any point along the line at any time step by implementing a path integral of the FD-TD–computed magnetic field along a contour extending around the strip conductor at its surface. The characteristic impedance of the line can then be found by forming the ratio of the discrete Fourier transforms of V and I. Tests of this method for canonical problems have shown that FD-TD–computed voltages, currents, and impedances typically agree with textbook values to the order of one percent or better.

Using circuit quantities derived in this manner from three-dimensional FD-TD electromagnetic field data, Vince Thomas, Mike Jones, Melinda Piket-May, Evans Harrigan, and I have developed a prototype interface that seamlessly and self-consistently connects the FD-TD model to the popular Spice circuit analysis software.[6] Local software links to appropriate Spice kernels effectively couple individual lumped-circuit devices or collections of circuit devices to the metal signal traces embedded in the FD-TD field model. This results in FD-TD subgrid models of single transistors or transistor arrays, single digital logic gates or gate arrays, and associated passive resistive and reactive components, including all relevant nonlinearities and parasitics. In effect, anything that Spice can model can be coupled into the FD-TD field grid, thereby permitting a combined distributed-field/lumped-circuit simulation to be conducted.

To date, this approach has had very good success. We have attained excellent agreement between FD-TD/Spice results and rigorous benchmark data. For example, in one test, we determined that the FD-TD/Spice methodology permits a self-consistent simulation of the flow of electromagnetic wave energy *in both directions* through a nonlinear two-port network embedded within a 3D field grid. In fact, the nonlinear two-port network can be analog or digital and can contain multiple transistors and other components.

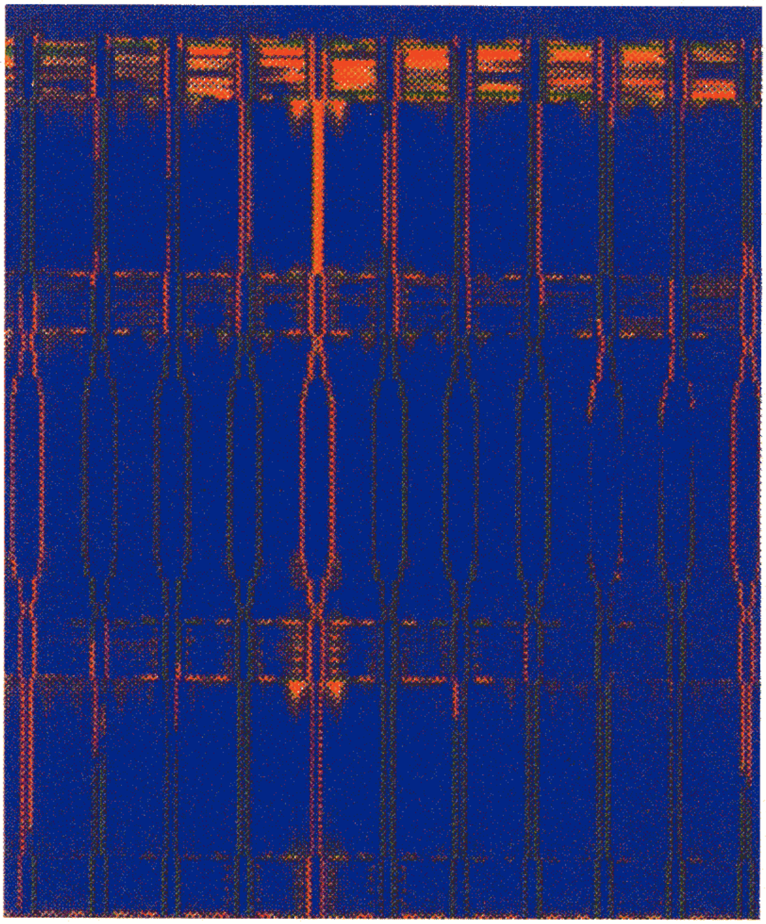

Figure 6. By computing and visualizing the magnitude and direction of current flowing through the complete four-board connector module (the same one shown in Figure 5), we can better understand the ground-loop coupling that can jam the operation of digital circuits. Red is downward-directed current, green is upward-directed current, and dark blue is negligible current.

There appears to be nothing to prevent FD-TD/Spice from being extended in a straightforward manner to arbitrary nonlinear multiport networks.

Continued progress in the FD-TD method and Spice should provide a novel and useful simulation tool for electrical engineers to obtain dynamic (time-domain) simulations of both digital and analog nonlinear circuits coupled directly to Maxwell's equations in three dimensions. This tool will be most useful when the speed of a circuit is so high and its physical embedding is so compact and complex that electromagnetic coupling, radiation, and ground-current artifacts are crucial in its operation, and when modeling the precise physical detail is required to properly understand these artifacts. An increasingly wide range of digital applications is expected as clock speeds approach microwave frequencies. These will include modeling the logical operation of chip assemblies mounted on 3D multilayer circuit boards and in multichip modules. Analog applications will include analysis of linearity, intermodulation, harmonic generation, and conversion efficiency of microwave and millimeter-wave integrated circuits embedded in similarly compact, complex structures. FD-TD/Spice should also enable us to model circuit upset due to external natural and manmade electromagnetic insults such as lightning, nuclear and conventionally generated electromagnetic pulse, and high-power microwaves.

Femtosecond all-optical devices

In electrical engineering, the phrase "DC to daylight" has often been used to describe electronic systems having the property of very wide bandwidth. Of course, no one actually meant that the system in question could produce or process signals over this frequency range. It just couldn't be done. Or could it?

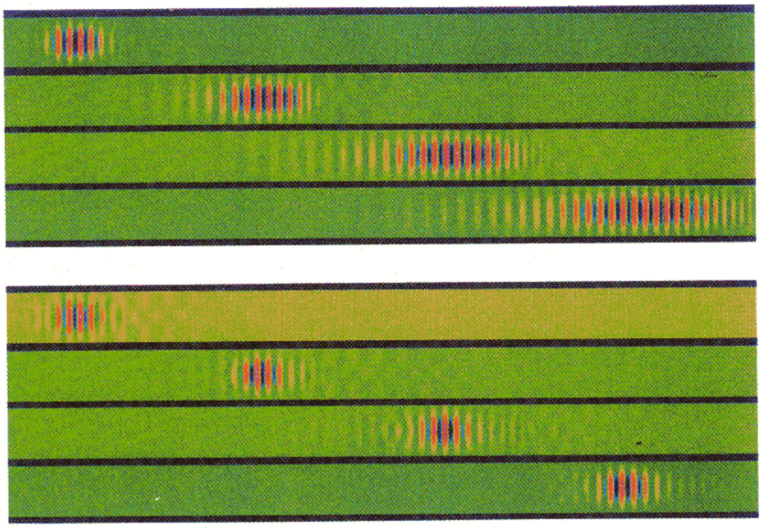

Figure 7. The electric field of a 50-fs optical carrier pulse propagating in a 1-μm-thick slab waveguide, computed by the FD-TD method. *Top*: Anomalous linear dispersion in the slab material causes the pulse to spread and the carrier frequency to vary. *Bottom*: Activation of a dispersive nonlinearity compensates for the effects of linear dispersion, yielding a temporal soliton that propagates indefinitely while maintaining its envelope shape. This demonstrates the capability of FD-TD to compute the propagation of ultrashort pulses generated by the most recent lasers.

In fact, a simple Fourier analysis argument shows that recent optical systems that generate laser pulses down to 6 fs in duration approach this proverbial bandwidth. (In contrast to continuous lasers which have very narrow bandwidths, these lasers are switched on and off so fast that spectral components over a very wide bandwidth are generated.) From a technology standpoint, it is clear that controlling or processing these short pulses involves understanding the nature of their interactions with materials over nearly "DC to daylight," and these interactions will most likely take place in high-beam-intensity regimes where the nonlinearity of material properties can play an important role. A key factor here is material dispersion, having two components. Linear dispersion is the change of the material's index of refraction (at low laser power levels) with frequency; nonlinear dispersion is the frequency-dependent change of the material's nonlinear coefficient (variation of refractive index with laser-beam power).

Two advances in our FD-TD computational solution of Maxwell's equations provide the basis for modeling both linear and nonlinear material dispersions in engineering glasses. These advances permit modeling ultrawide bandwidths sufficient to obtain the proper dynamics of femtosecond optical pulse propagation. The first advance was the development of a second-order-accurate algorithm for simulating femtosecond pulse propagation and scattering in linear materials having classical refractive index dispersions: the first-order (Debye) dispersion and the second-order resonant (Lorentz) dispersion.[7] Reflection coefficients computed using FD-TD were found to be accurate to six parts per 10,000 over the entire range of DC to visible light. This permitted for the first time the FD-TD computation of the delicate Sommerfeld precursor, a rapidly-propagating anticipatory pulse that is known to precede the main body of an impulse propagating in a dispersive medium. These computations were shown to be in excellent agreement with published, purely analytical (Laplace transform) theory.

The second advance was the development of an FD-TD algorithm for femtosecond optical pulse propagation and scattering for a nonlinear material having simultaneously a Lorentz linear dispersion and a Lorentz nonlinear dispersion.[8] (This behavior is characteristic of the glasses used today in optical fibers, which exhibit two key quantum interactions with light, the Kerr and Raman interactions.) This resulted in the first time-domain solution of the vector nonlinear Maxwell's equations to obtain the propagation and scattering of temporal optical solitons, including the sinusoidal optical carrier wave, in one and two space dimensions.[8,9] The latter is visualized in Figure 7. (A *temporal soliton* is a wave pulse whose envelope does not distort, even after propagating an indefinite distance, due to nonlinear effects in the medium that compensate for velocity dispersion. In effect, a temporal optical soliton is similar to a particle of light. Solitons have been proposed for both long-distance communications in undersea optical fibers as well as for optical-switching applications.)

Figure 8 provides a revealing example of the use of FD-TD modeling to provide a numerical space and time microscope to help design a proposed ultrahigh-speed photonic switch.[10] The switch would inject 100-fs signal and control optical pulses having a 0.65-μm beamwidth into a homogeneous Kerr-type nonlinear interaction region (glass) from a pair of input optical waveguides on the left. The signal and control pulses would interact in the glass medium and then couple into receptor waveguides on the right. In the absence of the control pulse, the signal pulse would propagate with zero deflection to the receptor waveguide 1, directly across from the injection point. In the presence of the control pulse, and depending upon its carrier phase relative to the signal pulse, FD-TD predicts that there would be either a single coalescence of the two pulses and then deflection to an alternate, laterally displaced collecting waveguide 2, or deflection to this waveguide without coalescence. Figure 8 visualizes the FD-TD–computed dynamics of this proposed switch, providing snapshots of the computed electric fields of the pulsed signal and control spatial solitons for a zero relative carrier phase at several simulation times. In fact, these are the first FD-TD Maxwell's equation calculations simulating *light switching light*. Such optical switching may one day be used to implement subpicosecond photonic logic gates that could be interfaced directly to optical fibers.

The novel FD-TD Maxwell's equations approach to computational nonlinear optics achieves robustness by retaining the optical carrier and by solving for fundamental quantities—the optical electric and magnetic fields in space and time—rather than a nonphysical envelope function, as did all previous approaches. It rigorously enforces the vector-field boundary conditions at all interfaces of dissimilar media in the time scale of the optical carrier, whether or not the media are dispersive or nonlinear. As a result, it is almost completely general and has the potential to provide unprecedented 2D and 3D pulse-dynamic modeling capability for submillimeter-scale integrated all-optical circuits. Digital switching rates for such circuits could reach 10,000 times that of the best semiconductor circuits today, and 100 times the speed of circuits constructed of Josephson junctions. The implications may be profound for the realization of *optonics*, a proposed successor technology to electronics in the 21st century that would integrate optical-fiber interconnects and all-optical microchips into systems of unimaginable information-processing capability.

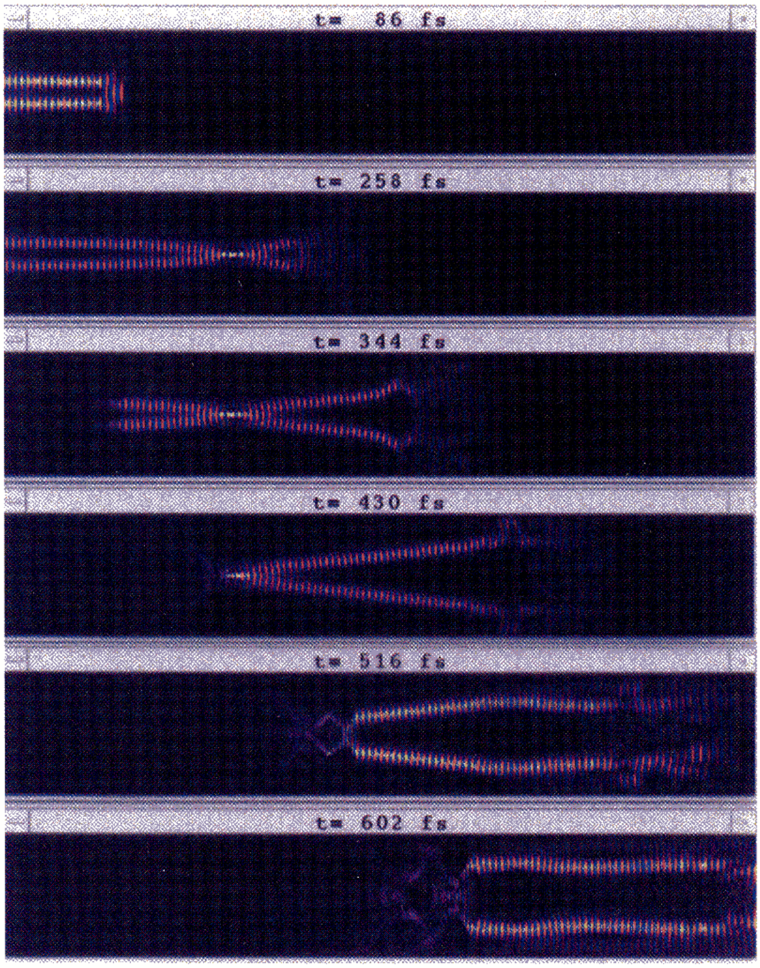

Figure 8. The electric field of equal-amplitude 100-fs signal and control spatial solitons (self-focussed laser pulses) was computed using FD-TD at various simulation times for the case of 0° relative carrier phase. This illustrates the dynamics of a potential ultrafast submillimeter-scale photonic switch (that is, light switching light), that operates thousands of times faster than current electronics.

SUPERCOMPUTERS OF THE LATE 1990S, achieving floating-point rates of more than 1 Tflops, will permit us to attack some "grand challenges" in electromagnetic wave interactions. One such challenge remains from the defense technology side: detailed simulation of the radar cross section of an entire aircraft at microwave frequencies. In fact, using the new machines and the new class of finite-difference and finite-volume time-domain Maxwell's equations solvers, it will be possible to obtain whole stealth fighter models in the 1- to 3-GHz range with predictive dynamic ranges up to 70 dB.

But of arguably more importance to society, the same Maxwell's equation algorithms implemented on the same computers could attack key problems in electrical and computer engineering analysis and design that are critically affected by electromagnetic wave phenomena. Besides the ones already mentioned, other design and analysis possibilities also appear feasible, including

- complete microwave and millimeter-wave integrated circuits;
- individual picosecond transistors, incorporating details of charge transport; and
- the propagation analysis of cellular and personal communication systems, including the high-resolution modeling of entire indoor microcells in three dimensions.

In fact, the ultralarge-scale solution of Maxwell's equations for electromagnetic wave phenomena using time-domain grid-based approaches may be fundamental to the advancement of electrical and computer engineering technology as we continue to push the envelope of complexity and speed. Simply speaking, Maxwell's equations provide the physics of electromagnetic wave phenomena from DC to light, and their accurate modeling is essential to understanding high-speed signal effects having wave transport behavior. A key goal is the computational unification of

- electromagnetic waves;
- charge transport in transistors, Josephson junctions, and electro-optic devices;
- surface and volumetric wave dispersions (including those of superconductors); and
- nonlinearities due to quantum effects.

We can then attack a broad spectrum of important problems to advance electrical and computer engineering and thereby directly benefit society. ◆

References

1. A. Taflove, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Norwood, Mass., 1995.
2. E.T. Thiele and A. Taflove, "Finite-Difference Time-Domain Analysis of Vivaldi Slot Antennas and Arrays," *IEEE Trans. Antennas and Propagation*, Vol. 42, No. 5, 1994, pp. 633–641.
3. M.J. Piket-May et al., "Initial Results for Automated Computational Modeling of Patient-Specific Electromagnetic Hyperthermia," *IEEE Trans. Biomedical Eng.*, Vol. 39, No. 3, 1992, pp. 226–237.
4. M.J. Piket-May, A. Taflove, and J.B. Troy, "Electrodynamics of Visible Light Interactions with the Vertebrate Retinal Rod," *Optics Letters*, Vol. 18, No. 8, 1993, pp. 568–570.
5. M.J. Piket-May, A. Taflove, and J. Baron, "FD-TD Modeling of Digital Signal Propagation in 3-D Circuits with Passive and Active Loads," *IEEE Trans. Microwave Theory and Techniques*, Vol. 42, No. 8, 1994, pp. 1,514–1,523.
6. V.A. Thomas et al., "The Use of Spice Lumped Circuits as Sub-Grid Models for FD-TD Analysis," *IEEE Microwave and Guided Wave Letters*, Vol. 4, No. 5, 1994, pp. 141–143.
7. R.M. Joseph, S.C. Hagness, and A. Taflove, "Direct Time Integration of Maxwell's Equations in Linear Dispersive Media with Absorption for Scattering and Propagation of Femtosecond Electromagnetic Pulses," *Optics Letters*, Vol. 16, No. 9, 1991, pp. 1,412–1,414.
8. P.M. Goorjian et al., "Computational Modeling of Femtosecond Optical Solitons from Maxwell's Equations," *IEEE J. Quantum Electronics*, Vol. 28, No. 10, 1992, pp. 2,416-2,422.
9. R.M. Joseph, P.M. Goorjian, and A. Taflove, "Direct Time Integration of Maxwell's Equations in 2-D Dielectric Waveguides for Propagation and Scattering of Femtosecond Electromagnetic Solitons," *Optics Letters*, Vol. 18, No. 7, 1993, pp. 491–493.
10. R.M. Joseph and A. Taflove, "Spatial Soliton Deflection Mechanism Indicated by FD-TD Maxwell's Equations Modeling," *IEEE Photonics Technology Letters*, Vol. 6, No. 10, 1994, pp. 1,251–1,254.

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