# Propagation of Transients in Dispersive Dielectric Media

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*Abstract*—**The propagation of transient electromagnetic fields in dispersive dielectric media is studied. The dielectric medium is assumed to be linear, isotropic, and homogeneous and is described by the Debye model. Incident fields are assumed to be TEM plane wave pulses. The dielectric body can assume the form of infinite half space or an infinite circular cylinder, either of which may be homogeneous or stratified. The electric fields induced in the dielectric are calculated from time-domain Maxwell equations using the finite-difference time-domain method. The results of this investigation can be used to study possible biological effects of pulsed electromagnetic fields.**

## I. Introduction

MOST of the research in biological effects of electromagnetic radiation has been done with continuous-wave radiation [1], [2]. Although there has been concern over the hazards of pulsed radiation [2], [3], little work has been done about it. Most of the work published so far has not included the dispersive dielectric properties of biological materials. In addition, there has been an interest in the propagation of transient electromagnetic waves through lossy dispersive dielectrics related to its applications to many important problems such as geophysical probing and subsurface studies of the moon and other planets [4]–[7]. The main motivation behind this work are studies of the potential health hazards of high-power pulsed RF radiation.

Transient fields in dispersive media have been the subject of a number of investigations. Some authors have used analytical approximation techniques to study pulse propagation problems. Wait [8] studied the distortion of a pulse propagating through a dispersive medium using various approximation procedures based on the stationary phase principle. Fuller and Wait [4] calculated the unit-step impulse response for a compound Debye dielectric model by taking the Laplace transform of the transfer function and then approximating the propagation constant for short and long time behaviors.

Other authors have studied the problem in the frequency domain. Sivaprasad *et al.* [9] studied the reflection for a sine-squared pulse incident at normal and oblique angles on a three-layer medium with the middle layer being a Debye dielectric. Suzuki *et al.* [6] obtained the waves reflected by two dielectric slabs for an incident pulse-modulated carrier wave analytically by expanding the reflection coefficient of an elementary plane wave into a series expansion. Bussey and Richmond [10] obtained a theoretical scattering solution in the frequency domain for a plane wave incident normally on a lossy dielectric multilayer circular cylinder of infinite length by assuming the solution to be in the form of a Fourier series of Bessel functions of the first and second kinds.

Still other authors have evaluated the steady-state transfer function as a function of frequency. King and Harrison [5] studied the transmission of an incident pulse of Gaussian shape from the air into the earth by evaluating the steady-state transfer function over a frequency spectrum. Lin [11] studied the interaction of electromagnetic transient radiation with biological materials by developing a steady-state transfer function at the interface of air and a Debye medium. Lin *et al.* [12], [13] also determined the transmitted field strengths in homogeneous spherical models of human and animal heads by convolving the Fourier transform of the incident pulse with the steady-state transfer function of the medium. The transmitted pulse in the time domain was then obtained by an inverse Fourier transformation.

Durney *et al.* [14], [15] used Fourier series expansion technique to expand the incident pulse train into a Fourier series to study the wave propagation in a dispersive dielectric half space irradiated by an electromagnetic plane wave pulse train.

Very few authors have studied the problem directly in the time domain. Lam [16] investigated the reflected waveform of a unit-step signal incident on a Debye dielectric half space and on an ice layer on water using an integrodifferential equation which was solved numerically by the finite-difference time-domain method. Bolomey *et al.* [17] studied the reflected field at the interface of a Debye medium illuminated by a ramp incident field from the air using a time-domain integral equation. Holland *et al.* [18] and Sullivan *et al.* [19] used the finite-difference time-domain method to calculate the electric field and the specific absorption rate (SAR) distribution in a model of the human body. The dielectric was assumed to be nondispersive.

The objective of this work is to investigate the propagation of pulsed electromagnetic fields in dispersive dielectrics using the finite-difference time-domain method.

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The dielectric is assumed to be linear, isotropic, and homogeneous and is described by the Debye model [20]. The dielectric body can assume the form of infinite half space or an infinite circular cylinder, either of which may be homogeneous or stratified. Incident fields are assumed to be TEM (transverse electromagnetic) plane wave pulses.

## II. Theory

In this section, we shall discuss in detail the finite-difference time-domain (FDTD) method for solution of the time-domain Maxwell equations in Debye media. We shall start from the examination of the time-domain Maxwell equations in a Debye medium and derive the expressions for the electric flux density and its first and second derivatives with respect to time. We shall then derive the numerical solution of the time-domain Maxwell equations for one- and two-dimensional problems. We shall also investigate the boundary conditions at the interface of two different media in order to be able to treat the pulse propagation in inhomogeneous media.

Source-free time-domain Maxwell equations are

$$\nabla \times \vec{E}(x,y,z,t) = -\frac{\partial \vec{B}(x,y,z,t)}{\partial t} \tag{1}$$

$$\nabla \times \vec{H}(x,y,z,t) = \frac{\partial \vec{D}(x,y,z,t)}{\partial t} + \sigma \vec{E}(x,y,z,t) \tag{2}$$

where $\vec{B}(t)$ and $\vec{D}(t)$ are the inverse Fourier transforms of $\vec{\mathscr{B}}(\omega)$ and $\vec{\mathscr{D}}(\omega)$, which are defined in the frequency domain:

$$\vec{\mathscr{B}}(\omega) = \mu^*(\omega)\vec{\mathscr{H}}(\omega) \tag{3}$$

$$\vec{\mathscr{D}}(\omega) = \epsilon^*(\omega)\vec{\mathscr{E}}(\omega). \tag{4}$$

The unknowns are the electric field, $\vec{E}(t)$, and the magnetic field, $\vec{H}(t)$. The medium is assumed homogeneous and isotropic within each layer. The permeability is that of free space, $\mu_0$. The conductivity, $\sigma$, is constant. The permittivity is assumed to have the form of the Debye model with a single relaxation time:

$$\epsilon^*(\omega) = \epsilon_\infty + \frac{\epsilon_0 - \epsilon_\infty}{1 + j\tau_0\omega} \tag{5}$$

where $\epsilon_0$ and $\epsilon_\infty$ are the low- and high-frequency permittivities, respectively, and $\tau_0$ is the relaxation time.

Taking the inverse Fourier transform of (5), (3), and (4), one obtains $\epsilon(t)$, $\vec{B}(t)$, and $\vec{D}(t)$:

$$\epsilon(t) = \epsilon_\infty \delta(t) + \frac{\epsilon_0 - \epsilon_\infty}{\tau_0} e^{-t/\tau_0} u(t)$$

$$\vec{B}(t) = \mu_0 \vec{H}(t)$$

$$\vec{D}(t) = \int_{-\infty}^{\infty} \epsilon(t-\beta)\vec{E}(\beta)\, d\beta.$$

Therefore, the electric flux density is

$$\vec{D}(t) = \epsilon_\infty \vec{E}(t) + \frac{\epsilon_0 - \epsilon_\infty}{\tau_0} \int_{-\infty}^{\infty} e^{-(t-\beta)/\tau_0} u(t-\beta) \vec{E}(\beta)\, d\beta.$$

Suppose we write

$$\vec{D} = D_x \vec{x} + D_y \vec{y} + D_z \vec{z}$$

then

$$D_x(t) = \epsilon_\infty E_x(t) + \frac{\epsilon_0 - \epsilon_\infty}{\tau_0} \int_{-\infty}^{\infty} e^{-(t-\beta)/\tau_0} u(t-\beta) E_x(\beta)\, d\beta.$$

By differentiating the above equation twice with respect to $t$, we obtain the first and second derivatives of $D_x(t)$ [21]:

$$\frac{\partial D_x(t)}{\partial t} = \epsilon_\infty \frac{\partial E_x(t)}{\partial t} + \frac{\epsilon_0 - \epsilon_\infty}{\tau_0}\left[E_x(t) - \frac{\Delta t}{\tau_0} S_x(t)\right] \tag{6}$$

$$\frac{\partial^2 D_x(t)}{\partial t^2} = \epsilon_\infty \frac{\partial^2 E_x(t)}{\partial t^2} + \frac{\epsilon_0 - \epsilon_\infty}{\tau_0} \cdot \left[\frac{\partial E_x(t)}{\partial t} - \frac{1}{\tau_0} E_x(t) + \frac{\Delta t}{\tau_0^2} S_x(t)\right] \tag{7}$$

where

$$S_x(t) = \frac{1}{\Delta t} \int_{-\infty}^{\infty} e^{-(t-\beta)/\tau_0} u(t-\beta) E_x(\beta)\, d\beta$$

and $\Delta t$ is the time increment. $S_x(t)$ can be reduced to the recursive form [21]

$$S_x(t) = e^{-\Delta t/\tau_0} S(t - \Delta t) + \frac{1}{2}\left[e^{-\Delta t/\tau_0} E_x(t-\Delta t) + E_x(t)\right]. \tag{8}$$

Suppose in the $k$th layer, the conductivity, $\sigma_k$, is constant and the permittivity, $\epsilon_k(t)$, assumes the Debye model. The permittivity for each layer can be written as

$$\epsilon_k(t) = \epsilon_{k\infty}\delta(t) + \frac{\epsilon_{k0} - \epsilon_{k\infty}}{\tau_{k0}} e^{-t/\tau_{k0}} u(t).$$

### A. One-Dimensional Problem

Suppose a stratified dispersive dielectric is irradiated by a $z$-directed plane wave pulse with normal incidence on the air/dielectric interface. Applying (7) and (8) to the wave equation for the electric field in the $k$th layer, we obtain

$$\frac{\partial^2 E_x(z,t)}{\partial t^2} = c_{k\infty}^2 \frac{\partial^2 E_x(z,t)}{\partial z^2} - \left(\frac{\sigma_k}{\epsilon_{k\infty}} + a_k \omega_{k0}\right) \frac{\partial E_x(z,t)}{\partial t} + a_k \omega_{k0}^2 E_x(z,t) - a_k \omega_{k0}^3 \Delta t S_x(z,t) \tag{9}$$

where

$$a_k = \frac{\epsilon_{k0} - \epsilon_{k\infty}}{\epsilon_{k\infty}}$$

$$\omega_{k0} = \frac{1}{\tau_{k0}}$$

$$c_{k\infty} = \frac{1}{\sqrt{\mu_0 \epsilon_{k\infty}}}$$

or, in finite difference form [21],

$$\alpha E_x^{n+1}(i) = -\beta E_x^{n-1}(i) + \left(\frac{c_{k\infty}\Delta t}{\Delta z_k}\right)^2 [E_x^n(i+1) - 2E_x^n(i) + E_x^n(i-1)] + 2E_x^n(i) + a_k(\omega_{k0}\Delta t)^2 E_x^n(i) - a_k(\omega_{k0}\Delta t)^3 S_x^n(i) \quad (10)$$

where $\Delta t$ is the time increment, $\Delta z_k$ is the space increment in the $k$th layer, and

$$\alpha = 1 + \frac{\Delta t}{2}\left(\frac{\sigma_k}{\epsilon_{k\infty}} + a_k\omega_{k0}\right)$$

$$\beta = 1 - \frac{\Delta t}{2}\left(\frac{\sigma_k}{\epsilon_{k\infty}} + a_k\omega_{k0}\right).$$

Boundary conditions derived specifically for stratified Debye dispersive dielectric media [21] are applied for points on the interfaces.

For stability, the following condition must be satisfied [16]:

$$\Delta z \leqslant c_\infty \Delta t.$$

Choosing

$$\Delta z = c_\infty \Delta t$$

results in three advantages [16]:

- The time increment, $\Delta t$, is the largest one permitted, thus allowing a problem to be solved with the minimal number of time steps.
- The calculations at each step are reduced to a minimum because (10) simplifies greatly.
- The exact solution is obtained because the truncation error in (10) vanishes.

For the far-end boundary, the infinite boundary can be terminated at the point [16]

$$I_{\text{END}} \geqslant I_{\text{obs}} + \frac{N - I_{\text{obs}}}{2} + 1$$

where $I_{\text{END}}$ is the truncation point, $I_{\text{obs}}$ is the observation point, and $N$ is the number of time steps to be calculated. When the above condition is satisfied, the backscattered signal originating at the truncation point does not reach the observation point. A one-dimensional FDTD program has been developed.

### B. Two-Dimensional Problem

The geometry under consideration consists of an infinitely long multilayered cylinder of dispersive dielectric in free space. The cylinder's axis is in the $z$ direction. The incident wave is assumed to be a $+y$-directed plane wave whose electric field vector is in the $z$ direction. Because there is no variation of either scatterer geometry or incident fields in the $z$ direction, this problem is treated as the two-dimensional scattering of the incident wave, with only $E_z$, $H_x$, and $H_y$ fields present.

Applying (6) and (8) to (1) and (2) in the $k$th layer, we obtained the magnetic field, $H$, and the electric field, $E$, in finite difference forms as [21]

$$H_x^{n+1/2}\left(i, j+\frac{1}{2}\right) = H_x^{n-1/2}\left(i, j+\frac{1}{2}\right) - \frac{\Delta t}{\mu_0 \Delta l}[E_z^n(i, j+1) - E_z^n(i, j)] \quad (11)$$

$$H_y^{n+1/2}\left(i+\frac{1}{2}, j\right) = H_y^{n-1/2}\left(i+\frac{1}{2}, j\right) + \frac{\Delta t}{\mu_0 \Delta l}[E_z^n(i+1, j) - E_z^n(i, j)] \quad (12)$$

$$E_z^{n+1}(i,j) = \left[1 - \Delta t\left(\frac{\sigma_k}{\epsilon_{k\infty}} + \frac{\epsilon_{k0} - \epsilon_{k\infty}}{\epsilon_{k\infty}\tau_{k0}}\right)\right] E_z^n(i,j) + \frac{\Delta t}{\epsilon_{k\infty}\Delta l}\left\{H_y^{n+1/2}\left(i+\frac{1}{2}, j\right) - H_y^{n+1/2}\left(i-\frac{1}{2}, j\right) - \left[H_x^{n+1/2}\left(i, j+\frac{1}{2}\right) - H_x^{n+1/2}\left(i, j-\frac{1}{2}\right)\right]\right\} + \left(\frac{\epsilon_{k0} - \epsilon_{k\infty}}{\epsilon_{k\infty}}\right)(\omega_{k0}\Delta t)^2 S_z^n(i,j). \quad (13)$$

For any given cell size, $\Delta l$, there is a restriction on the step $\Delta t$ to ensure stability. This restriction can be described as [24]

$$v_{\max}\Delta t \leqslant \left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right)^{-1/2}$$

where $v_{\max}$ is the velocity of the propagating wave. Since the cylinder is in free space,

$$v_{\max} = c_0$$

where $c_0$ is the velocity of light in free space, and

$$\Delta x = \Delta y = \Delta l.$$

Thus the stability criterion can be written as

$$c_0 \Delta t \leqslant \frac{\Delta l}{\sqrt{2}}$$

or as

$$\frac{\Delta t}{\Delta l} \leqslant \frac{1}{c_0\sqrt{2}}.$$

The problem is an open problem, but because the domain in which we compute the field is limited, we must create absorbing boundary conditions at the artificial boundaries produced by truncating the mesh to simulate the conditions of unbounded space. The absorbing conditions used here are those suggested by Reynolds [22].

A two-dimensional FDTD program has been developed specifically for a multilayered circular cylinder filled with Debye media.

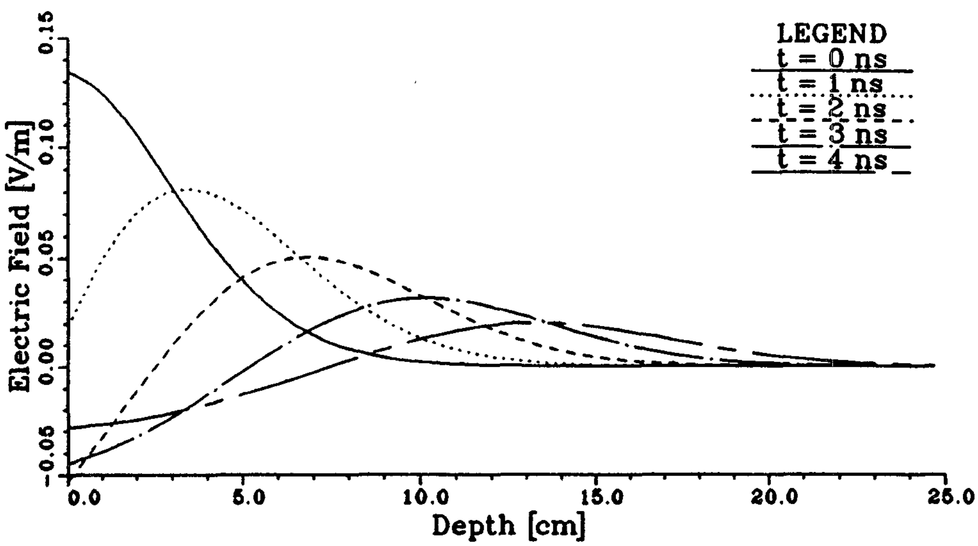


Fig. 1. Transmitted waveforms of a Gaussian pulse incident on a stratified half space filled with skin, fat, and muscle as a function of depth.

## III. Numerical Results

The FDTD method was applied to various dielectric structures and for different types of incident pulses.

### A. One-Dimensional Problem

The transmitted fields inside a stratified half space filled with skin, fat, and muscle were calculated. The parameters of skin, fat, and muscle were obtained by converting the data collected by Stuchly [23] and Hurt [25] into the Cole–Cole form using the least-square method. The incident field was a Gaussian pulse characterized by

$$E_0(z,t) = e^{-(t-z/c_0)^2/2t_1^2}$$

where $t_1 = 1$ ns is the pulse width in time, $c_0$ is the velocity of light in free space, and $z = 0$ at the interface.

Skin with a thickness of 1 mm has a conductivity $\sigma = 0$, a low-frequency permittivity $\epsilon_0 = 700$, a high-frequency permittivity $\epsilon_\infty = 41.7$, and an angular relaxation frequency $\omega_0 = 6.67 \times 10^8$ rad/s. Fat with a thickness of 5 mm has a conductivity $\sigma = 0$, a low-frequency permittivity $\epsilon_0 = 46.9$, a high-frequency permittivity $\epsilon_\infty = 5.51$, and an angular relaxation frequency $\omega_0 = 5.55 \times 10^8$ rad/s. Muscle with infinite thickness has a conductivity $\sigma = 0$, a low-frequency permittivity $\epsilon_0 = 6.7 \times 10^3$, a high-frequency permittivity $\epsilon_\infty = 52.5$, and an angular relaxation frequency $\omega_0 = 1.33 \times 10^7$ rad/s. The $\Delta t$ was chosen to be equal to 10 ps. The program was initialized at $t = -4t_1$ ($-4$ ns) and time stepped to 4 ns (800 time steps).

Fig. 1 shows the transmitted field as a function of depth at various times $t = 0$, 1, 2, 3, and 4 ns.

### B. Two-Dimensional Problem

The geometry of the scatterer relative to the grid is illustrated in Fig. 2. The cylinder axis was chosen as the line $(i\max\frac{1}{2}, (j\max/2)\frac{1}{2}, k)$. Because the scatterer was evenly symmetric about the grid line $i = i\max\frac{1}{2}$, we had

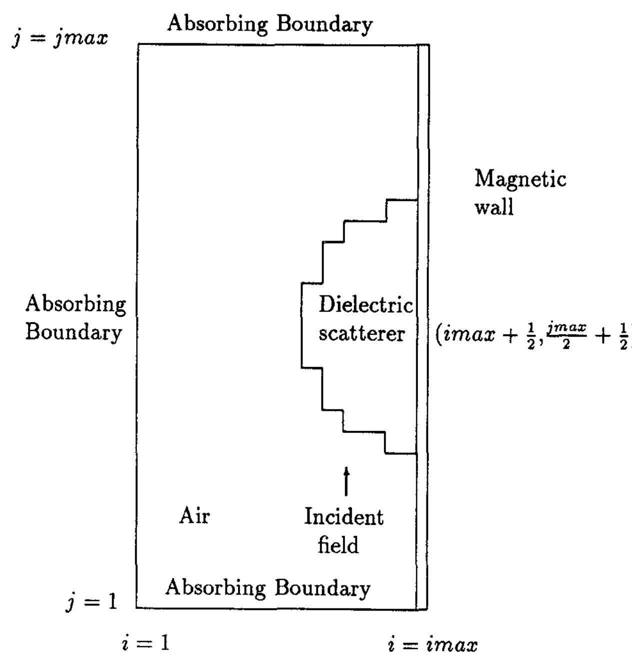


Fig. 2. Geometry of the scatterer relative to the grid.

the symmetry condition

$$E_z^n(i\max+1, j) = E_z^n(i\max, j).$$

Absorbing boundary conditions were used to truncate the grid at $i = 1$, $j = 1$, and $j = j\max$.

In all following cases, $i\max$ and $j\max$ were equal to 80 and 80 and the incident wave was generated at line $j = 10$. The grid coordinates inside the cylinder were determined by

$$\left(\left(i - 80\frac{1}{2}\right)^2 + \left(j - 40\frac{1}{2}\right)^2\right)^{1/2} \leqslant 20.$$

*1) Homogeneous Circular Dielectric Cylinder:* For comparison, the data used for calculations in this case were those used by Taflove *et al.* [24]. The dielectric had a

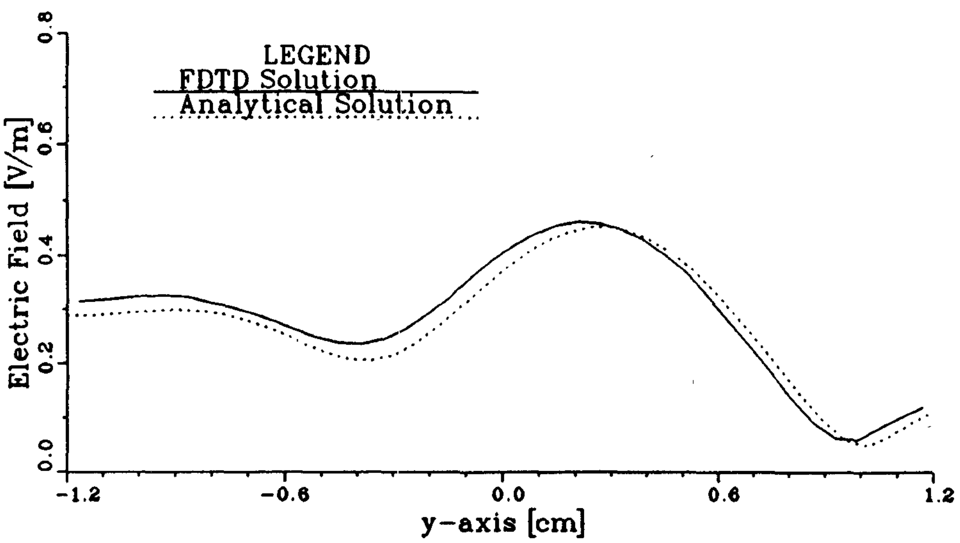


Fig. 3. $E$-field distribution inside a homogeneous circular cylinder of $\epsilon_r = 47$, $\sigma = 2.2$ S/m. Continuous, sinusoidal plane-wave incident field of frequency 2.5 GHz. FDTD solution compared with analytical solution.

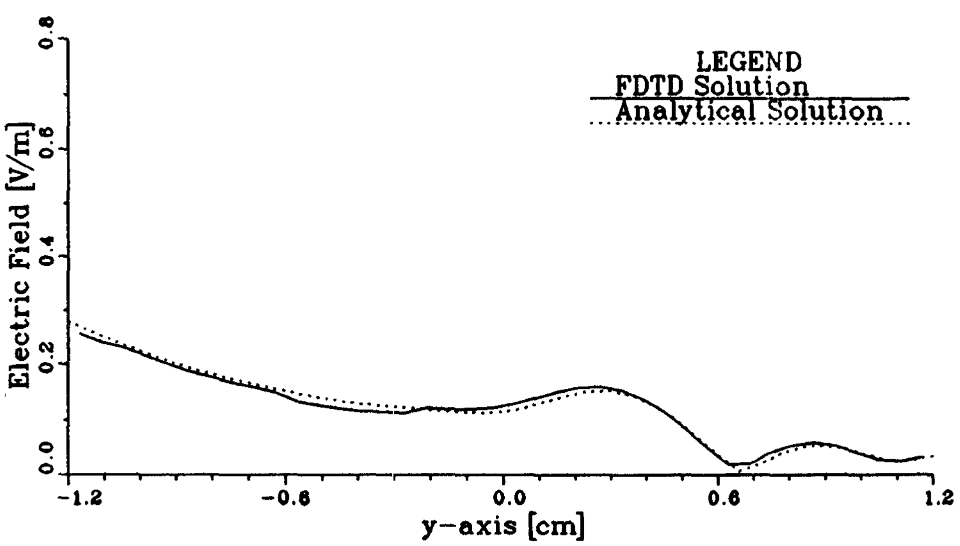


Fig. 4. $E$-field distribution inside a homogeneous circular cylinder of $\epsilon_r = 44$, $\sigma = 5.3$ S/m. Continuous, sinusoidal plane-wave incident field of frequency 5 GHz. FDTD solution compared with analytical solution.

conductivity $\sigma = 2.2$ S/m and a relative permittivity $\epsilon_r = 47$. The incident field was a continuous, sinusoidal plane wave of frequency $f = 2.5$ GHz. The radius of the cylinder was one tenth of a wavelength in free space (1.2 cm).

The node separation was chosen to be $\Delta l = 0.6$ mm and the time increment $\Delta t = 1$ ps. The program was timed stepped to 1800 time steps.

The envelope of $E_z$ for $1600 \leqslant n \leqslant 1800$ is plotted in Fig. 3, with the analytical solution calculated using the summed-series technique [10] for comparison.

Fig. 4 shows the results of the same calculation at frequency $f = 5$ GHz, conductivity $\sigma = 5.3$ S/m, and relative permittivity $\epsilon_r = 44$. The radius of the cylinder was also 1.2 cm.

*2) Multilayered Circular Cylinder of Skin, Fat, and Muscle:* The outer radius of the multilayered circular cylinder was 12 cm. The outer layer was a layer of skin with a thickness of 0.6 cm. The middle layer was a layer of fat with a thickness of 1.2 cm. The core, with a radius of 10.2 cm, was filled with muscle. The parameters of the media were those used in the one-dimensional problem. The incident field was a Gaussian pulse with a pulse width of $t_1 = 1$ ns. The node separation was chosen to be $\Delta l = 0.6$ cm and the time increment $\Delta t = 10$ ps. Then, the radius length was subdivided into 20 segments.

The program was initialized at $t = -4t_1$ ($-4$ ns) and time stepped to 14 ns (1800 time steps).

Fig. 5 shows the electric field distributions along the diameter parallel to the propagation direction of the incident pulse as the pulse begins to penetrate into the skin and fat layers (time: $t = -2.5$, $-2$, $-1.5$, $-1$, and $-0.5$ ns).

Fig. 6 shows the electric field distributions along the diameter parallel to the propagation direction of the

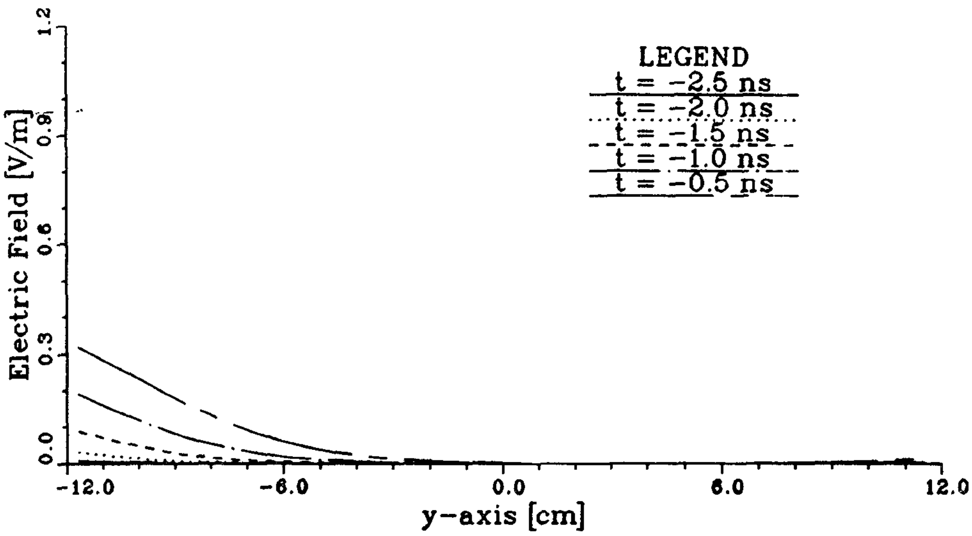


Fig. 5. Electric field distributions along the diameter of a multilayered circular cylinder of skin, fat, and muscle. Gaussian incident pulse of $t_1 = 1$ ns. Penetration through skin and fat layers.

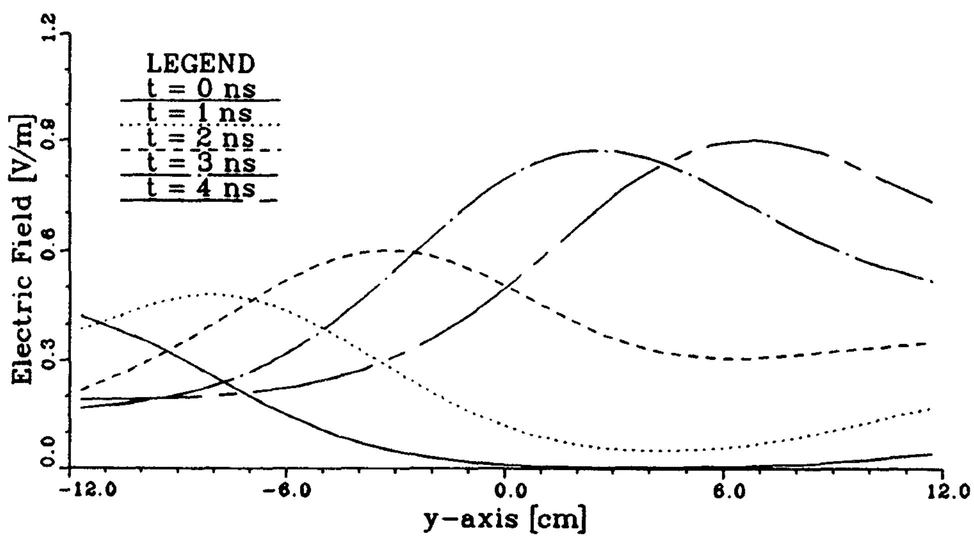


Fig. 6. Electric field distributions along the diameter of a multilayered circular cylinder of skin, fat, and muscle. Gaussian incident pulse of $t_1 = 1$ ns. Penetration through muscle layer.

incident pulse as the pulse penetrates into the muscle layer (time: $t = 0$, 1, 2, 3, and 4 ns).

## IV. Discussion and Conclusions

In this section, we shall discuss the results of numerical computations of the problems presented in Section III.

Fig. 1 presents the transmitted waveforms of a Gaussian pulse incident in a stratified half space filled with skin, fat, and muscle as a function of depth for various times from 0 to 4 ns. Note that the pulse strength decreases and the pulse shape is distorted as the pulse propagates deep inside muscle.

The results presented in Figs. 3 and 4 show relatively good agreement between the FDTD solution and the analytical solution [10]. There are two main sources of differences in the results. The first is the imperfection of the absorbing boundary conditions (reflections). The second is the stepped-edge approximation of the boundary of the cylinder. Thus, to improve the accuracy of the solution, one can increase the resolution of the mesh. However, larger mesh size requires more computer time and memory. Overall, the FDTD solution may be considered accurate up to 1800 time steps for a mesh size of $(80 \times 80)$.

Fig. 5 shows the formation of the transmitted pulse for a Gaussian pulse incident on a multilayered circular cylinder of skin, fat, and muscle. It can be seen that as the transmitted pulse is formed at the front end of the cylinder, the electric field at the rear end is also building up. Fig. 6 shows the electric field penetrations for various times from 0 to 4 ns.

One can observe the increase of the pulse strength as the pulse propagates along the diameter of the cylinder. The cause for this increase may be the superposition of the electric fields penetrating from all directions into the cylinder.

In general, the FDTD method presented in Section II is very powerful. It allows modeling of arbitrarily shaped structures and is easy to implement. In addition, the method requires relatively little computer time and memory. One disadvantage of the method is that all the nodes of the mesh have to be calculated regardless of whether the node is needed or not. Besides, the imperfection of the absorbing boundary conditions (reflections) does not allow the method to be used to analyze the propagation of extremely short pulses in high-permittivity media. An enormous number of time steps would be required to allow the observation of the pulse propagation.

The primary objective of this study was to investigate the propagation of pulsed electromagnetic fields in dispersive dielectrics. An FDTD technique for solving one- and two-dimensional problems of propagation of pulsed electromagnetic fields has been presented. Many problems of propagation with different types of incident pulses and various kinds of dispersive media of different geometries have been investigated.

The results obtained indicate that the pulse does not disperse when the pulse width is very small or very large compared with the relaxation time of the medium. For two-dimensional problems, the results suggest that the pulsed electromagnetic fields penetrate into a dispersive dielectric cylinder not only from the direction of propagation of the incident pulse but also from all other directions. Therefore, in many cases, the maximum pulse amplitude is reached when the pulse has penetrated deep inside the cylinder.

In conclusion, the FDTD technique is applicable to most one- and two-dimensional problems. However, the technique is not suitable for extremely short pulses propagating in a medium of very high permittivity because a huge number of time steps would be required to allow observation of the pulse propagation. Further study of the absorbing boundary conditions is needed to overcome this limitation.

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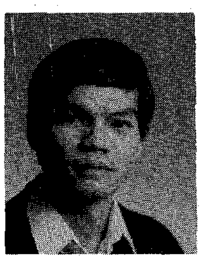


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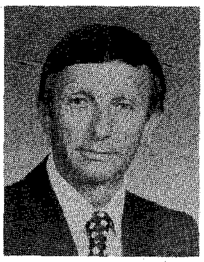


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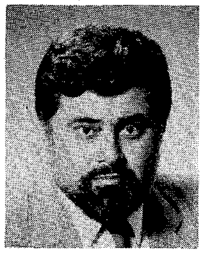

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