A Selective Survey of the Finite-Difference Time-Domain Literature

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1. Abstract

The Finite-Difference Time-Domain (FDTD) method is arguably the most popular numerical method for the solution of problems in electromagnetics. Although the FDTD method has existed for nearly 30 years, its popularity continues to grow as computing costs continue to decline. Furthermore, extensions and enhancements to the method are continually being published, which further broaden its appeal. Because of the tremendous amount of FDTD-related research activity, tracking the FDTD literature can be a daunting task. In this paper we present a selective survey of FDTD publications. This survey presents some of the significant works that made the FDTD method so popular, and tracks its development up to the present-day state-of-the-art in several areas. An "on-line" BibTEX database, which contains bibliographic information about many FDTD publications, is also presented.

The Finite-Difference Time-Domain (FDTD) method, as first proposed by Yee in 1966 [1], is a simple and elegant way to discretize the differential form of Maxwell's equations. Yee used an electric-field (E) grid, which was offset both spatially and temporally from a magnetic-field (H) grid, to obtain update equations that yield the present fields throughout the computational domain, in terms of the past fields. The update equations are used in a leap-frog scheme, to incrementally march the E and H fields forward in time. Despite the simplicity and elegance of Yee's algorithm, it did not receive much interest immediately after its publication. One could attribute the lack of attention to the high computational cost of the day, as well as to some of the limitations inherent in the original publication (such as the inability to model an "open" problem for any significant period of time). However, as the shortcomings of the original FDTD implementation were alleviated and the cost of computing fell, the interest in the FDTD method began to soar. In fact, based on the information we have gathered, the number of publications related to the FDTD method has, as shown in Figure 1, experienced nearly exponential growth in the past ten years.

Since the body of FDTD literature is so large, this survey paper is necessarily incomplete. Therefore, the goal of this paper is merely to highlight some of the more-successful extensions to, and applications of, the FDTD method. Those interested in further exploring the FDTD literature are directed to the on-line database described in Section 16.

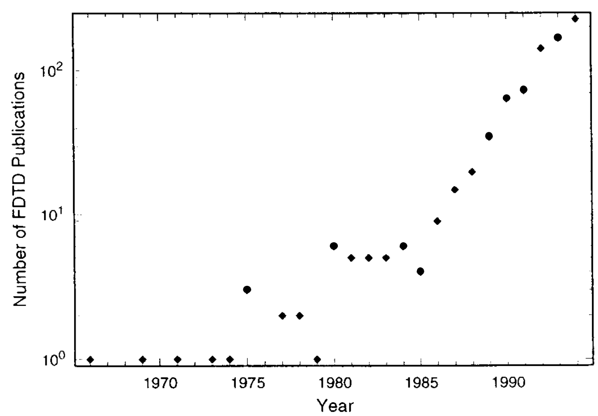

Figure 1. The number of publications related to FDTD published per year. No symbol is present for years with no publications. The last year for which reliable data is available is 1994.

3. Fundamental issues

The original Yee FDTD algorithm is second-order accurate in both space and time. Numerical-dispersion and grid-anisotropy errors can be kept small by having a sufficient number of grid spaces per wavelength. Taflove was among the first to rigorously analyze these errors [2]. Taflove was also the first to present the correct stability criteria for the original orthogonal-grid Yee algorithm [3]. With the introduction of more-complicated gridding schemes, algorithm stability and accuracy continue to be areas of active research, as will be discussed in Sections 9 and 10.

The FDTD method can be used to calculate either scattered fields or total fields. When calculating only the scattered fields, the source of the fields is a function of the known incident field, and the difference in material parameters from those of the background medium [4,5]. When using total fields, the total fields are often calculated only over an interior subsection of the computational domain [6-8], while scattered fields are calculated in the remaining (exterior) portion of the grid. By using scattered fields in this way, the field incident on the absorbing boundary condition (ref. Section

4) is more readily absorbed. To obtain this division of the computational domain, into scattered-field and total-field regions, the incident field must be specified over the boundary between these two regions. Holland and Williams presented a comparison of scattered-field formulations (i.e., only the scattered fields were computed throughout the computational domain) and total-field formulations (i.e., the total fields were computed in a subdomain that contained the objected under study) [8]. They determined, due to numerical dispersion, that the total-field FDTD approach is superior to the scattered-field approach. Furthermore, the scattered-field approach has the disadvantage that it does not easily accommodate nonlinear media. However, for certain problems, such as those that contain only linear media and do not contain shielded cavities, the scattered-field formulation may be the more-desired approach [9]. The relative merits of the total-field and scattered-field formulations were also explored by Fang [10].

4. Absorbing boundary conditions

In order to model open-region problems, an absorbing boundary condition (ABC) is often used to truncate the computational domain, since the tangential components of the electric field along the outer boundary of the computational domain cannot be updated using the basic Yee algorithm. The quest for an ABC that produces negligible reflections has been, and continues to be, an active area of FDTD research. Most of the popular ABCs can be grouped into those that are derived from differential equations, or those that employ a material absorber. Differential-based ABCs are generally obtained by factoring the wave equation, and by allowing a solution which permits only outgoing waves. Material-based ABCs, on the other hand, are constructed so that fields are dampened as they propagate into an absorbing medium. Other techniques sometimes used are exact formulations and superabsorption. ABCs tailored for specific applications have also been developed and used with the FDTD method.

4.1 Differential-based ABCs

Early techniques, used to truncate the FDTD computational domain, have included differential-based ABCs, such as those proposed by Merewether [11], Engquist and Madja [12], Lindman [13], and Mur [14]. These early techniques were vastly improved in the mid-1980s by formulations proposed by Higdon [15,16], Liao et al. [17], and Keys [18]. Many other extensions of these differential-based ABCs have since been proposed. The interested reader is referred to the on-line database described in Section 16 to survey such extensions.

4.2 Material ABCs

The idea of using a material-based absorbing boundary condition has existed for some time [8]. However, early material ABCs did not provide a sufficiently low level of boundary reflection, since the characteristic impedance of the material boundary was matched to the characteristic impedance of free space only at normal incidence. In the early 1990s, Rappaport et al. [19,20] proposed a new ABC, termed the sawtooth-anechoic-chamber ABC. This ABC employs pyramidally-shaped absorber material, similar to that which is often found in anechoic chambers. The most-recent advance in material-based ABCs was put forward by Berenger [21]. His ABC, termed the perfectly-matched-layer (PML) absorbing boundary condition, appears to yield a major improvement in the reduction of boundary reflections, compared to any ABC proposed previously. Although the ABC is new, it has enjoyed enormous attention already [22-28].

4.3 Other techniques

Exact ABCs have the advantage of giving accurate results, but since they are non-local, they are computationally expensive. Such approaches have been investigated by Ziolkowski et al. [29], Olivier [30], De Moerloose and De Zutter [31], and Tromp and Olivier [32]. In 1992, Mei and Fang [33] proposed a technique, "superabsorption," which can be applied to many absorbing boundary conditions to improve their performance. In certain applications, such as the termination of a waveguide or a microstrip, dispersive boundary conditions have been used [34-39]. Lastly, many researchers, including Fang [10], Blaschak and Kriegsman [40], Moore et al. [41], Railton and Daniel [42], and, most recently, Andrew et al. [43], have compared the accuracy of various ABCs. Comparative studies of the accuracy of ABCs have also been performed for dispersive media [44,45].

5. Gridding

5.1 Orthogonal grids

As originally formulated, the Cartesian grids used in the FDTD method dictate that a smoothly varying surface must be approximated by one that is "staircased." This approximation may lead to significant errors in certain problems [46,47]. Furthermore, if an object under consideration has small-scale structure, such as a narrow slot, the original method would have to use an excessively fine grid to accurately model the associated fields. To address these shortcomings, several solutions have been proposed.

If the object under consideration is more naturally described in an orthogonal coordinate system other than Cartesian, it is rather simple to develop update equations appropriate for that coordinate system, as was done by Merewether in 1971 [11] and by Holland in 1983 [48]. Alternatively, a grid that uses varying spatial increments along the different coordinate directions can be used. In general, for a Cartesian grid, this results in rectangular cells, and permits finer discretization in areas of rapid field fluctuation. Kunz and Lee [49,50] used this approach to calculate the external response of an aircraft to EMP. Monk and Süli have shown that this scheme preserves the second-order accuracy of the original algorithm [51,52]. Furthermore, subdomains can be gridded more finely than the rest of the problem space. This type of "subgridding," where information is passed between the coarse and fine grids, was put forward by a number of researchers [53-56]. An alternative subgridding scheme was proposed by Kunz and Simpson [57]. Their formulation requires two runs. The first is done for a coarse grid that spans the entire computational domain, while the second is done for the finely-gridded subdomain, and takes its boundary values from the stored values calculated during the coarse simulation.

Following the work of Yee [58], Umashankar et al. [59] and Taflove et al. [60] derived update equations that were suitable for modeling sub-cellular structures, such as wires, narrow slots, and lapped joints in conducting screens. These equations were obtained from the integral form of Faraday's law, rather than from the differential form, and they resulted in modified equations only for cells where the sub-cellular structure was present. Several other researchers, including Holland and Simpson [61,62], Gilbert and Holland [63], Demarest [64], Turner and Bacon [65], Riley and Turner [66,67], Oates and Shin [68], and Wang [69,70], have developed techniques to handle sub-cellular structures.

5.2 Other grids

In 1983, Holland published the first FDTD algorithm for generalized non-orthogonal coordinates [71]. In this approach, the fields are expressed in terms of their covariant (flow along a coordinate direction) and contravariant (flux through a constant-coordinate surface) components, and an integral formulation is used to obtain the update equations. In an orthogonal-coordinate system, the covariant and contravarient components are co-linear, while in a non-orthogonal one, they are not, and auxiliary equations must be obtained to express one form in terms of the other. Holland's formulation was later revisited by Fusco [72,73], Lee et al. [74,75], and Harms et al. [76,77]. Fusco applied the algorithm to cylindrical scatterers, while Lee et al. applied it to waveguide problems and derived stability equations. Navarro et al. [26,78] have studied aspects of non-orthogonal grids, including numerical dispersion and non-zero divergence, and have adapted the Berenger PML for use in such grids.

Mei et al. [79] presented a conformal technique that employed second-order polynomials and six grid points (ten grid points for three dimensions). In order to take advantage of all the work that had been done using Cartesian grids, and yet gain the benefit of a conformal approach, Yee et al. [80] developed an FDTD overlapping-grid technique which used a conformal grid in the neighborhood of material boundaries, and a Cartesian grid elsewhere. Jurgens et al. [81] and Jurgens and Taflove [82] extended the technique previously used to model sub-cellular structures so that it was suitable for modeling curved surfaces. This "contour-path" method used a Cartesian grid everywhere, except in the vicinity of the material boundaries, where a distorted grid was used to conform to the boundary.

Conformal modeling is an area of increasing interest, and several new techniques have recently been proposed. Many of these conformal methods, such as the finite-volume time-domain (FVTD) method [83], and the discrete-surface-integral (DSI) method [84], are only loosely related to the original FDTD method. Although these techniques fall outside the scope of this paper, several of the publications that describe them are listed in the on-line database, and the interested reader is directed there.

6. Material modeling

FDTD modeling of "complicated" materials has recently gained much attention. One of the major advantages the FDTD method has over other numerical techniques is the ability to obtain wideband results using transient excitation. To obtain accurate results over a broad spectrum, it is often necessary to include the frequency-dependent properties of the material (i.e., it may not be possible to treat the permittivity, conductivity, or permeability as constants over the entire spectrum). Several techniques have been proposed to account for this frequency dependence. Additionally, the use of a surface-impedance boundary condition or a thin-material-sheet model has been shown to provide significant computational savings over a full-FDTD model. Furthermore, the FDTD algorithm has been extended to account for materials that are anisotropic and nonlinear, but for those publications the interested reader is directed to the on-line database.

6.1 Frequency-dispersive material

In 1990, Luebbers et al. published the first frequency-dependent FDTD formulation [85], by using a recursive-convolution (RC) scheme to model Debye media. They did this by relating the electric-flux density to the electric field through a convolution integral, discretizing the integral as a running sum, and assuming that the susceptibility function is described by a decaying exponential. Independently, in 1991, Bui et al. [86] also developed a RC FDTD model for modeling Debye media. Luebbers et al. [87] modified the frequency-dependent RC formulation to study wave propagation in a Drude material, and soon thereafter generalized their RC approach to treat Mth-order dispersive media [88]. The approach requires storage of $M/2$ complex variables per electric-field location, while the original scheme for a first-order Debye media required storage of M real numbers. In 1992, Hunsberger et al. [89] extended the RC FDTD approach to model an anisotropic-magnetoactive plasma, while in 1993, Luebbers et al. [90] formulated a scattered-field frequency-dispersive method and applied it to three-dimensional spheres. In 1994, Pontalti et al. [91] independently proposed an RC approach, which could handle Debye media of Mth-order. More recently, Melon et al. [92] have extended the frequency-dispersive RC FDTD approach to ferrite material. Applications of the FDTD RC include Sullivan's modeling of three-dimensional biological problems [93], and Hum et al.'s [94] experimentally verified model of a cylindrical cavity composed of Debye media.

While Luebbers and others were developing the frequency-dispersive RC FDTD method, several other researchers were developing an alternate frequency-dispersive method, termed the auxiliary-differential-equation (ADE) method. The first papers utilizing this approach were by Kashiwa and co-workers [95-97] in 1990 for Debye media, Lorentz media, and media obeying the Cole-Cole Circular Arc law, respectively. While this research was progressing, Joseph et al. [98] independently developed a similar ADE model for Debye media. Goorjian and Taflove [99] soon extended this model to include effects for nonlinear-dispersive media. Independently, a third research group, headed by Gandhi, proposed the ADE method for treating Mth-order dispersive media [100,101]. An approach similar to the ADE method, for modeling the dispersive ionosphere, was developed by Nickisch and Franke [102] in 1992. Additional FDTD modeling of wave propagation in a plasma, using the joint equations of Euler and Maxwell, was developed by Young [103].

The disadvantage of the ADE approach is that it requires storage on the order of $2M-1$ additional real variables, nearly twice that of the RC method. However, recent research has shown how to reduce this storage requirement. For example, state-space-variable approaches, by Pereda et al. [104] and Young [105], have reduced the storage of the frequency-dispersive ADE method to a level similar to that of the RC approach.

While the major thrust of FDTD modeling of frequency-dispersive media has utilized either the RC or ADE approach, in 1992 Sullivan [106] proposed a dispersive formulation based on Z transforms. Recently, Sullivan [107] has extended the Z-transform approach to treat nonlinear-optical phenomena. Finally, a comparison of the stability and phase error of some frequency-dispersive FDTD methods was provided by Petropoulos [108].

6.2 Impedance-boundary conditions

In 1992, several independent surface-impedance-boundary-condition (SIBC) formulations were proposed for the FDTD method. Maloney and Smith [109] presented a frequency-dispersive formulation for a SIBC, which could be used over the spectrum of the incident pulse. In this work, E and H were related by a convolution sum, which was subsequently modified using Prony's method. Beggs et al. [110] also presented a frequency-dispersive SIBC formulation, although their SIBC is limited to the case of high conductivities. Yee et al. [111] presented two SIBC algorithms, one for an inductive SIBC and one for a capacitive SIBC, that can be used for monochromatic excitation. Kashiwa et al. [112] also presented a constant-SIBC algorithm, though their algorithm is limited to problems which can be expressed by an equivalent circuit. In 1993, Kellali et al. [113,114] presented a frequency-dispersive SIBC formulation which, unlike previous formulations which assumed normal incidence, is valid for any single angle of incidence. Lee et al. [115] have also presented a SIBC for use with the FDTD method, in which they relate the tangential fields to their normal derivatives by a partial-differential equation. Wang [116,117] has extended this alternate approach to both parallel- and perpendicularly-polarized two-dimensional electromagnetic waves.

6.3 Thin material sheets

In 1990, Railton and McGeehan [118] presented the first FDTD model for thin sheets of conducting or dielectric material. In 1991, Tirkas and Demarest [119] presented an FDTD model for thin dielectric sheets that treated not only the tangential component of the electric field at the air/sheet interface, but also treated the normal component of the field in the sheet. Independently, in 1992, Maloney and Smith [120] presented a somewhat similar formulation, but also allowed for the modeling of thin conducting sheets. Luebbers and Kunz [121] and Boonzaaier and Pistorius [122] have also presented methods for treating thin material sheets, all of which treat only the tangential component of the electric field at the thin-sheet/air interface. Finally, a comparison of the FDTD methods for modeling thin dielectric and conducting sheets was given by Maloney and Smith [123].

7. Active and passive device modeling

Another FDTD area, which has gained recent attention, is the area of active and passive device modeling. Sui et al. [124] extended the two-dimensional FDTD method to model lumped elements, including nonlinear elements such as diodes and transistors. Ko [125], meanwhile, used the FDTD technique to model various microwave-integrated-circuit components, such as branch-line couplers and filters. Wolff et al. [126] used the FDTD method to model planar-microwave circuits, containing nonlinear active components. Toland and co-workers [127-129] have also used the FDTD method to model nonlinear active elements, including a cavity oscillator and a two-element active antenna. Luebbers et al. [130] investigated antennas with both linear and nonlinear loads. Thomas et al. [131] have developed an approach for coupling SPICE lumped elements into the FDTD method, and used this method to model the same active antenna that was originally investigated by Toland [132]. Recently, Piket-May et al. [133] have extended Sui's two-dimensional analysis to model full-wave propagation in three-dimensional circuits containing both active and passive loads.

8. Transformations

In some of the first FDTD calculations of the radar cross section of discrete scatterers, harmonic illumination was used, to determine equivalent electric and magnetic currents over a surface that bounded the scatterer [7,134,135]. These currents were then transformed to the far field. An alternative far-field transformation for harmonic illumination was presented in 1991, by Lee et al. [136]. However, by using harmonic illumination in this way, a different simulation had to be run for each frequency of interest. Alternatively, as shown by Furse et al. [137], results could be obtained over several frequencies, by using pulsed illumination and a Fourier transform of the equivalent surface currents. These approaches were not well suited for the determination of the temporal far fields. In 1989, Britt [141] presented temporal far-field results, but the means by which he obtained these results were not fully described. Therefore, it was not until the independent work of Yee et al. [139], Luebbers et al. [140], and Barth et al. [141] that efficient, three-dimensional, time-domain, near-field-to-far-field transformations were developed and described in detail. Luebbers et al. [142] also proposed an efficient two-dimensional, time-domain, near-field-to-far-field transformation. Barth et al. [141] and Shlager and Smith [143,144] have also proposed full time-domain near-field-to-near-field transformations for use with the FDTD method.

Other types of transformations are used in FDTD modeling, in order to make the algorithm more efficient. By using digital-signal-processing techniques, relevant data (such as frequency-domain scattering parameters) can be extracted from FDTD simulations of shorter duration than would otherwise be possible. Ko and Mittra [145], Pereda et al. [146], and Naishadham and Lin [147] have all used Prony's method in this manner, while Houshmand et al. [148], Huang et al. [149], Craddock et al. [150], and Kumpel and Wolff [151] have used the system-identification method. Bi et al. [152] have used digital-filtering and spectral-estimation techniques to improve the FDTD method for eigenvalue problems. Finally, Jandhyala et al. [153,154] and Chen et al. [155] have recently employed autoregressive methods to reduce FDTD computation time.

Analysis of two-dimensional scatterers, illuminated by a three-dimensional source, is possible using a two-dimensional FDTD grid. This so-called two-and-one-half-dimensional formulation, put forward by Moghaddam and co-workers [156,157], uses sine and cosine transforms to reduce the inherently three-dimensional problem to two-dimensional. However, the full temporal solution must be constructed from the linear superposition of several transformed-field components.

9. Error analysis and algorithm comparisons

Many researchers have studied the numerical-dispersion error inherent in the FDTD method, including Taflove [2], Choi [158], and Kim and Hoefer [159]. In 1993, Ray [160] presented a dispersion analysis for a non-orthogonal FDTD mesh, while in 1994, Monk and Süli [51,52] presented a convergence analysis of Yee's algorithm for non-uniform rectangular grids. Shlager et al. [161] have presented a comparison of the dispersion errors of several orthogonal-grid FDTD methods. Cangellaris and Wright [46] analyzed staircasing errors at PEC surfaces for the regular FDTD method. Recently, Shlager [162] presented a new criterion for insuring that staircasing errors are small, when modeling horn-like and wedge-shaped objects.

10. Higher-order techniques

While the second-order-in-time-and-in-space Yee algorithm has been the primary FDTD algorithm used to date, higher-order FDTD methods have been proposed, in order to reduce the numerical phase error. In 1989, Fang [10] proposed both a second-order-accurate-in-time, fourth-order-accurate-in-space FDTD algorithm, and a fourth-order-accurate-in-time, fourth-order- accurate-in-space FDTD algorithm. Independently, Deveze et al. [163,164] published a similar higher-order FDTD method, and also developed an absorbing boundary condition for the method.

11. Radiating structures

The analysis and design of antennas, using the FDTD method, have received considerable attention recently, and are areas of growing activity.

11.1 Simple antennas

In 1990, Maloney et al. [165] presented accurate results for the radiation from rotationally symmetric simple antennas, such as cylindrical and conical monopoles. Boonzaaier and Pistorius [166,167] presented results for the radiation from thin-wire dipoles and thin-wire Yagi antennas. More recently, Yagi antennas were also studied by Kashiwa et al. [168]. In 1992, Tirkas and Balanis [169] presented results for a monopole on a ground plane, while Luebbers and co-workers [170,171] presented mutual-coupling and gain computations for a pair of wire dipoles. Subsequently, Maloney et al. [172] presented a simple one-dimensional approximate TEM-feed model for the FDTD method, and used it to analyze a monopole backed by a plane reflector.

11.2 Horn antennas

In 1991, Katz et al. [173] used the FDTD method to analyze both two-dimensional and three-dimensional horn antennas, while a year later, Tirkas and Balanis [169] also analyzed three-dimensional horn antennas. In 1994, Tirkas and Balanis [174] extended the contour-path FDTD method, and used it to analyze pyramidal horns with composite inner E-plane walls.

11.3 Antennas for pulse radiation

Maloney and Smith [175] optimized a two-dimensional parallel-plate radiator for pulse radiation, using the FDTD method, in 1992. A year later, they studied the radiation from a Wu-King resistive monopole [176], and used the FDTD method to optimize a conical antenna for pulse radiation [177]. More recently, Shlager and co-workers [162,178] have used the technique to optimize bow-tie and TEM-horn antennas for pulse radiation.

11.4 Microstrip antennas

Reineix and Jecko [179] were the first to apply the FDTD method to the analysis of microstrip antennas. In 1992, Leveque et al. [180] modeled frequency-dispersive microstrip antennas, while Wu et al. [181] used the FDTD method to accurately measure the reflection coefficient of various microstrip-patch configurations. Uehara and Kagoshima [182] presented an analysis of the mutual coupling between two microstrip antennas, while Oonishi et al. [183] and Kashiwa et al. [184] used one of the conformal FDTD approaches to analyze microstrip antennas on a curved surface. In 1994, Qian et al. [185] used the FDTD method to design twin-slot antennas. Recently, Reineix and co-workers [186-188] have expanded their FDTD analysis to include the input impedance of microstrips with slots, to obtain the radar cross section of microstrip-patch antennas, and to model the radiation from microstrip patches with a ferrite substrate.

11.5 Hand-held antennas

In 1992, Luebbers et al. [189] and Chen et al. [190] analyzed hand-held antennas, using an FDTD model of a monopole antenna on a conducting or dielectric box. Toftgård et al. [191] calculated the effect the presence of a person has on the radiation from such an antenna. In 1994, Jensen and Rahmat-Samii [192] presented results for the input impedance and gain of monopole, PIFA, and loop antennas on hand-held transceivers. The interaction of a hand-held antenna and a human were also studied by Jensen and Rahmat-Samii [193]. Also in 1994, Chen and Wang [194] calculated the currents induced in the human head with a dipole-antenna model for a cellular phone. Recently, Martens et al. [195] have used a dipole model and a full model for a hand-held antenna to compute the fields induced in the human head.

11.5 Antenna arrays

Cherry and Iskander [196,197] have used the FDTD method to model an array of interstitial antennas for hyperthermia purposes. In 1994, Ren et al. [198] analyzed two-dimensional phased-array antennas with Floquet boundary conditions. Also in 1994, Thiele and Taflove [199] presented results for the radiation from Vivaldi flared-horn antennas and arrays, while Naito et al. [200] presented results for a single radiator of a circularly polarized printed array, composed of strips and slots. Uehara and Kagoshima [201] have recently analyzed microstrip-phased-array antennas.

11.6 Other radiating structures

In 1993, Beggs et al. [202] used the FDTD method to analyze the radiation from shaped-end radiators, while Maeshima et al. [203] investigated a two-dimensional cavity-backed antenna. Toland et al. [128] and Thomas et al. [132] have investigated active antennas using the FDTD method. In 1994, Penney and Luebbers [204,205] analyzed both square and semi-circular spiral antennas using the FDTD method, while recently Shum and Luk [206-208] analyzed aperture-coupled dielectric-resonator antennas.

12. Microwave devices and guiding structures

The FDTD method has also found widespread application in the area of microwave devices and guiding structures, such as waveguides, resonators, junctions, microstrips, vias, interconnects, and transmission lines.

12.1 Waveguides, resonators, feeds, and junctions

In 1985, DePourcq [209] used the FDTD method to analyze various three-dimensional waveguide devices. A year later, Choi and Hoefer [210] applied the FDTD method to model a finline cavity and an anisotropic microstrip. Olivier and McNamara [211-215] have used the FDTD method to study discontinuities in homogeneous dispersive waveguides, edge slots, an H-plane T-junction, and coupling between waveguide apertures. Bi et al. [216] and Navarro et al. [35,217] have also applied the FDTD method to H-plane waveguide discontinuities. Navarro and co-workers [218-220] have also investigated rectangular, circular, and T-junctions in square-coaxial waveguides, and narrow-wall multiple-slot couplers.

In 1990, Chu and Chaudhuri [221] investigated dielectric-waveguide problems, while in 1991, Jarem [222] presented FDTD results for a probe-sleeve-fed rectangular waveguide. Alinikula and Kunz [223] investigated waveguide-aperture coupling, using the FDTD method. In 1992, Van Hese and De Zutter [224] modeled coaxial-waveguide structures with discontinuities, using the FDTD method in both Cartesian and cylindrical coordinates. Feng and Junmei [225] analyzed a dielectric post in a rectangular waveguide, while Dib and Katehi [226] analyzed the transition from a rectangular waveguide to a shielded dielectric-image guide. In 1994, Kraut et al. [227] analyzed edge slots in waveguides. Meanwhile, ferrite-loaded waveguides have been investigated by Pereda and co-workers [228-231]. Okoniewski and Okoniewska [232] have recently proposed an alternative FDTD algorithm for ferrites, and have successfully applied it to ferrite-loaded waveguides.

In the early 1990s, Navarro et al. [233,234] used the FDTD method to obtain results for cylindrical-homogeneous and dielectrically-loaded resonators. Shen et al. [235] and Pereda et al. [146] have extended the FDTD analysis to open cylindrical-dielectric resonators. Wang et al. [236] also studied the Q-factors of resonators using the FDTD method.

There has also been active research in reducing the computations needed to analyze three-dimensional guided-wave devices. In 1992, Xiao et al. [237] presented a new compact FDTD method for analyzing guided-wave structures. By introducing a phase shift along the direction of propagation, the authors reduced the three-dimensional mesh to two-dimensional. Independently, Asi and Shafai [238,239] and Brankovic et al. [240] introduced similar methods to reduce three-dimensional guided-wave problems to two-dimensional. In 1993, Cangellaris [241] presented a stability and dispersion analysis of Asi and Shafai's two-dimensional compact FDTD method. Noting that the above algorithms introduce complex numbers into an otherwise-real process, Okoniewski [242] presented an alternate compact two-dimensional FDTD method, using a vector-wave-equation approach. By doing this, Okoniewski retained only real variables in the FDTD algorithm. Krupeuzevic et al. [243] have also developed a vector-wave-equation approach, to investigate various waveguide structures. Xiao and Vahldieck [244] introduced a variable transformation to their original compact FDTD method so that it contained only real variables. The amount of computation needed to analyze waveguide-like structures has also been reduced by using a non-orthogonal FDTD method [74-77].

Techniques to improve the absorbing boundary conditions used in guided-wave structures were discussed in Section 4.

12.2 Microstrips

There has been tremendous interest in applying the FDTD method to microstrip circuits. Fang, Zhang, Mei, and Liu [245-247] were among the first to investigate the dispersive characteristics of microstrips using this approach. Meanwhile, Liang et al. [248] used the FDTD method to analyze coplanar waveguides and slotlines. In 1990, Sheen et al. [249] presented FDTD results for various microstrip structures, including a rectangular-patch antenna, a low-pass filter, and a branch-line coupler. Independently, Moore and Ling [250] and Feix et al. [251] analyzed 90° microstrip bends using the FDTD method. Other early 1990s FDTD research results for microstrips were presented by Railton and McGeehan [118], Wu and Chang [252], Zheng and Chen [253-257], and Shibata and Sano [258,259].

Shorthouse and Railton [260] incorporated static-field solutions into the FDTD method for microstrip discontinuities. Railton et al. [261] also introduced an approach to model narrow microstrip lines using the FDTD algorithm. Fang and Ren [262] have presented a locally-conformable FDTD algorithm for arbitrary planar strips. Other FDTD applications to microstrip problems in the mid-1990s have been presented by Kitamura et al. [263,264], Cresson et al. [265], Qian et al. [266], Li et al. [267], and Seo [268].

Dispersive boundary conditions to terminate microstrip problems were first presented in 1992 by Bi et al. [269]. Other absorbing-boundary-condition techniques for terminating dispersive microstrip structures can be found in the on-line FDTD database.

12.3 Vias, interconnects, and transmission lines

In 1992, Maeda et al. [270] used the FDTD method to analyze microstrip via holes. Becker et al. [271] presented FDTD-computed results for both rectangular and cylindrical vias. In 1993, Harms et al. [272] utilized a non-orthogonal FDTD method to analyze cylindrical vias. Recently, Mezzanotte et al. [273] and Pillai and Wiesbeck [274] have presented further FDTD results for vias. The characterization of interconnects in integrated-circuit modules has independently been studied using the FDTD method by Gribbons et al. [275], Visan et al. [276], and Yook et al. [277]. Wang [278] has recently analyzed super-conductive interconnects using the FDTD method.

In 1994, Paul [279] used the FDTD method to analyze multi-conductor-transmission lines. The problem of analyzing crosstalk between parallel microstrip-transmission lines has been investigated using the FDTD method by Maeda et al. [280], Pothecary and Railton [281], Cerri et al. [282], and Kitamura et al. [283].

13. Discrete scatterers

Two of the primary areas for the application of the FDTD algorithm, since its inception, have been in the study of electromagnetic scattering and the calculation of surface currents. In addition to Yee's original paper, other early applications of the FDTD method to scattering problems were by Taylor et al. [284], Merewether and co-workers [6,11], Taflove and co-workers [3,7,135,285], Holland [4], and Kunz et al. [49,50]. In 1989, Harfoush et al. [286] used the FDTD method to analyze scattering from moving surfaces. Also in 1989, Britt [138] was among the first FDTD researchers to use a pulse excitation, in conjunction with a near-field-to-far-field transformation, to compute the radar cross section for both two-dimensional and three-dimensional perfectly-conducting and non-perfectly-conducting scatterers. In 1990, Furse et al. [137] suggested additional improvements to the FDTD method for calculating the radar cross section of perfectly conducting objects. Recently, Luebbers and Penney [287] extended the FDTD method to allow for scattering from apertures in infinite ground planes.

While the above research used the standard staircasing FDTD, several researchers in the 1990s have developed and applied conformal FDTD methods to analyze scattering problems. Some of this research includes the work by Fusco [72,73], Lee [288], Holland et al. [289], Jurgens et al. [81,82], and Yee et al. [80,83].

14. Miscellaneous applications

In addition to the previously mentioned applications, the FDTD method has also been applied to problems involving periodic structures, scattering from random surfaces, and to nondestructive-evaluation problems.

In 1991, Chan et al. [290] was the first to use the FDTD method in conjunction with periodic boundary conditions to investigate scattering from two-dimensional randomly-rough surfaces. Later, Fung et al. [291] used the FDTD method to model the scattering from three-dimensional randomly-rough surfaces. Navarro et al. [292] used the FDTD method in combination with the Floquet theorem to model scattering from a two-dimensional metallic-strip grating. At the same time, Tsay and Pozar [293] investigated a similar two-dimensional metallic-strip-grating problem, using a periodic boundary condition. Both these studies presented results only for the normal-incidence case. Extensions and improvements, including results for the oblique-incidence periodic case, were presented shortly afterward by Prescott and Shuley [294] and by Veysoglu et al. [295]. Ren et al. [198] presented a two-dimensional FDTD analysis for phased-array antennas, incorporating the Floquet boundary conditions. Harms et al. [296] soon extended the FDTD analysis to full three-dimensional periodic structures. Recently, Celuch-Marcysiak and Gwarek [297] have investigated waveguide structures which are periodic in the direction of propagation. Also, Cangellaris et al. [298] used a hybrid spectral-FDTD method to investigate the propagation of waves in a guided-wave periodic structure.

Other applications of the FDTD method include nondestructive evaluation. Moghaddam et al. [156,157] applied the FDTD method to model a subsurface radar. Their results were restricted to excitation by canonical point or line sources. Maeshima et al. [203] used the FDTD method to model a two-dimensional subsurface radar, using a more-complex cavity-backed antenna. He et al. [299] have also analyzed two-dimensional scattering from the air-earth interface using the FDTD method. Recently, Bourgeois and Smith [300] have applied the three-dimensional FDTD method to a subsurface radar for the detection of buried pipes, in which they incorporate both a transmitting and receiving bow-tie antenna, fed by parallel-wire transmission lines. In addition, they also model the frequency-dispersive characteristics of the earth.

15. Hybrid techniques

The FDTD method has been used in conjunction with other techniques. In 1982, Taflove and Umashankar [285] used a hybrid FDTD-Method-of-Moments approach to investigate coupling problems. More recently, other hybrid-FDTD techniques were introduced. In 1993, Aoyagi et al. [301] used the Yee algorithm, in conjunction with the scalar wave equation, to reduce the computations needed to model a Vivaldi antenna, while Cangellaris et al. [298] used a hybrid spectral-FDTD method to analyze propagation in anisotropic, inhomogeneous periodic structures. Lee and Chia [302] introduced a hybrid ray-FDTD method, and used it to investigate scattering from a cavity with a complex termination. In 1994, Mrozowski [303] introduced a hybrid FDTD-PEE (partial-eigenfunction-expansion) method, to speed up the FDTD method when solving shielded-structure problems.

16. On-line FDTD bibliographic database

We have cataloged as many publications related to the FDTD method as we practicably could, and we have made that information available via anonymous ftp and the World Wide Web (WWW). This database currently contains nearly 1,000 entries, and grows almost daily. Entries include journal publications, PhD theses, technical reports, conference presentations, etc. We have not recorded all conference material, but have rather restricted entries to those that were published as papers in conference proceedings (i.e., conferences that merely publish abstracts were not included). The entries in the database are suitable for use with BibTEX, which is an automatic bibliography generation utility. Along with the database itself, there are PostScript files available that list all the entries in the database. Furthermore, there is a query utility provided from the WWW interface, so that logical searches of the database may be performed. To find out more, use anonymous ftp to connect to the host `ftp.eecs.wsu.edu` and peruse the material in the subdirectory `/pub/FDTD`. Alternatively, use a WWW browser and connect to the URL `http://www.eecs.wsu.edu/~schneidj/fdtd-bib.html`

17. Conclusions

Over the past thirty years, the FDTD algorithm has been shown to be a remarkably robust and accurate tool for the analysis of problems in electromagnetics. Indeed, the FDTD algorithm, or one of its variant forms, has been successfully applied in a number of disciplines outside of "traditional" electromagnetics, including acoustics, optics, and biology. Many of these publications can be found in the on-line database, but were not mentioned here in the interest of brevity. Since the FDTD method has attracted attention from so many researchers, the number of FDTD-related publications is quite large, and keeping track of this growing body of literature can be challenging. It is our hope that the on-line database we have compiled can facilitate the exploration and tracking of FDTD-related publications. Alternatively, for those interested in exploring a broad range of FDTD-related issues from a single source, Kunz and Luebbers [9] and Taflove [304] have written books that are devoted to the FDTD method. The FDTD method has also been discussed in other texts that are not solely devoted to the topic, e.g., [305].

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19. References

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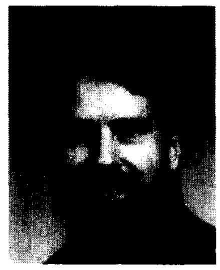

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