CHAPTER VII

DEVELOPMENT OF 3D FDTD APPROACH FOR MICROSTRIP ANTENNA ON GRADED SUBSTRATE

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7.1 INTRODUCTION

Solutions to Maxwell’s equations play a fundamental role in solving electromagnetic problems. Finite Difference Time Domain (FDTD) technique is an efficient tool that can be used to analyse electromagnetic problems such as radiations, microwave devices and scattering by solving the Maxwell’s equations on any scale with almost all kinds of environments [1-6]. The technique can be effectively applied to analyse the electric field distribution inside the antenna structure as well as in the surrounding area of interest [1].

Kane S. Yee in 1966 [1] was first to develop the algorithm for FDTD method to determine initial boundary value problems involving Maxwell’s equations in isotropic media. The FDTD method discretizes the time dependent Maxwell’s equation for vector components using central difference approximations for space and partial derivatives for time. The em wave solution in FDTD is fully worked out in space grid and time-stepping algorithm within the computation domain, where, at any point in space the updated value of the E-field in time is dependent on the stored value of the E-field and the numerical curl of the local distribution of the H-field in space. Similarly, the updated value of the H-field in time is dependent on the stored value of the H-field and the numerical curl of the local distribution of the E-field in space (leap frog arrangement) [1-4].

The 3D FDTD formulation developed here is for rectangular microstrip antenna on graded composite substrates fed at 50 Ω impedance matching point within the patch. A Gaussian discrete pulse is used to excite the radiating patch at the feed point. The substrate is dielectric and the permittivity is taken isotropic.

Initially, the FDTD method analyzes rectangular microstrip patch antenna on single layer composite systems and then extends for graded system. The implementation of numerical features like the computational domain, stability criteria, boundary conditions, subsequent gridding and time stepping for updating electric and magnetic fields is discussed. An in-house program is developed to analyze the field distribution of the antenna.
7.2 PROBLEM FORMULATION

The FDTD method provides a direct time domain solutions of Maxwell’s equations in differential form by discretizing both the physical region and time interval using a uniform grid, known as Yee cells (figure 7.1(a)). An electromagnetic wave interaction structure is mapped into the three dimensional space lattice by assigning appropriate values of permittivity to each electric field component, and permeability to each magnetic field component as shown in figure 7.1(b).

![Figure 7.1](a) Three dimensional gridding in FDTD (b) Basic Yee cell in three dimensions

The general form of Maxwell’s equation for the dielectric media are given as [22],

\[
\frac{\partial D}{\partial t} = \nabla \times H \tag{7.1 a}
\]

\[
D(\omega) = \varepsilon_0 \varepsilon_r E(\omega) \tag{7.1 b}
\]

\[
-\mu \frac{\partial H}{\partial t} = \nabla \times E \tag{7.1 c}
\]

Where, \(E\) is the electric field, \(H\) is the magnetic field, \(B\) is the magnetic flux density, \(\varepsilon_r\) relative electrical permittivity of substrate and \(\varepsilon_0\) is the free space electrical permittivity. \(\mu\) is the magnetic permeability and is expressed as \(\mu = \mu_0 \mu_r\), where \(\mu_0\) is the free space magnetic permeability and \(\mu_r\) is the relative magnetic permeability. The geometry considered is a planar homogeneous dielectric composite system taken in cartesian co-ordinate system. The origin of co-ordinate system is \((i, j, k) = (0, 0, 0)\). EM wave is fed at the 50 Ω impedance point calculated using TLM technique.
The 3D FDTD scheme for microstrip antenna on dielectric substrates can be realized in two modules:

a) Maxwell’s curl equations are expressed in partial differential form
b) These scalar equations are expressed in finite differential form in spatial and temporal coordinates

The electric field and magnetic field gets updated, both at every space grid coordinates and time stepping.

### 7.2.1 Expression of E and H curl equations in partial differential form

The Maxwell’s curl equations 7.1 (a) and (c) are quite similar. As \( \mu_0 \) and \( \varepsilon_0 \) differ by several orders of magnitude, \( E \) and \( H \) also differ by several orders of magnitude. This is circumvented by normalizing the Maxwell’s curl equations considering the following change of the variables as

\[
E = \sqrt{\frac{\varepsilon_0}{\mu_0}} E
\]  
(7.2)

\[
H = \sqrt{\frac{\varepsilon_0}{\mu_0}} H
\]  
(7.3)

All the \( E \) and \( H \) components of isotropic dielectric systems from the Maxwell’s equations 7.1 (a) and 7.1 (c) can be expressed in scalar form as,

\[
\frac{\partial D_x}{\partial t} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right)
\]  
(7.4 a)

\[
\frac{\partial D_y}{\partial t} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right)
\]  
(7.4 b)

\[
\frac{\partial D_z}{\partial t} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right)
\]  
(7.4 c)

\[
\frac{\partial H_x}{\partial t} = -\frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{\partial E_y}{\partial y} - \frac{\partial E_y}{\partial z} \right)
\]  
(7.5 a)

\[
\frac{\partial H_y}{\partial t} = -\frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{\partial E_z}{\partial z} - \frac{\partial E_x}{\partial x} \right)
\]  
(7.5 b)
\[ \frac{\partial H_z}{\partial t} = -\frac{1}{\sqrt{\varepsilon_0 \mu_0}} \left( \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right) \] (7.5 c)

### 7.2.2 Expression of E and H partial differential equations in finite differential form in spatial and temporal coordinates

![Yee's mesh](image)

**Figure 7.2 Yee's mesh**

Finite difference approximation solution of the Maxwell’s partial differential equations 7.4 (a-c) and 7.5 (a-c) are found by discretizing the problem space over a finite three dimensional computational domain in spatial and temporal coordinates in accordance to the Yee’s mesh as shown in figure 7.2.

\[ D_x^{\alpha+1/2} \left( i + \frac{1}{2}, j, k \right) = D_x^{\alpha-1/2} \left( i + \frac{1}{2}, j, k \right) + \frac{\Delta t}{\Delta y \cdot \sqrt{\varepsilon_0 \mu_0}} \left[ H_x^{\alpha} \left( i + \frac{1}{2}, j + \frac{1}{2}, k \right) - H_x^{\alpha} \left( i + \frac{1}{2}, j, k - \frac{1}{2} \right) \right] \] (7.6 b)

\[ D_y^{\alpha+1/2} \left( i, j + \frac{1}{2}, k \right) = D_y^{\alpha-1/2} \left( i, j + \frac{1}{2}, k \right) + \frac{\Delta t}{\Delta z \cdot \sqrt{\varepsilon_0 \mu_0}} \left[ H_y^{\alpha} \left( i, j + \frac{1}{2}, k + \frac{1}{2} \right) - H_y^{\alpha} \left( i, j + \frac{1}{2}, k - \frac{1}{2} \right) \right] \] (7.6 a)

\[ D_z^{\alpha+1/2} \left( i, j, k + \frac{1}{2} \right) = D_z^{\alpha-1/2} \left( i, j, k + \frac{1}{2} \right) + \frac{\Delta t}{\Delta x \cdot \sqrt{\varepsilon_0 \mu_0}} \left[ H_z^{\alpha} \left( i + \frac{1}{2}, j, k + \frac{1}{2} \right) - H_z^{\alpha} \left( i - \frac{1}{2}, j, k \right) \right] \] (7.6 c)

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The modified finite difference equations for the scalar equations 7.5 a through 7.5 c are,

\[ H_{x}^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) = H_{x}^{n-\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) - \frac{\Delta t}{\Delta y \cdot \sqrt{\varepsilon_{0} \mu_{0}}} \left[ E_{z}^{n}(i, j+1, k+\frac{1}{2}) \right] - E_{z}^{n}(i, j, k+\frac{1}{2}) \]

\[ H_{y}^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k+\frac{1}{2}) = H_{y}^{n-\frac{1}{2}}(i+\frac{1}{2}, j, k+\frac{1}{2}) - \frac{\Delta t}{\Delta z \cdot \sqrt{\varepsilon_{0} \mu_{0}}} \left[ E_{x}^{n}(i+1, j, k+\frac{1}{2}) \right] - E_{x}^{n}(i, j, k+\frac{1}{2}) \]

\[ H_{z}^{n+\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k) = H_{z}^{n-\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k) - \frac{\Delta t}{\Delta x \cdot \sqrt{\varepsilon_{0} \mu_{0}}} \left[ E_{y}^{n}(i+1, j, k) \right] - E_{y}^{n}(i, j+1, k) \]

(7.7 a) (7.7 b) (7.7 c)

7.3 IMPLEMENTATION OF FDTD CODE

At first the computational domain is to be defined over which the FDTD will be implemented. Figure 7.3 shows the computational domain. The gridding of the 3D structure (figure 7.1 (a)) is carried out considering the stability conditions. The geometry of the concern structure is expressed in terms of material properties and the PML boundary conditions are initialized to define the actual computational domain. A Gaussian pulse is applied as the input stimulus at the feed point and at discreet time steps, the \( E \) and the \( H \) field components are updated in leap frog manner. The spatial field distribution can be visualized from the simulated \( E \) and \( H \) components in

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three dimensions. To extract the scattering parameters, Fourier transformation of the transient response is taken.

![Three dimensional problem cell](image)

Figure 7.3 Three dimensional problem cell

Important numerical features of the 3D FDTD scheme implementation are described in the following sub-sections:

### 7.3.1 Stability criteria in FDTD

In order to ensure that the central-difference algorithm is numerically stable, there exists a maximum value for the time step and also space discretization which can be used. An electromagnetic wave propagating in free space cannot go faster than the speed of light. To propagate a distance of one cell of dimension $\Delta x$, required a minimum time of $\Delta t = \Delta x / c_{\text{max}}$. Kunz and Luebbers [2] recommend that to ensure stability, there should be at least four cells per minimum wavelength. For good stability, some particularly sensitive problems [1-12], up to twenty cells per wavelength is required at the frequency of interest in order to get the required accuracy. Depending on the cell size, the size of the time step, $\Delta t$, can be determined from the Courant’s stability criterion. For the three dimensional case, the Courant’s stability criterion is defined as [1-6]
\[ \Delta t \leq \frac{1}{c_{\text{max}} \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} \]  

(7.8)

where, $c_{\text{max}}$ is the maximum velocity of light within the computational volume. Typically, $c_{\text{max}}$ is taken as the velocity of light in free space unless the entire volume is filled with dielectric. $\Delta x$, $\Delta y$ and $\Delta z$ are the Cartesian space increments which must be within an order or magnitude of each other. In $n$ dimensional simulation, the maximum time step can be defined in simplified form as

\[ \Delta t = \frac{\Delta x}{\sqrt{n \cdot c_{\text{max}}}} \]  

(7.9)

### 7.3.2 Absorbing boundary conditions

The finite computational capacity of the computers puts a restriction in implementation of infinite FDTD mesh in all the three dimensions. Thus, effective absorbing boundary conditions (ABC) are to be used to truncate an infinite or unbound simulation region. A two dimensional boundary condition proposed by Berenger in 1994, called the perfectly matched layer (PML), enables the efficient absorption of outgoing radiation \[17-21\]. The work of Katz et al has demonstrated that the PML ABC is easily extensible to three dimensions \[19\]. Considering the issues such as problem definition, efficient memory utilization and execution speed, implementation of PML ABC has been demonstrated by Saario in his Ph. D. thesis \[15\].

The basic scheme of the PML is that if a wave is propagating in medium A and it impinges upon medium B, the amount of reflection is dictated by the intrinsic impedances of the two media, $\eta_A$ and $\eta_B$ (figure 7.4)

\[ \Gamma = \frac{\eta_A - \eta_B}{\eta_A + \eta_B} \]  

(7.10)

Where,
and are determined by the permittivity $\varepsilon$ and permeability $\mu$ of the two media.

$$\eta = \sqrt{\frac{\mu}{\varepsilon}} \quad (7.11)$$

![Figure 7.4](image)

**Figure 7.4** The reflection at the interface of two media

The propagating pulse in the absorbing medium covering the computational domain should die out before it reaches the external boundary. For this “fictitious” dielectric constant and permeability of the absorbing media is considered to be lossy and is added to the implementation codes. Thus, the flux density formulations of the Maxwell’s curl equations with “fictitious” $\varepsilon$ and $\mu$ are,

$$\varepsilon^* \frac{\partial E}{\partial t} = \nabla \times H \quad (7.12)$$

$$D(\omega) = \varepsilon^*(\omega)E(\omega) \quad (7.13)$$

$$\mu^* \frac{\partial H}{\partial t} = -\nabla \times E \quad (7.14)$$

There are two conditions to formulate a PML [20, 21]:

1. The impedance going from the background medium to the PML must be constant,

$$\eta_0 = \eta_m = \sqrt{\frac{\mu^*_{Fx}}{\varepsilon^*_{Fx}}} = 1 \quad (7.15)$$

The impedance is one because of our normalized units (free space).
2. In the direction perpendicular to the boundary (the x direction, for instance), the relative dielectric constant and relative permeability must be the inverse of those in the other directions, i.e.,

\[
\varepsilon^*_{Fx} = \frac{1}{\varepsilon^*_{Fy}} \quad (7.16 \text{ a})
\]

\[
\mu^*_{Fx} = \frac{1}{\mu^*_{Fy}} \quad (7.16 \text{ b})
\]

The 3D PML ABC [23] is included in developing the algorithm for the absorbing boundary treatment and the detail formulation is given as Appendix-A.

### 7.3.3 Source considerations

The excitation can be of any shape, but, normally a Gaussian pulse is considered. This type of pulse has a frequency spectrum that is also Gaussian and thus provides frequency domain information from dc up to a desired cut-off frequency by adjusting the width of the pulse [22, 23]. In order to simulate a voltage source excitation, the pulse is fed as the vertical electric field, \( E_z \), in a rectangular region underneath the patch. The form of the input signal in a continuous form is

\[
E_z = f(t) = e^{-\frac{(t-T_0)^2}{T_1}} \quad (7.17)
\]

where, \( T \) is the current time-step, \( T_0 \) the pulse delay time-step and \( T_1 \) the width of the pulse in time-steps. The width of the Gaussian pulse sets the required cut-off frequency. The pulse width is normally chosen to have at least 20 points per wavelength at the highest frequency significantly represented in the pulse. The numerical dispersion and truncation error is minimized. Initially, in the simulation, all the electric and magnetic fields are set to zero. The Gaussian pulse applied at the source has only a field component which is perpendicular to the ground plane (i.e, \( E_z \)). Thus, \( E_y \) and \( E_x \), at the source, are always zero. A change in the electric field at the source with respect to time causes a change in the magnetic field in the x-direction.
7.3.4 Frequency dependent parameters

The final transient $E$ field values, obtained after the FDTD simulation, are used to get wide band frequency response. The Fourier transform of the $E$ field $E(t)$ at a frequency $f_i$ is done by the equation [3]

$$E(f_1) = \int_0^{t_T} E(t) \cdot e^{-j2\pi \cdot f_i t} \, dt$$

(7.18)

The lower limit of the integral in equation (7.18) is 0, because the FDTD program assumes all casual functions. The upper limit is $t_T$, the time at which the FDTD iteration is halted. Equation (7.18) can be rewritten in a finite difference form as

$$E(f_1) = \sum_{n=0}^{T} E(n \cdot \Delta t) \cdot e^{-j2\pi \cdot f_i (n \cdot \Delta t)}$$

(7.19)

Where $T$ is the number of iterations and $\Delta t$ is the time step and hence $t_T = T \cdot \Delta t$. Equation (7.19) is now divided into its real and imaginary parts as

$$E(f_1) = \sum_{n=0}^{T} E(n \cdot \Delta t) \cdot \cos(2\pi f_1 \cdot \Delta t \cdot n) - j \sum_{n=0}^{T} E(n \cdot \Delta t) \cdot \sin(2\pi f_1 \cdot \Delta t \cdot n)$$

(7.20 a)

$$\Rightarrow E(f_1) = \text{Re}(E) - \text{Im}(E)$$

(7.20 b)

7.4 IMPLEMENTATION IN COMPUTER PROGRAM

The existing finite difference approximation equations for simple rectangular microstrip antenna are modified for single layer and graded composite dielectric substrate materials. Performance of microstrip antenna is analysed by $S_{11}$ parameter. In the formulation the antenna $S_{11}$ parameter and internal field distribution are focused rather than the radiation pattern. The microstrip antenna is modelled with a small surrounding area. As $S_{11}$ parameter depends on the geometry of the antenna, so it is crucial to model
the antenna with minimum possible dimensional error. Thus, different cell
dimensions in different directions are used [3, 24, 25].

**Table 7.1** Cell size in different directions for microstrip antennas on single layer and graded
substrate

<table>
<thead>
<tr>
<th>Substrate</th>
<th>dimension of the patch (w x l) (mm)</th>
<th>Δx (mm)</th>
<th>Δy (mm)</th>
<th>Δz (mm)</th>
<th>Δt (picosec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 % VF of titania in LDPE</td>
<td>11.4 x 8.3</td>
<td>0.259</td>
<td>0.285</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>Graded Substrate</td>
<td>11.2 x 8.1</td>
<td>0.253</td>
<td>0.28</td>
<td>0.25</td>
<td>0.41</td>
</tr>
</tbody>
</table>

In case of graded substrates five material layers are to be considered; free space, three composite material layers and the metal as shown in figure 7.5.

![FDTD computational domain showing different material zones](image)

**Figure 7.5** FDTD computational domain showing different material zones

The materials are defined in the FDTD code with their relative permittivity. From equation 7.1 (a), the electric field in the media is given by expressions,

\[ E_x[i, j,k] = gax[i, j,k] \times D_x[i, j,k] \]  \hspace{1cm} (7.21 a)

\[ E_y[i, j,k] = gay[i, j,k] \times D_y[i, j,k] \]  \hspace{1cm} (7.21 b)

\[ E_z[i, j,k] = gaz[i, j,k] \times D_z[i, j,k] \]  \hspace{1cm} (7.21 c)

Where,

\[ gax[i, j,k] = 1/\varepsilon_r \]  \hspace{1cm} (7.22 a)
\[ \varepsilon_{r}[i,j,k] = 1/\varepsilon_r \] (7.22 b)

\[ \varepsilon_{z}[i,j,k] = 1/\varepsilon_r \] (7.22 c)

where, \( \varepsilon_r \) is the relative permittivity of the media. The metal can be modelled by considering \( \varepsilon_{ax}, \varepsilon_{ay} \) and \( \varepsilon_{az} \) to be zero at those points constituting the patch and the ground plane.

The complete flowchart for FDTD algorithm is shown in figure 7.6, highlighting the electric field and magnetic field updating modules. A program in MATLAB is developed to implement this algorithm for study of microstrip antenna and E and H updating code modules are listed in Appendix B. Other considerations in the algorithm for implementation in the code are summarised in the following sub-sections.

![Main modules of 3D FDTD simulation algorithm](image)

**Figure 7.6** Main modules of 3D FDTD simulation algorithm

### 7.4.1 Stability criteria

The microstrip patch geometry, fabricated on different composite substrates has different patch dimensions. The height of the substrate is fixed for all the designs. The Yee’s mesh is generated for the geometry by dividing
the geometry into grid of different dimensions in different directions in the computational domain. The computational volume is only partially filled with the composite dielectric material, hence the maximum velocity, $c_{\text{max}}$, is taken as the velocity of light in free space. In choosing the time step, the smallest grid dimension ($\Delta x$, $\Delta y$ or $\Delta z$) is used in the Courant stability criterion, given by equation 7.8. Table 7.1 gives the time steps for different element sizes modelled.

### 7.4.2 Source consideration

The width of the Gaussian pulse for the specified cut-off frequency is determined from the equation 7.17. The pulse delay, $T_0$, is set at 50 time steps. The width of the pulse, $T_1$, is set as 20 time-step in order to achieve larger bandwidth. This pulse width of 20 time step and $\Delta t = 0.031$ picoseconds, gives a 15 GHz bandwidth. The Gaussian pulse has optimum pulse-width and desired cut-off frequency and is used as excitation from port 1.

### 7.4.3 PML terminating condition

![Figure 7.7 Gaussian pulses applied at the input feed point](image)

**Figure 7.7** Gaussian pulses applied at the input feed point
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The PML ABC is employed in the current program. Figure 7.7 illustrates the effectiveness of a 15 point PML with the source offset of one cell from the centre in the x, y and z directions. The outgoing pulse gets partially reflected when the pulse gets within fifteen points of the edge, which is inside the PML, where the distortion starts to occur.

7.4.4 Post processing of the results

After completion of the simulation process, the full wave distribution of the E and H wave is viewed in all the planes of interest.

To calculate the $S_{11}$ we need the information at a single point (for microstrip antenna it is at the feed point). After the simulation is over, the frequency response is calculated over the entire range of frequencies using Fourier transform. $S_{11}$ parameter is calculated by gathering the voltage information at the point of interest. When the voltage is known, the values of $E_z$ field at the ground plane and the point of interest can be found. For first 350 time steps, the field values at the point are considered as input and the rest is considered as the reflected signal. The $S_{11}$ in decibels is then expressed as,

$$S_{11}(f)_{dB} = 10 \log \frac{E_{\text{out}}(f)}{E_{\text{in}}(f)}$$

(7.23)

7.5 FULL-WAVE FDTD ANALYSIS OF RECTANGULAR MICROSTRIP ANTENNA ON SINGLE LAYER AND GRADED COMPOSITE SUBSTRATE

The FDTD full wave analysis is applied to microstrip antenna designed on LDPE/titania single layer and graded dielectric substrates. For implementation of FDTD simulation design parameters given in table 7.1 are used. The FDTD simulation implementation is realizes as following:

The FDTD simulation generates data which helps in visualizing the time progression of vector fields throughout the three-dimensional solution space. It gives a physical insight of complex field interactions at different
stages of field propagation. In the present analysis, snap shot of E and H field distribution in 3D space is taken at different time step.

The radiation response of the microstrip antenna is analyzed by finding the scattering parameters by taking Fourier transformation of the transient E field component.

The 3D algorithm applied for the microstrip antenna on substrate is given by the flow chart shown in figure 7.8.

![FDTD algorithm flow chart for microstrip antenna analysis](image)

**Figure 7.8** FDTD algorithm flow chart for microstrip antenna analysis
7.5.1 $E_z$ field distribution within microstrip antenna substrate

Figures 7.9 to 7.17 gives the mode of propagation of $E_z$ component of electric field in the plane perpendicular to the patch and parallel to the non radiating edges through the antenna geometry at different time steps.

**Figure 7.9** The FDTD simulated electric field components within the substrate of microstrip antenna at 200 time steps (a) Single layer substrate (b) Graded substrate
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Figure 7.10 The FDTD simulated electric field components within the substrate of microstrip antenna at 250 time steps (a) Single layer substrate (b) Graded substrate

Figure 7.11 The FDTD simulated electric field components within the substrate of microstrip antenna at 300 time steps (a) Single layer substrate (b) Graded substrate
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Figure 7.12 The FDTD simulated electric field components within the substrate of microstrip antenna at 350 time steps (a) Single layer substrate (b) Graded substrate

Figure 7.13 The FDTD simulated electric field components within the substrate of microstrip antenna at 400 time steps (a) Single layer substrate (b) Graded substrate
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Figure 7.14 The FDTD simulated electric field components within the substrate of microstrip antenna at 450 time steps (a) Single layer substrate (b) Graded substrate

Figure 7.15 The FDTD simulated electric field components within the substrate of microstrip antenna at 500 time steps (a) Single layer substrate (b) Graded substrate
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Figure 7.16 The FDTD simulated electric field components within the substrate of microstrip antenna at 550 time steps (a) Single layer substrate (b) Graded substrate

Figure 7.17 The FDTD simulated electric field components within the substrate of microstrip antenna at 600 time steps (a) Single layer substrate (b) Graded substrate
7.5.2 $S_{11}$ parameter analysis

$S_{11}$ parameters of the antennas are calculated in the FDTD program using the equation 7.23. The $S_{11}$ obtained for both the single layer substrate microstrip antenna and the graded substrate antenna are compared with the measured and simulated (using CST Microwave Studio) results and shown in figure 7.18-7.19.

![Figure 7.18](image1.png)  
Figure 7.18 $S_{11}$ parameter of rectangular patch antenna on 2 % VF of titania in LDPE composite substrate

![Figure 7.19](image2.png)  
Figure 7.19 $S_{11}$ parameter of rectangular patch antenna on graded composite substrate
The S\(_{11}\) results show that the -10 dB bandwidth and the S\(_{11}\) at the resonating frequency are increasing in microstrip antenna on graded substrate in comparison to the single layer substrate.

### 7.6 CONCLUSION

The FDTD technique is implemented for analysis of microstrip antenna structure on graded substrate, having isotropic permittivity over the layer. This technique is successfully analyses the full-wave electric field distribution and return loss of microstrip antenna, fabricated on LDPE/titania dielectric composite substrate. The electric field pattern shows that due to change in permittivity at different sections of the graded substrate, the field distribution changes in comparison to the single layer counter part. This could be due to suppression of surface waves within the graded substrate leading to enhancement of the radiation phenomena and S\(_{11}\) parameter.
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Numerical analysis: FDTD

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