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### 3.

가.

FDTD

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conformal

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# SUMMARY

The interest in accurate dosimetric measurements inside phantoms that simulate biological bodies has burgeoned since regulatory commissions began calling for or recommending the testing for compliance with safety standards of low power devices. To measuring the near field such as this, many probes are presented and produced. Electric field probe for measuring near-field is consist of a dipole antenna, RF detector, nonperturbing transmission line, and readout device. The objective of this study was to investigate the characteristics of the E-field probe using Finite-Difference Time-Domain techniques. FDTD simulations can describe not only the probes's characteristics by modelling the components(dipole- diode- line) but also the influence of the dielectric supporting materials of the probe, which can completely distort the theoretical dipole-charateristics.

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# 1

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 가 , , 가 , .  
 ,  
 가  
 가 .  
 ,  
(maximum permissible exposure, MPE) .  
 , .  
 가 .  
 가 ,  
 .  
 .  
 ANSI/IEEE C95.1 - 1992  
 가 ,  
(controlled environments) 가

(uncontrolled environments)

. 1 g SAR  
가 1.6 W/kg , , , 10 g  
SAR 가 4W/kg , SAR  
0.08 W/kg . ,  
1 g  
SAR 가  
가 .  
SAR  
E- field . SAR 가  
, ,  
. 가  
, ,  
가 .  
. ,  
가 .  
(EMC) 가  
, ,  
, 가  
, .  
, (electronic probe),  
(temperature sensing probe), (photonic  
probe) . DC  
, ,  
. ,  
가 .  
가 .

. SAR

가

가

, FDTD

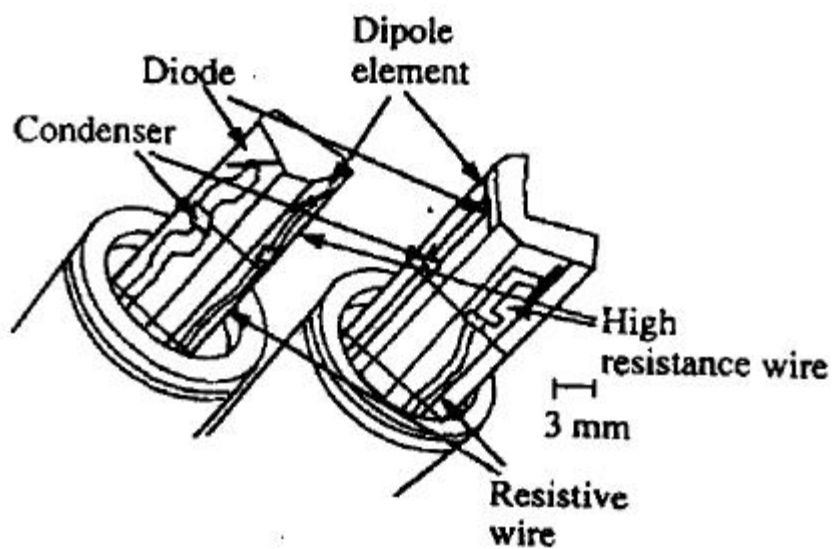
Schmid & Partner Eng.

1-1

ER3DV5

가 ET3DV5가

[1].



1-1 SAR

ET3DV5

FDTD

. FDTD  
 2 1 5 , FDTD  
 Conformal 6  
 . , 7  
 , FDTD  
 , 가 가 FDTD  
 , 8 , 3  
 4 .

## 2 FDTD

### 1 Yee

FDTD (finite difference method, FDM) Maxwell

. FDTD 1966 Kane Yee ,

Maxwell  
[2]. FDTD Mur, Berenger, Taflove, Umashanker  
가 ,  
(full wave) [3].

Maxwell .

Faraday :

$$-\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} - \mathbf{J}_m \quad (2.1)$$

$$-\frac{\partial}{\partial t} \int \int_s \mathbf{B} \cdot d\hat{s} = - \oint_c \mathbf{E} \cdot d\hat{l} - \int \int_s \mathbf{J}_m \cdot \hat{s} \quad (2.2)$$

Ampere :

$$-\frac{\partial \mathbf{D}}{\partial t} = \nabla \times \mathbf{H} - \mathbf{J}_e \quad (2.3)$$



$$-\frac{\partial}{\partial t} \int \int_s \mathbf{D} \cdot d\hat{s} = \oint_c \mathbf{H} \cdot d\hat{l} - \int \int_s \mathbf{J}_e \cdot \hat{s} \quad (2.4)$$

Gauss :

$$\nabla \cdot \mathbf{D} = 0 \quad (2.5)$$

$$\oint \oint_s \mathbf{D} \cdot d\hat{s} = 0 \quad (2.6)$$

Gauss :

$$\nabla \cdot \mathbf{B} = 0 \quad (2.7)$$

$$\oint \oint_s \mathbf{B} \cdot d\hat{s} = 0 \quad (2.8)$$

$\mathbf{E}$  (electric field),  $\mathbf{D}$  (electric flux density),  $\mathbf{H}$  (magnetic field),  $\mathbf{B}$  (magnetic flux density),  $\mathbf{J}_e$  (electric conduction current),  $\mathbf{J}_m$  (magnetic conduction current) .

$\oint_s \hat{s} \cdot d\mathbf{s} = \oint_c \hat{l} \cdot d\mathbf{l} = 0$  .  
 $\omega$  (frequency)  
 dispersive)  $\mathbf{E}, \mathbf{D}, \mathbf{H}, \mathbf{B}$

$$\mathbf{B} = \mu \mathbf{H} \quad (2.9)$$

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (2.10)$$

가 ,  
 (electric loss) (magnetic loss) 가

$$\mathbf{J}_m = \sigma^* \mathbf{H} \quad (2.11)$$

$$\mathbf{J}_e = \sigma \mathbf{E} \quad (2.12)$$

$$\sigma \quad \sigma^* \quad \text{Maxwell curl} \quad (2.1) \quad (2.12)$$

$$-\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \mathbf{E} - \frac{\sigma^*}{\mu} \mathbf{H} \quad (2.13)$$

$$-\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\varepsilon} \nabla \times \mathbf{H} - \frac{\sigma}{\varepsilon} \mathbf{E} \quad (2.14)$$

$$(2.13) \quad (2.14) \quad x, y, z \quad 3$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - \sigma^* H_x \right) \quad (2.15)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - \sigma^* H_y \right) \quad (2.16)$$

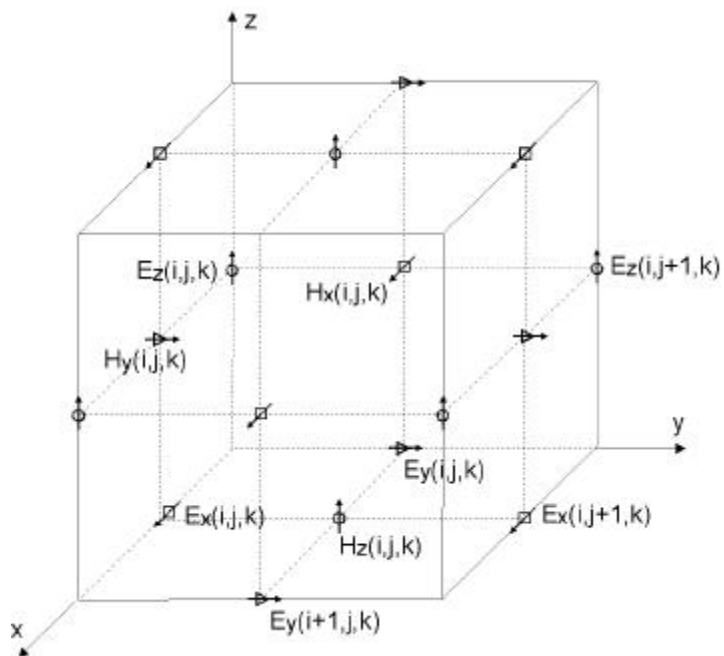
$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - \sigma^* H_z \right) \quad (2.17)$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x \right) \quad (2.18)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\mu} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y \right) \quad (2.19)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\mu} \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z \right) \quad (2.20)$$

6 FDTD 가 Yee FDTD  
2-1 Yee 가  
curl ,  
(2.5) (2.8) Gauss



2-1 Yee

1966 Kane Yee가 FDTD

1. Yee , Maxwell  
 curl

가 .

2. 2-1  $E$  가 4  $H$   
 $, H$  4  $E$

Faraday Ampere  
 가 Yee Maxwell

2  
 가  
 Gauss , Yee FDTD  
 가 (divergence free)

3. 2-1  $E$   $H$  (leapfrog)  
 $H$   $E$

가  
 2 가

$$(2.15) \quad (2.20)$$

$$, \quad (n \Delta t) \quad (i \Delta x, j \Delta y, k \Delta z)$$

$$(i, j, k) = (i \Delta x, j \Delta y, k \Delta z) \quad (2.21)$$

$$u(i \Delta x, j \Delta y, k \Delta z, i \Delta t) = u|_{i, j, k}^n \quad (2.22)$$

$$u$$

$$-\frac{\partial u}{\partial x}(i, j, k, n) = \frac{u|_{i+1/2, j, k}^n - u|_{i-1/2, j, k}^n}{\Delta x} + O[(\Delta x)^2] \quad (2.23)$$

$$-\frac{\partial u}{\partial t}(i, j, k, n) = \frac{u|_{i, j, k}^{n+1/2} - u|_{i, j, k}^{n-1/2}}{\Delta t} + O[(\Delta t)^2] \quad (2.24)$$

$$(2.21) \quad (2.24) \quad (2.15) \quad (2.20)$$

Maxwell

$$m = MEDIA [H_x(i, j, k)]$$

$$H_x|_{i, j, k}^{n+1/2} = D_a(m) H_x|_{i, j, k}^{n-1/2} +$$

$$D_b(m) (E_y|_{i, j, k+1/2}^n - E_y|_{i, j, k-1/2}^n + E_z|_{i, j-1/2, k}^n - E_z|_{i, j+1/2, k}^n) \quad (2.25)$$

$$m = MEDIA [H_y(i, j, k)]$$

$$\begin{aligned}
H_y|_{i,j,k}^{n+1/2} &= D_a(m)H_y|_{i,j,k}^{n-1/2} + \\
&D_b(m)(E_z|_{i+1/2,j,k}^n - E_z|_{i-1/2,j,k}^n + E_x|_{i,j,k-1/2}^n - E_x|_{i,j,k+1/2}^n)
\end{aligned} \tag{2.26}$$

$$m = MEDIA [H_z(i, j, k)]$$

$$\begin{aligned}
H_z|_{i,j,k}^{n+1/2} &= D_a(m)H_z|_{i,j,k}^{n-1/2} + \\
&D_b(m)(E_x|_{i,j+1/2,k}^n - E_x|_{i,j-1/2,k}^n + E_y|_{i-1/2,j,k}^n - E_y|_{i+1/2,j,k}^n)
\end{aligned} \tag{2.27}$$

$$m = MEDIA [E_x(i, j, k)]$$

$$\begin{aligned}
E_x|_{i,j,k}^{n+1} &= C_a(m)E_x|_{i,j,k}^n + \\
&C_b(m)(H_z|_{i,j+1/2,k}^{n+1/2} - H_z|_{i,j-1/2,k}^{n+1/2} + H_y|_{i,j,k-1/2}^{n+1/2} - H_y|_{i,j,k+1/2}^{n+1/2})
\end{aligned} \tag{2.28}$$

$$m = MEDIA [E_y(i, j, k)]$$

$$\begin{aligned}
E_y|_{i,j,k}^{n+1} &= C_a(m)E_y|_{i,j,k}^n + \\
&C_b(m)(H_x|_{i,j,k+1/2}^{n+1/2} - H_x|_{i,j,k-1/2}^{n+1/2} + H_z|_{i-1/2,j,k}^{n+1/2} - H_z|_{i+1/2,j,k}^{n+1/2})
\end{aligned} \tag{2.29}$$

$$m = MEDIA [E_z(i, j, k)]$$

$$\begin{aligned}
E_z|_{i,j,k}^{n+1} &= C_a(m)E_z|_{i,j,k}^n + \\
&C_b(m)(H_y|_{i+1/2,j,k}^{n+1/2} - H_y|_{i-1/2,j,k}^{n+1/2} + H_x|_{i,j-1/2,k}^{n+1/2} - H_x|_{i,j+1/2,k}^{n+1/2})
\end{aligned} \tag{2.30}$$

,

$$C_a(m) = \left(2 - \frac{\sigma_{i,j,k}\Delta t}{2\varepsilon_{i,j,k}}\right) / \left(1 + \frac{\sigma_{i,j,k}\Delta t}{2\varepsilon_{i,j,k}}\right) \tag{2.31}$$

$$C_b(m) = \left(-\frac{\Delta t}{\varepsilon_{i,j,k}\Delta}\right) / \left(1 + \frac{\sigma_{i,j,k}\Delta t}{2\varepsilon_{i,j,k}}\right) \tag{2.32}$$

$$D_a(m) = \left( 2 - \frac{\sigma_{i,j,k}^* \Delta t}{2\mu_{i,j,k}} \right) / \left( 1 + \frac{\sigma_{i,j,k}^* \Delta t}{2\mu_{i,j,k}} \right) \quad (2.33)$$

$$D_b(m) = \left( \frac{\Delta t}{\mu_{i,j,k} \Delta} \right) / \left( 1 + \frac{\sigma_{i,j,k}^* \Delta t}{2\mu_{i,j,k}} \right) \quad (2.34)$$

$$\Delta x = \Delta y = \Delta z = \Delta \quad (2.35)$$

$$(2.25) \quad (2.30) \quad m$$

$$C_a, C_b, D_a, D_b \quad .$$

$$(2.25) \quad (2.30) \quad (2.2), \quad (2.4)$$

$$\text{Faraday} \quad \text{Ampere} \quad , \text{ Yee}$$

$$\text{Faraday} \quad \text{Ampere} \quad .$$

$$\text{Gauss}$$

$$, \quad \text{Gauss}$$

$$.$$

$$\begin{aligned} -\frac{\partial}{\partial t} \oint \oint_{Yee\ cell} \mathbf{D} \cdot d\hat{\mathbf{s}} &= \varepsilon \frac{\partial}{\partial t} (E_x|_{i,j+1/2,k+1/2} - E_x|_{i-1,j+1/2,k+1/2}) \Delta y \Delta z \\ &+ \varepsilon \frac{\partial}{\partial t} (E_y|_{i-1/2,j+1,k+1/2} - E_y|_{i-1/2,j,k+1/2}) \Delta x \Delta z \\ &+ \varepsilon \frac{\partial}{\partial t} (E_z|_{i-1/2,j+1/2,k+1} - E_z|_{i-1/2,j+1/2,k}) \Delta x \Delta y \end{aligned} \quad (2.36)$$

$$(2.36) \quad (2.18) \quad (2.20)$$

$$(2.36) \quad 0 \quad .$$

$$\text{Gauss} \quad . \quad \text{Yee}$$

$$\text{FDTD}$$

가  
(spurious solution) .

$$\oint \oint_{Yee\ cell} \mathbf{D}(t) \cdot \hat{s} = \oint \oint_{Yee\ cell} \mathbf{D}(t=0) \cdot \hat{s} = 0 \quad (2.37)$$

## 2 Yee

(2.25) (2.35) FDTD  
 $\Delta x, \Delta y, \Delta z, \Delta t$   
 가 가 .  $\Delta x, \Delta y, \Delta z, \Delta t$   
 (stability) .  $\Delta x, \Delta y, \Delta z$   
 $1/10 \quad 1/20$   
 .  
 $\Delta x, \Delta y, \Delta z$   
 $1/10$  가 ,  $1/4$   
 (numerical instability) .  
 가  
 가 가 .  
 Courant, Friedrich, Levy  
 (CFL) von Neumann  
 [3].

(node)  
 Fourier , Fourier  
 가 .  
 von Neumann  
 Fourier



TM FDTD

$$\frac{H_x|_{i,j}^{n+1/2} - H_x|_{i,j}^{n-1/2}}{\Delta t} = -\frac{1}{\mu} \left( \frac{E_z|_{i,j+1/2}^n - E_z|_{i,j-1/2}^n}{\Delta y} \right) \quad (2.38)$$

$$\frac{H_y|_{i,j}^{n+1/2} - H_y|_{i,j}^{n-1/2}}{\Delta t} = \frac{1}{\mu} \left( \frac{E_z|_{i+1/2,j}^n - E_z|_{i-1/2,j}^n}{\Delta x} \right) \quad (2.39)$$

$$\frac{E_z|_{i,j}^{n+1} - E_z|_{i,j}^n}{\Delta t} = \frac{1}{\epsilon} \left( \frac{H_y|_{i+1/2,j}^{n+1/2} - H_y|_{i-1/2,j}^{n+1/2}}{\Delta x} - \frac{H_x|_{i,j+1/2}^{n+1/2} - H_x|_{i,j-1/2}^{n+1/2}}{\Delta y} \right) \quad (2.40)$$

(2.38) (2.40) eigenmode가

가

eigenvalue

eigenvalue

eigenvalue

$$\frac{H_x|_{i,j}^{n+1/2} - H_x|_{i,j}^{n-1/2}}{\Delta t} = \Lambda H_x|_{i,j}^n \quad (2.41)$$

$$\frac{H_y|_{i,j}^{n+1/2} - H_y|_{i,j}^{n-1/2}}{\Delta t} = \Lambda H_y|_{i,j}^n \quad (2.42)$$

$$\frac{E_z|_{i,j}^{n+1} - E_z|_{i,j}^n}{\Delta t} = \Lambda E_z|_{i,j}^{n+1/2} \quad (2.43)$$

(2.41) (2.43) V ,

$$\frac{V|_{i,j}^{n+1/2} - V|_{i,j}^{n-1/2}}{\Delta t} = \Lambda V|_{i,j}^n \quad (2.44)$$

$$(2.44) \quad \text{가} \quad (\text{growth factor}) \quad q_{i,j}$$

$$(2.44) \quad .$$

$$q_{i,j} = \frac{V|_{i,j}^{n+1/2}}{V|_{i,j}^n} = \frac{V|_{i,j}^n}{V|_{i,j}^{n-1/2}} \quad (2.45)$$

$$\frac{q_{i,j} V|_{i,j}^n - (V|_{i,j}^n / q_{i,j})}{\Delta t} = \Lambda V|_{i,j}^n \quad (2.46)$$

$$(2.45) \quad (2.46) \quad \text{von Neumann}$$

가

$$|q_{i,j}| \leq 1 \quad . \quad \text{eigenvalue}$$

.

$$- \frac{2}{\Delta t} \leq \text{Im}(\Lambda) \leq \frac{2}{\Delta t} \quad (2.47)$$

$$(2.38) \quad (2.40)$$

$$\text{eigenvalue} \quad .$$

$$- \frac{1}{\mu} \left( \frac{E_z|_{i,j} - E_z|_{i,j-1/2}}{\Delta y} \right) = \Lambda H_x|_{i,j} \quad (2.48)$$

$$\frac{1}{\mu} \left( \frac{E_z|_{i+1/2,j} - E_z|_{i-1/2,j}}{\Delta x} \right) = \Lambda H_y|i,j \quad (2.49)$$

$$\frac{1}{\varepsilon} \left( \frac{H_y|_{i+1/2,j} - H_y|_{i-1/2,j}}{\Delta x} - \frac{H_x|_{i,j+1/2} - H_x|_{i,j-1/2}}{\Delta y} \right) = \Lambda E_z|_{i,j} \quad (2.50)$$

$n$   
 $i, j$  Fourier  
 $2$  -  
 (spatial- frequency spectrum) eigenmode .

$$E_z|_{I,J} = E_{z0} e^{j(k_x I \Delta x + k_y J \Delta y)} \quad (2.51)$$

$$H_x|_{I,J} = H_{x0} e^{j(k_x I \Delta x + k_y J \Delta y)} \quad (2.52)$$

$$H_y|_{I,J} = H_{y0} e^{j(k_x I \Delta x + k_y J \Delta y)} \quad (2.53)$$

$$(2.51) \quad (2.53) \quad (2.48) \quad (2.50)$$

$k$  eigenvalue  $\Lambda$  가 .

$$Re(\Lambda) = 0$$

$$-2c \sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2}} \leq Im(\Lambda) \leq 2c \sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2}} \quad (2.54)$$

$c$  가  
 , (2.47)  
 eigenvalue (2.54) 가  
 , FDTD  
 , Caurant .

$$\Delta t \leq \frac{1}{c \sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2}}} \quad (2.55)$$

3

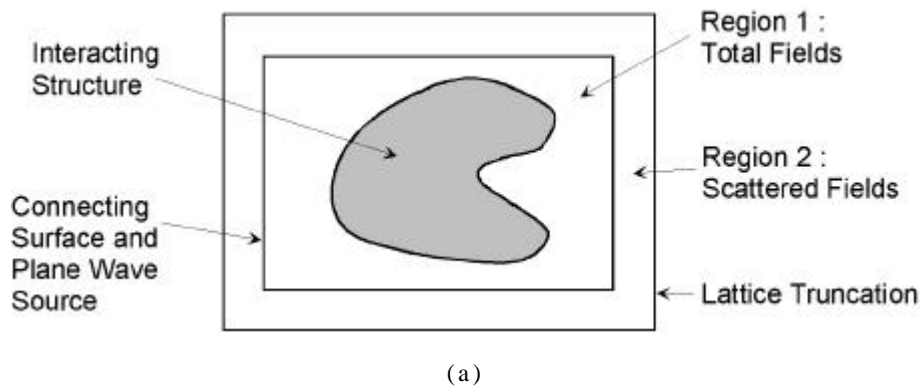
$$\Delta t \leq \frac{1}{c \sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \quad (2.56)$$

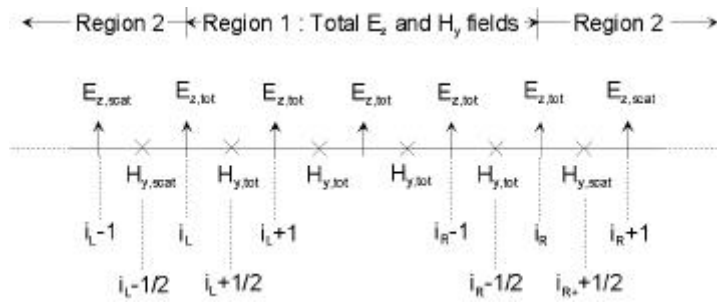
3 /

/ (total- field/scattered- field) 1982

, 가 (steady state)

Maxwell





(b)

2-2 /

$$\mathbf{E}_{tot} = \mathbf{E}_i + \mathbf{E}_{scat} \quad (2.57)$$

$$\mathbf{H}_{tot} = \mathbf{H}_i + \mathbf{H}_{scat} \quad (2.58)$$

$\mathbf{E}_i$   $\mathbf{H}_i$  , FDTD

. 가 가

.  $\mathbf{E}_{scat}$   $\mathbf{H}_{scat}$

,

. Yee

,

.

/

2-2 (a)

가

,

FDTD

,

,

(connection condition)

/

.

1.

.

2- 2 (a)

Region 1

2.

- Region 1

3.

가 .

- Shadow

가

가

가

, /

4.

Region

2

가

가

가

5.

가

2- 2 (b) 1

Region 1

Region 2

$$\begin{aligned}
& , \quad i_L \quad i_R \quad . \\
H_{y, scat} |_{i_L - 1/2} & , \quad E_{z, tot} |_{i_L} \\
& .
\end{aligned}$$

$$E_{z, tot} |_{i_L}^{n+1} = -\frac{\Delta t}{\epsilon_o \Delta x} (H_{y, tot} |_{i_L + 1/2}^{n+1/2} - H_{y, tot} |_{i_L - 1/2}^{n+1/2}) \quad (2.59)$$

$$H_{y, scat} |_{i_L - 1/2}^{n+1/2} = -\frac{\Delta t}{\mu_o \Delta x} (E_{z, scat} |_{i_L}^n - E_{z, scat} |_{i_L - 1}^n) \quad (2.60)$$

$$(2.59) \quad (2.60) \quad H_{y, tot} |_{i_L - 1/2}^{n+1/2}, \quad E_{z, scat} |_{i_L}^n \quad 2-2$$

(b)

$$E_{z, tot} |_{i_L}^{n+1} = -\frac{\Delta t}{\epsilon_o \Delta x} (H_{y, tot} |_{i_L + 1/2}^{n+1/2} - H_{y, scat} |_{i_L - 1/2}^{n+1/2} - H_{y, i} |_{i_L - 1/2}^{n+1/2}) \quad (2.61)$$

$$H_{y, scat} |_{i_L - 1/2}^{n+1/2} = -\frac{\Delta t}{\mu_o \Delta x} (E_{z, tot} |_{i_L}^n - E_{z, scat} |_{i_L - 1}^n - E_{z, i} |_{i_L}^n) \quad (2.62)$$

## 4

FDTD

Gaussian

Gaussian

DFT

.  $x$  가  
 , .

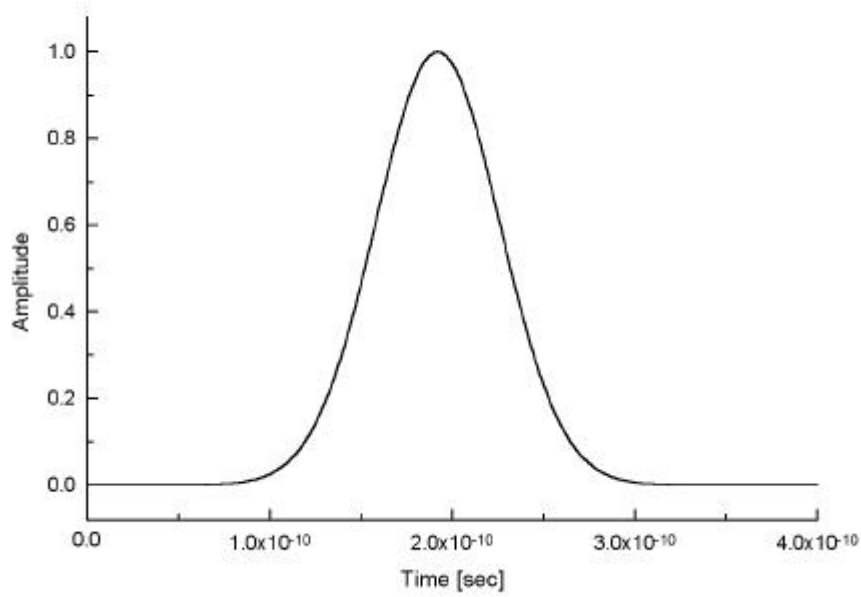
$$E_x^i = E_x \exp(-\alpha[\tau - \beta\Delta t]^2) \quad (2.63)$$

.

$$\tau = n\Delta t + \mathbf{r}' \cdot \hat{\mathbf{r}}/C + R/C \quad (2.64)$$

$\mathbf{r}'$  FDTD  
 ,  $\hat{\mathbf{r}}$  ,  $R$  ,  $C$   
 . (2.63)  $\alpha, \beta$   
 Gaussian  
 Gaussian - + 가 FDTD  
 Gaussian . ,  
 (2.63) Gaussian  $\tau = \beta\Delta t$  가  
 $\tau = 0$   $\tau = 2\beta\Delta t$  0  
 . Gaussian 가  $\tau = 0$   
 $\tau = 2\beta\Delta t$   $\alpha$  ,  $\alpha$   $\beta$   
 가 exp(-16)  
 가  $\alpha = (4/(\beta\Delta t))^2$  .



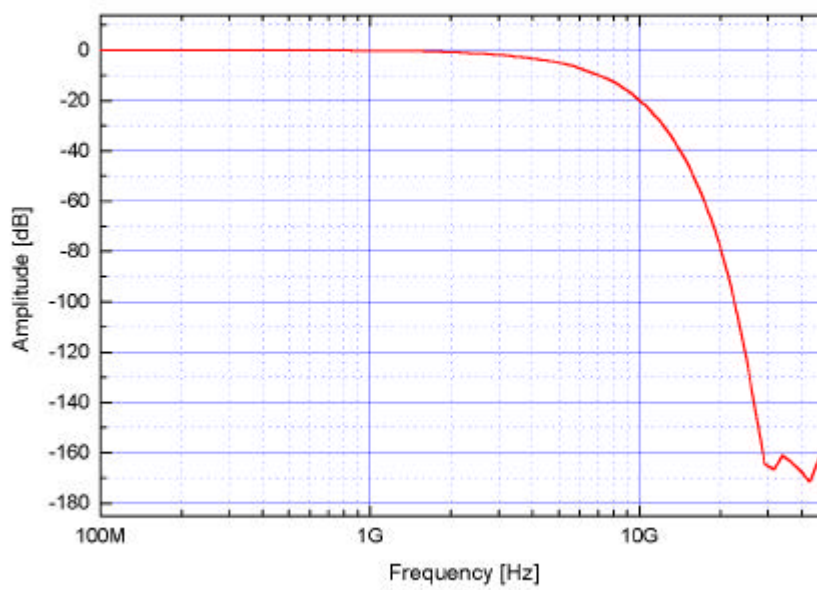


### 2- 3 Gaussian

FDTD 가 ,  
 CFL  $\Delta t$  가 .  
 Gaussian  
 $\alpha, \beta$  가 . ,  
 가 가  
 $1/\sqrt{\epsilon\mu}$

$\epsilon_r = 14.0$  ,  $\mu_r = 1.0$  10 GHz  
 $\Delta = 0.5$  mm , CFL  $\Delta t = 9 \times 10^{-13}$   
 가 .  $\beta = 240$  ,  $\alpha = (4/(\beta \Delta t))^2$  Gaussian  
 2- 3 , Gaussian  
 2- 4 . 2- 4  
 17 10 GHz DC

- 20 dB 가 ,  
 4 가 40 GHz  
 - 160 dB가 .  
 ,  
 FDTD 가  
 FDTD 가 . DC  
 Gaussian DC - 20 dB 가  
 Gaussian

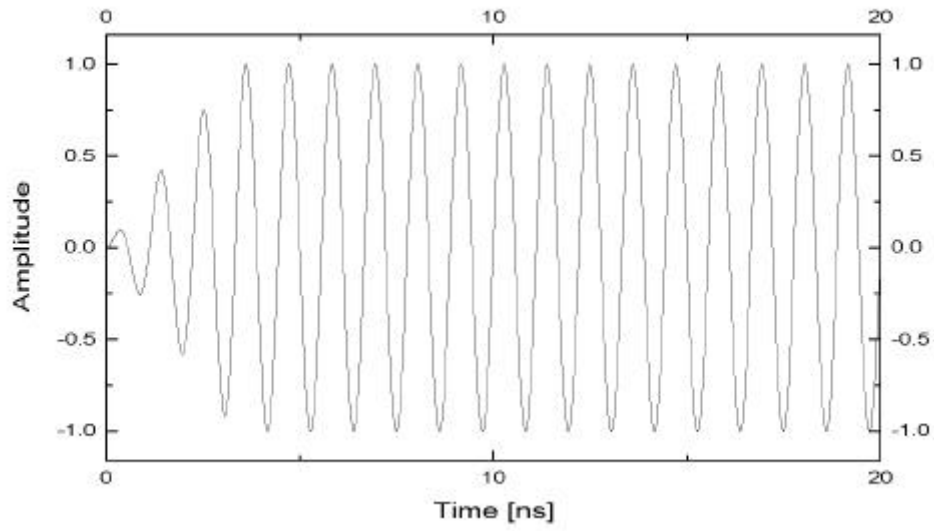


## 2- 4 Gaussian

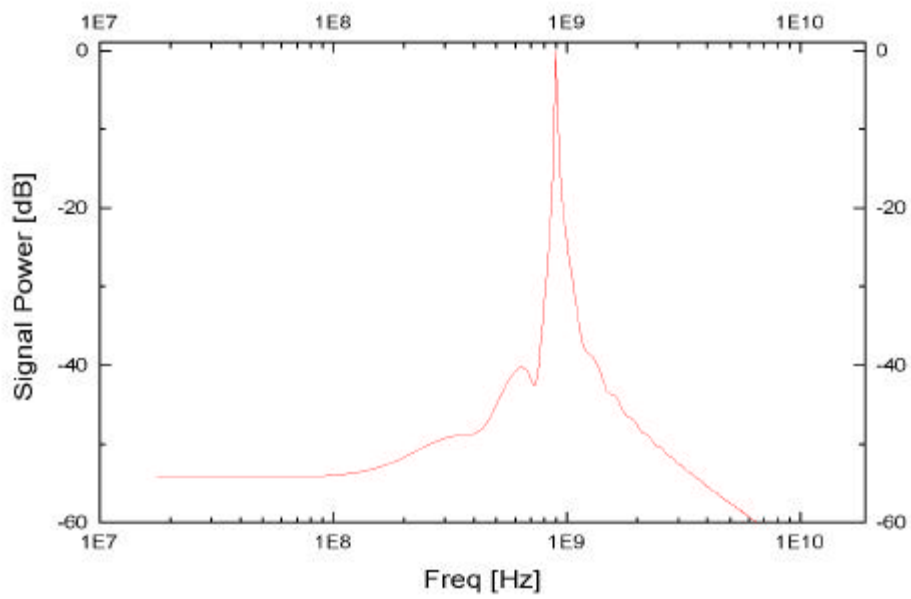
가  
 overshoot가 steady state가  
 가 (2.65)  
 . (2.65)

2- 5, 2- 6 .

$$V_i(t) = \begin{cases} \frac{t}{3T} \sin\left(\frac{2\pi t}{T}\right) & , \quad t < 3T \\ \sin\left(\frac{2\pi t}{T}\right) & , \quad t \geq 3T \end{cases} \quad (2.65)$$



2-5



2- 6

## 5 PML

FDTD

가

가

가

Condition ; ABC)

(Absorbing Boundary

ABC ABC가 ABC가 . ABC  
1 1977  
Engquist- Majda가 [4].  
Taylor ,  
Mur [5]. ,  
가 가 가  
1% - 5% 가  
.  
ABC ,  
가 .  
가 ,  
 ,  
 .  
가 ,  
가 ,  
가 ,  
가 ,  
ABC Berenger PML (Perfectly Matched  
Layer) , 1994 [6].  
PML , TM  
TM Maxwell

$$\epsilon_o \frac{\partial E_{zx}}{\partial t} + \sigma_x E_{zx} = \frac{\partial H_y}{\partial x} \quad (2.66)$$

$$\epsilon_o \frac{\partial E_{zy}}{\partial t} + \sigma_y E_{zy} = \frac{\partial H_x}{\partial y} \quad (2.67)$$

$$\mu_o \frac{\partial H_x}{\partial t} + \sigma_y^* H_x = - \frac{\partial (E_{zx} + E_{zy})}{\partial y} \quad (2.68)$$

$$\mu_o \frac{\partial H_y}{\partial t} + \sigma_x^* H_y = \frac{\partial (E_{zx} + E_{zy})}{\partial x} \quad (2.69)$$

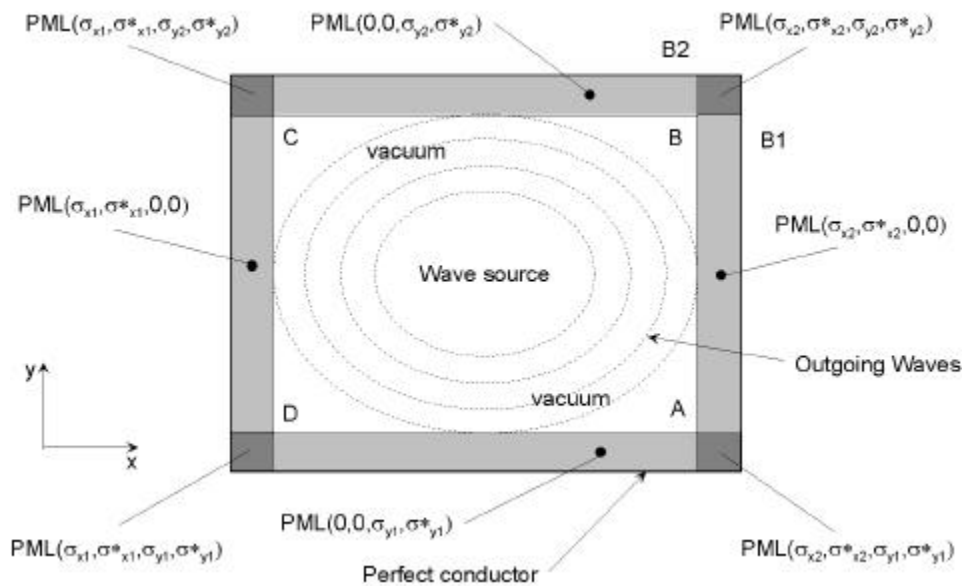
$$(2.66) \quad (2.69) \quad \sigma_x \quad \sigma_x^* \quad x$$

$$, \quad \sigma_y \quad \sigma_y^* \quad y$$

. TM 가 (  $\sigma_x, \sigma_x^*, \sigma_y, \sigma_y^*$  )

가

$$\frac{\sigma_x}{\epsilon_o} = \frac{\sigma_x^*}{\mu_o}, \quad \frac{\sigma_y}{\epsilon_o} = \frac{\sigma_y^*}{\mu_o} \quad (2.70)$$



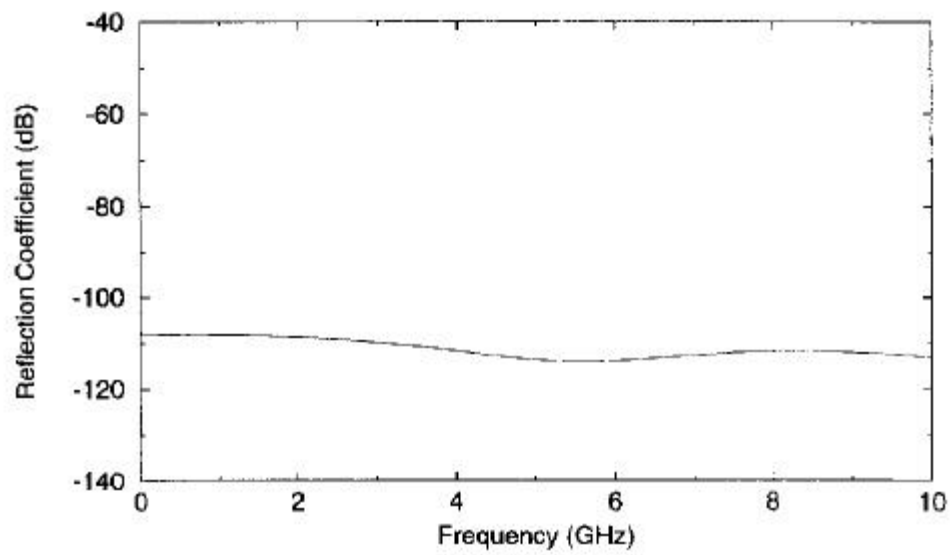
2-7 Berenger PML 2 FDTD

(2.66) (2.70) TM PML

2-7 . (  $\sigma_x, \sigma_x^*, \sigma_y, \sigma_y^*$  ) 2-7

,  
가

. Berenger  
가 가 .



2- 8 PML (  $R(0) = 10^{-6}$ , 16 )

$$\sigma(\rho) = \sigma_{\max} (\rho/\delta)^n \quad (2.70)$$

$\sigma_{\max}$   $\delta$  PML ,  
 $\rho$  가 PML 0  $\delta$   
 ,  $n$  2 3 .  $\sigma$   
 TE

$$R(\theta) = e^{-2\sigma_{\max} \delta \cos \theta ((n+1)\epsilon_0 c)} \tag{2.71}$$

16

PML

2- 6

- 100dB

.

2- 6

$10^{-6}$

PML

.  $100 \times 100 \times 50$

FDTD

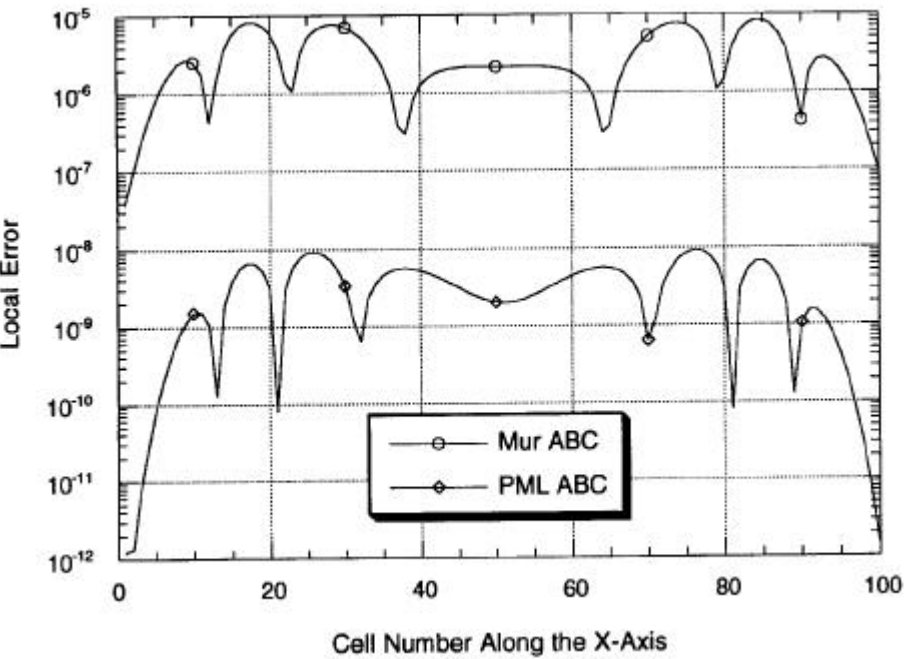
$x$

Local error

Mur

2- 9

[3].



2- 9

Local error :  $x$

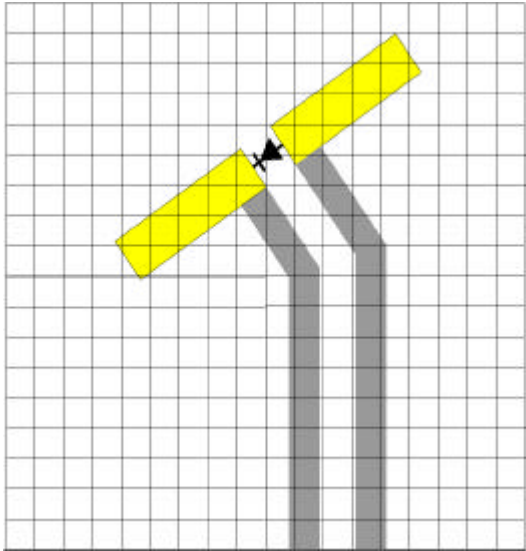
$(100 \times 100 \times 50)$

# 6 Conformal

FDTD

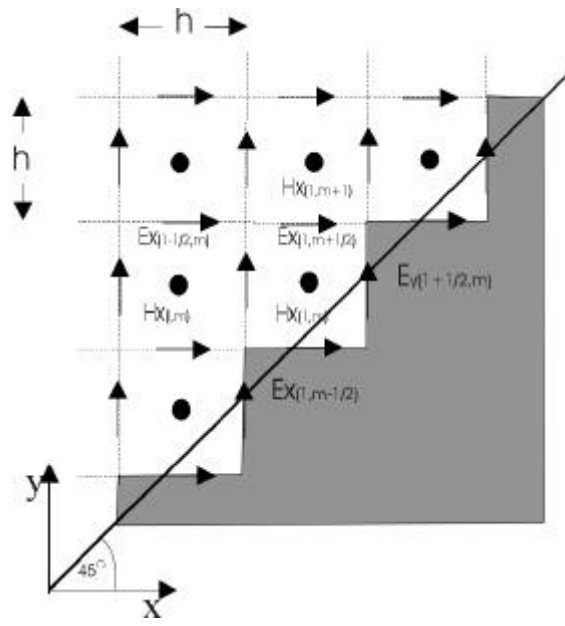


. , FDTD  
가 가 ,  
가 FDTD .



2- 10 ET3DV5 FDTD  
2- 10 dipole coplanar strip  
grid Yee's FDTD  
FDTD .  
FDTD  
Locally conformal  
FDTD method .

1.



2- 11

가

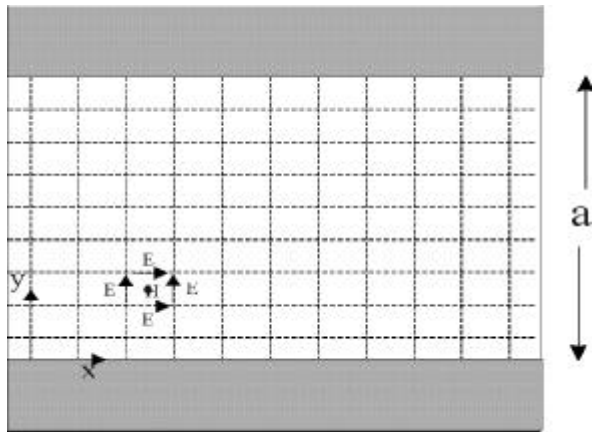
2- 11

가

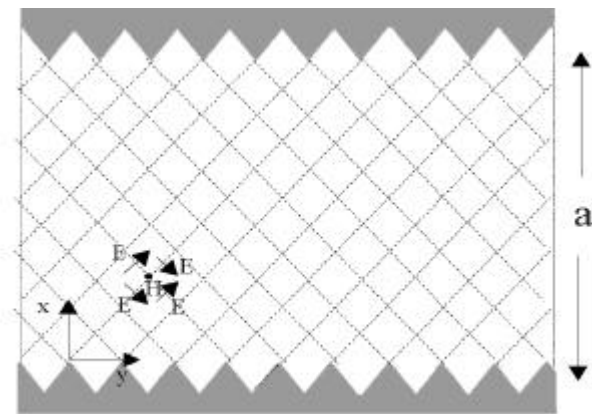
FDTD

[7]. TEz

TEz



(a)



(b)

2- 12 TEz

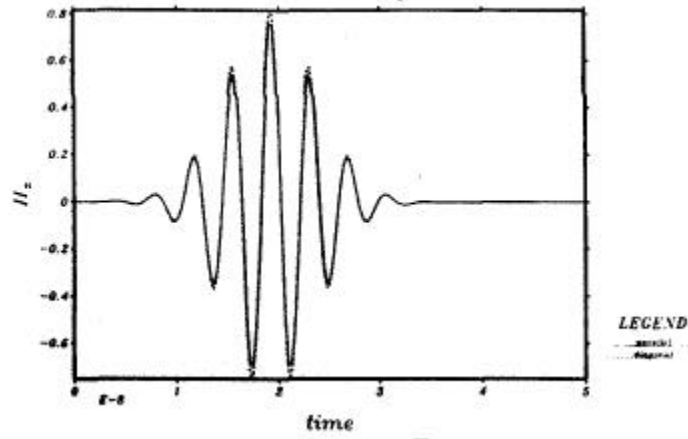
TE1z  
Gaussian

$$x(t) = e^{-t^2/T^2} \cos(\omega t)$$

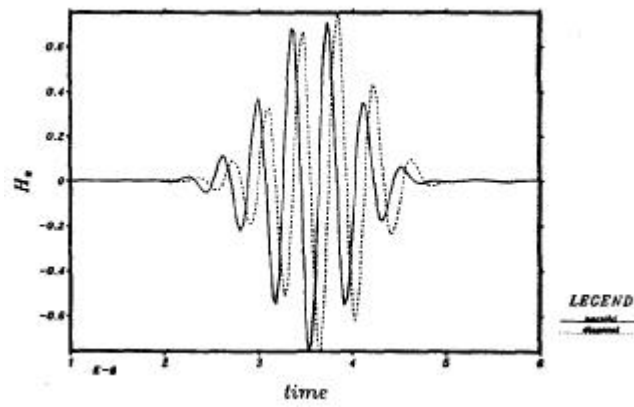
x

y

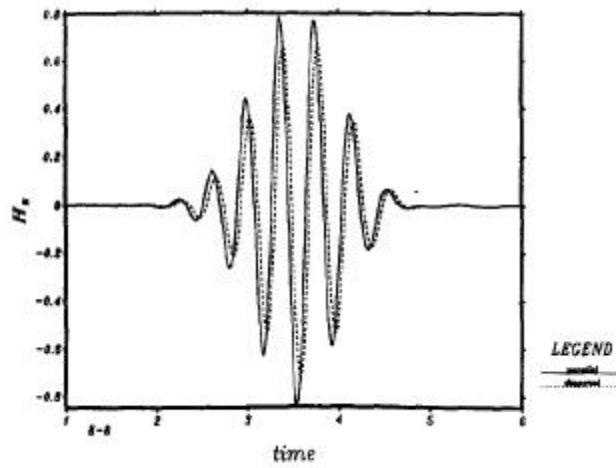
TEz



2- 13  $a = 1m = 7h_p = 7\sqrt{2}hd$ ,  $x=0.2a$ ,  $y=0$  (  $C_n=0.95$  )



2- 14  $a = 1m = 7h_p = 7\sqrt{2}hd$ ,  $x=0.2a$ ,  $y = 3.85a$  (  $C_n=0.95$  )



2- 15  $a = 1m = 15hp = 15\sqrt{2}hd$ ,  $x = 0.2a$ ,  $y = 3.86a$  ( $Cn=0.95$ )

2- 13  $y=0$  TEz . y

TEz

2- 14 y  $y=3.85a$  TEz .

y

2- 15

가

가

가

2. Contour Path FDTD(CPFDTD)

FDTD

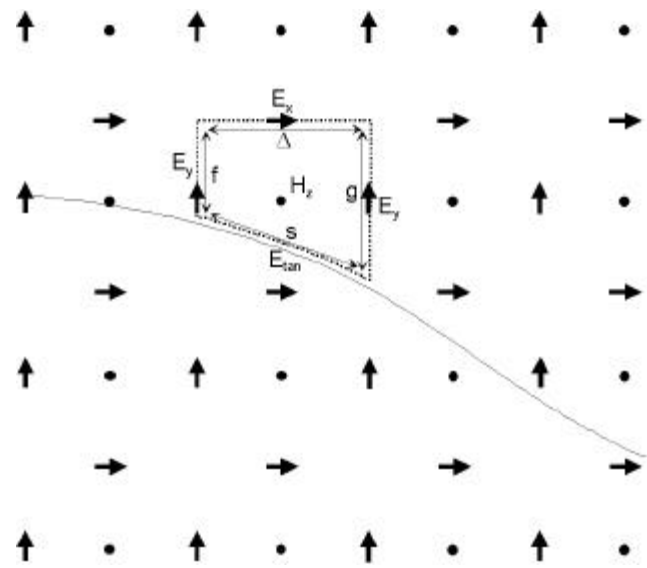
path FDTD)

T. G. Jurgén

A. Taflove

(CPFDTD, contour

[8].



2- 16 Standard subcell

2- 16

2- 17

CPFDTD

FDTD

FDTD

2- 16

$H_z|_{i,j}^{n+1/2}$

standard subcell

2- 17

$H_{z1}|_{i,j}^{n+1/2}$

standard stretched cell

$H_{z2}|_{i,j}^{n+1/2}$

nonstandard subcell

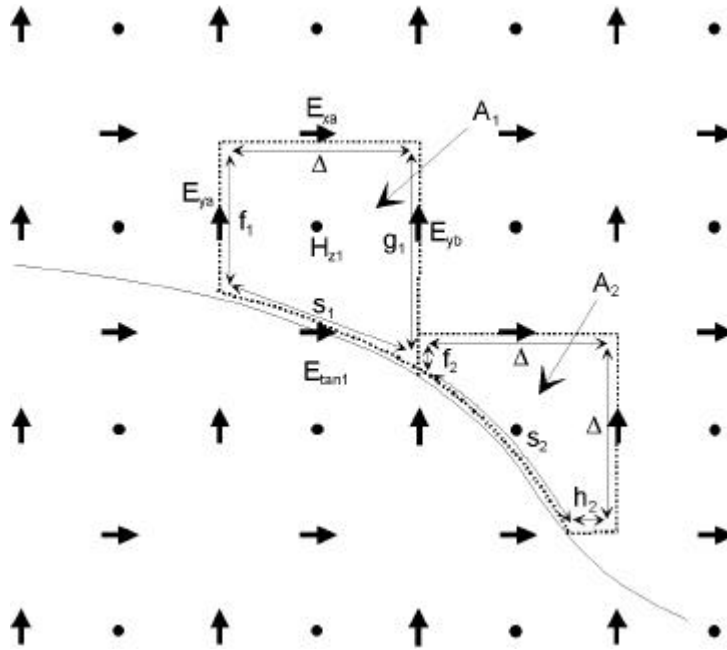
가

가

.

가

Faraday



2-17 Standard stretched cell Nonstandard subcell

Standard subcell

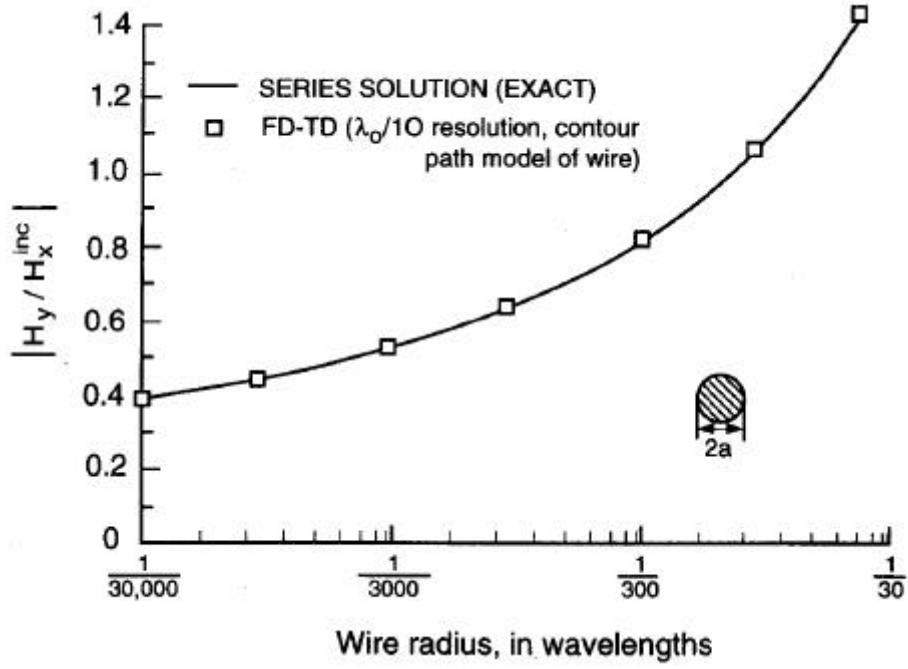
$$\begin{aligned}
 H_z|_{i,j}^{n+1/2} = & H_z|_{i,j}^{n-1/2} \\
 & + \frac{\Delta t}{\mu_0 A} (E_y|_{i-1/2,j}^n f - E_y|_{i+1/2,j}^n g + E_x|_{i,j+1/2}^n \Delta)
 \end{aligned}
 \tag{2.72}$$

Standard stretched subcell

$$\begin{aligned}
|H_{z1}|^{n+1/2} &= |H_{z1}|^{n-1/2} \\
&+ \frac{\Delta t}{\mu_0 A_1} (|E_{ya}|^n f_1 - |E_{yb}|^n g_1 + |E_{xa}|^n \Delta)
\end{aligned}
\tag{2.73}$$

Nonstandard subcell

$$\begin{aligned}
|H_{z2}|^{n+1/2} &= |H_{z2}|^{n-1/2} \\
&+ \frac{\Delta t}{\mu_0 A_2} (|E_{yb}|^n f_2 - |E_{yc}|^n \Delta + |E_{xb}|^n \Delta - |E_{xc}|^n h_2)
\end{aligned}
\tag{2.74}$$



2- 18

CPFDTD

CPFDTD

2- 18



가

가

FDTD 가

(2.74)

$H_{z2}$   $f_2$  ,  $H_{z2}$

가 가  $E_{yb}$

non-causal

, non-reciprocal

FDTD

FDTD

### 3. Locally Conformal Finite-Difference Time-Domain(LCFDTD)

sub-cell sub-cell

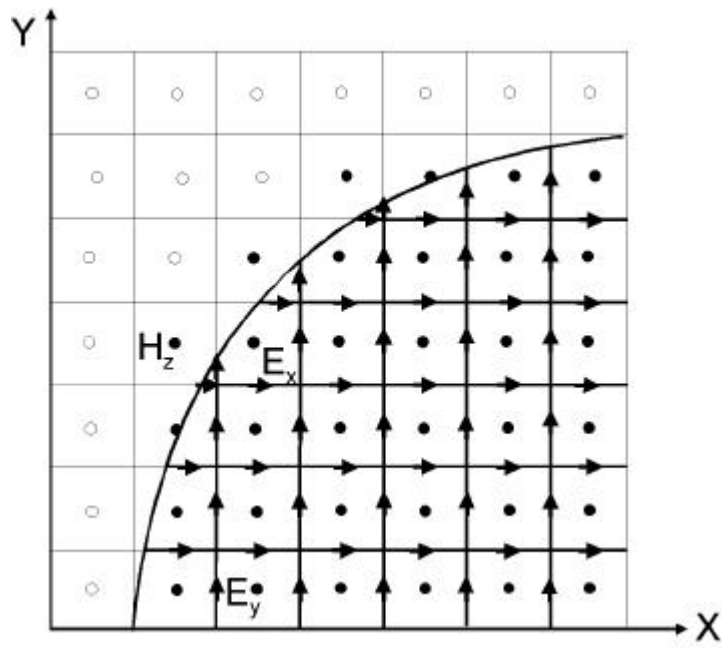
Supriyo Dey Raj Mittra CPFDTD

LCFDTD(Locally conformal FDTD)

[9].

13% 가 LCFDTD

0.7 %



2- 19 LCFDTD

LCFDTD

2- 19

가

FDTD

가

가 . ,

가

0 .

2- 19

가

가 z

가

$$\begin{aligned}
H_z|_{i,j,k}^{n+1/2} = & H_z|_{i,j,k}^{n-1/2} + \frac{\Delta t}{\mu \text{Area}(i,j,k)} \{ E_x|_{i,j,k}^n l_x(i,j,k) \\
& - E_x|_{i,j-1,k}^n l_x(i,j-1,k) - E_y|_{i,j,k}^n l_y(i,j,k) \\
& + E_y|_{i-1,j,k}^n l_y(i-1,j,k) \}
\end{aligned} \quad (2.75)$$

$$Area(i, j, k) \quad i, j, k \quad H_z \text{ 가}$$
$$l_x(i, j, k) \quad i, j, k \quad E_x \text{ 가}$$
$$\cdot$$
$$\text{FDTD}$$

$$\begin{aligned}
E_x |_{i,j,k}^{n+1} = & E_x |_{i,j,k}^n + \frac{\Delta t}{\varepsilon \Delta y} \{ H_z |_{i,j+1,k}^{n+1/2} - H_z |_{i,j,k}^{n+1/2} \} \\
& + \frac{\Delta t}{\varepsilon \Delta z} \{ H_y |_{i,j,k+1}^{n+1/2} - H_y |_{i,j,k}^{n+1/2} \}
\end{aligned} \quad (2.76)$$

LCFDT D

LCFDT D

가

LCFDT D

가 LC-FDTD

7

CPS(Coplanar strip)

CPS

3 FDTD

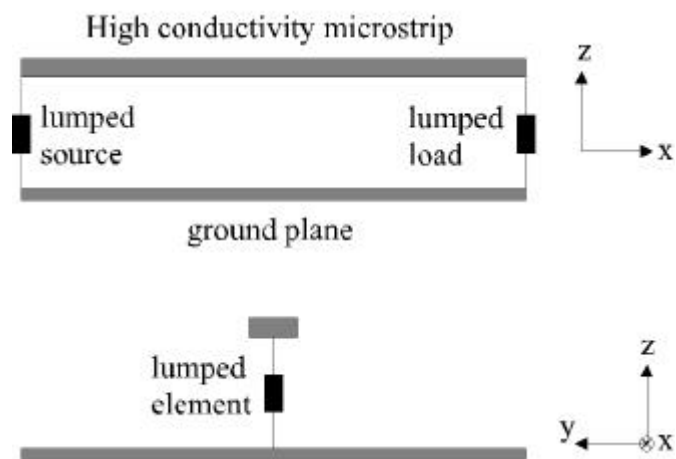
[10],[11].

2- 20

x

z

가



2- 20

1. FDTD

$$\hat{J}_c = \sigma \hat{E} \quad \hat{D} = \epsilon \hat{E} \quad \text{가} \quad \text{Maxwell}$$

$$\nabla \times \hat{H} = \hat{J}_c + -\frac{\partial \hat{D}}{\partial t} \quad (2.76)$$

,

$$E_z \Big|_{i,j,k}^{n+1} = \left[ \frac{1 - \frac{\sigma_{i,j,k} \Delta t}{2\epsilon_{i,j,k}}}{1 + \frac{\sigma_{i,j,k} \Delta t}{2\epsilon_{i,j,k}}} \right] E_z \Big|_{i,j,k}^n + \left[ \frac{-\frac{\Delta t}{\epsilon_{i,j,k}}}{1 + \frac{\sigma_{i,j,k} \Delta t}{2\epsilon_{i,j,k}}} \right] \left\{ \frac{H_y \Big|_{i+\frac{1}{2},j,k}^{n+\frac{1}{2}} - H_y \Big|_{i-\frac{1}{2},j,k}^{n+\frac{1}{2}}}{\Delta x} + \frac{H_x \Big|_{i,j-\frac{1}{2},k}^{n+\frac{1}{2}} - H_x \Big|_{i,j+\frac{1}{2},k}^{n+\frac{1}{2}}}{\Delta y} \right\} \quad (2.77)$$

$$(2.77) \quad H \quad E_z \Big|_{i,j,k}^n$$

$$E_z \Big|_{i,j,k}^{n+1} \quad n+1/2 \quad , \quad \text{가} \quad (2.78) \quad \text{가} \quad n+1/2 \quad \text{가}$$

$$J_c \Big|_{i,j,k}^{n+\frac{1}{2}} = \sigma_{i,j,k} E_z \Big|_{i,j,k}^{n+\frac{1}{2}} = \sigma_{i,j,k} (E_z \Big|_{i,j,k}^n + E_z \Big|_{i,j,k}^{n+1}) \quad (2.78)$$

$$\text{가} \quad (2.79)$$

,

$$\nabla \times H \mid_{i,j,k}^{n+1/2} = \frac{H_y \mid_{i+\frac{1}{2},j,k}^{n+\frac{1}{2}} - H_y \mid_{i-\frac{1}{2},j,k}^{n+\frac{1}{2}}}{\Delta x} \quad (2.79)$$

$$+ \frac{H_x \mid_{i,j-\frac{1}{2},k}^{n+\frac{1}{2}} - H_x \mid_{i,j+\frac{1}{2},k}^{n+\frac{1}{2}}}{\Delta y}$$

(2.78)

$$E_z \mid_{i,j,k}^{n+1} = E_z \mid_{i,j,k}^n + \frac{-\Delta t}{\epsilon_0} \nabla \times H \mid_{i,j,k}^{n+\frac{1}{2}} \quad (2.80)$$

$$J_L \quad (2.76) \quad \text{가} \quad (2.81)$$

$$\nabla \times \widehat{H} = \widehat{J}_c + \frac{\partial \widehat{D}}{\partial t} + \widehat{J}_L \quad (2.81)$$

$$I_L$$

$$J_L = \frac{I_L}{\Delta x \Delta y} \quad (2.82)$$

$$I_L \quad \text{가} \quad , \quad , \quad , \quad (2.81) \quad (2.82)$$

(2.80)

$$E_z \Big|_{i,j,k}^{n+1} = E_z \Big|_{i,j,k}^n + \frac{\Delta t}{\epsilon_0} \nabla \times H \Big|_{i,j,k}^{n+\frac{1}{2}} - \frac{\Delta t}{\epsilon_0 \Delta x \Delta y} I_L^{n+1/2} \quad (2.83)$$

$$E_z \Big|_{i,j,k}^{n+1} = E_z \Big|_{i,j,k}^n + \frac{\Delta t}{\epsilon_0} \nabla \times H \Big|_{i,j,k}^{n+\frac{1}{2}} - \frac{\Delta t}{\epsilon_0 \Delta x \Delta y} I_L^{n+1/2}$$

2.

CPS

FDTD

FDTD

$$R = \rho L / A$$

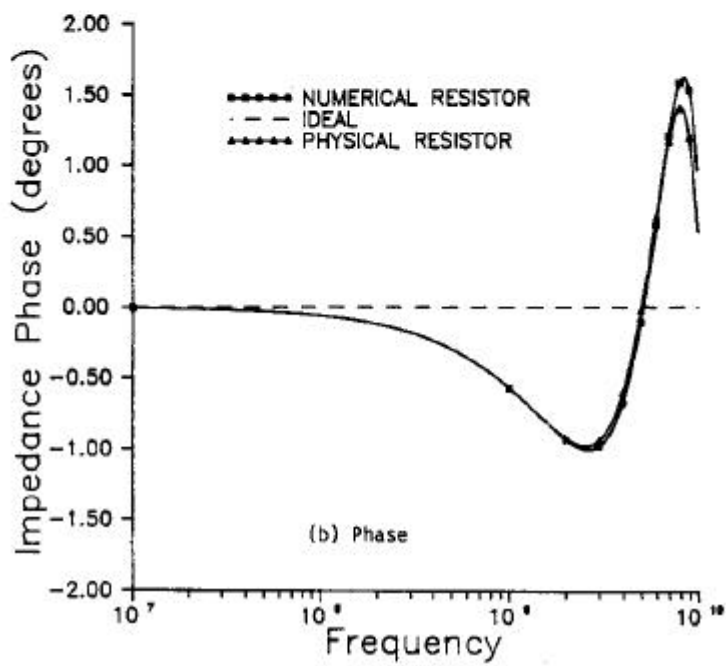
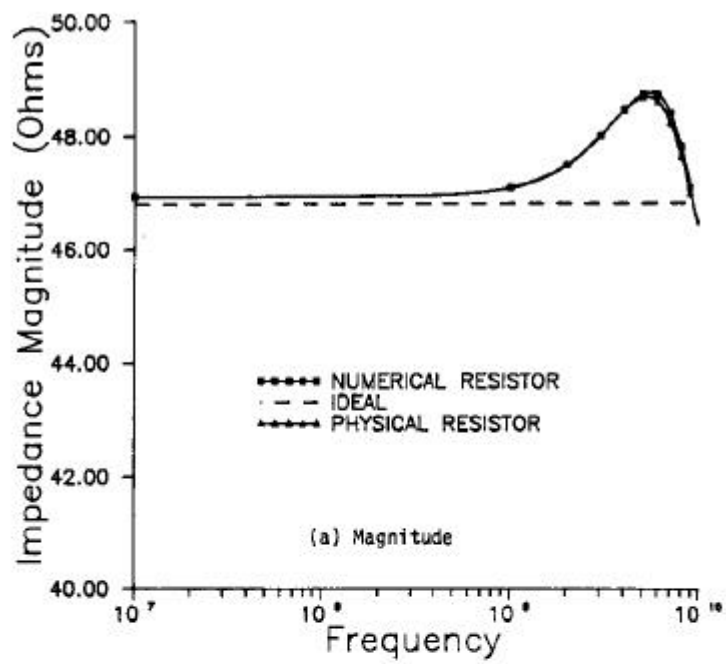
z- 가 ,

$$I_z \Big|_{i,j,k}^{n+1/2} = -\frac{\Delta z}{2R} (E_z \Big|_{i,j,k}^{n+1} + E_z \Big|_{i,j,k}^n) \quad (2.84)$$

$$J_L = \frac{I_z \Big|_{i,j,k}^{n+1/2}}{\Delta x \Delta y}$$

, R ,  $\Delta x$ ,  $\Delta y$   $\Delta z$  x, y, z

$$E_z \Big|_{i,j,k}^n \quad (2.83) \quad E_z \Big|_{i,j,k}^n \quad (2.85) ,$$





$$E_z \Big|_{i,j,k}^{n+1} = \left[ \frac{1 - \frac{\Delta z \Delta t}{2R \epsilon_0 \Delta x \Delta y}}{1 + \frac{\Delta z \Delta t}{2R \epsilon_0 \Delta x \Delta y}} \right] E_z \Big|_{i,j,k}^n + \left[ \frac{\frac{\Delta t}{\epsilon_0}}{1 + \frac{\Delta z \Delta t}{2R \epsilon_0 \Delta x \Delta y}} \right] \nabla \times H \Big|_{i,j,k}^{n+\frac{1}{2}} \quad (2.85)$$

(2.85)

2-21 . 90psec 가

50Ω

1%

3. (Resistive Voltage Source)

FDTD

.

- (2.86) .

$$I_z \Big|_{i,j,k}^{n+1/2} = -\frac{\Delta z}{2R_s} (E_z \Big|_{i,j,k}^{n+1} + E_z \Big|_{i,j,k}^n) + \frac{V_s^{n+1/2}}{R_s} \quad (2.86)$$

$$J_L = \frac{I_z \Big|_{i,j,k}^{n+1/2}}{\Delta x \Delta y}$$

,  $V_s^{n+1/2}$  ,  $R_s$  .

$$(2.83) \quad E_z \Big|_{i,j,k}^n$$

$$\begin{aligned}
E_z \Big|_{i,j,k}^{n+1} = & \left[ \frac{1 - \frac{\Delta z}{2R_s \varepsilon_0 \Delta x \Delta y} \frac{\Delta t}{\Delta y}}{1 + \frac{\Delta z}{2R_s \varepsilon_0 \Delta x \Delta y} \frac{\Delta t}{\Delta y}} \right] E_z \Big|_{i,j,k}^n \\
& + \left[ \frac{-\frac{\Delta t}{\varepsilon_0}}{1 + \frac{\Delta z}{2R_s \varepsilon_0 \Delta x \Delta y} \frac{\Delta t}{\Delta y}} \right] \nabla \times H \Big|_{i,j,k}^{n+\frac{1}{2}} \\
& + \left[ \frac{\frac{\Delta t}{R_s \varepsilon_0 \Delta x \Delta y}}{1 + \frac{\Delta z}{2R_s \varepsilon_0 \Delta x \Delta y} \frac{\Delta t}{\Delta y}} \right] V_s^{n+1/2}
\end{aligned} \tag{2.87}$$

4.

FDTD

가 .

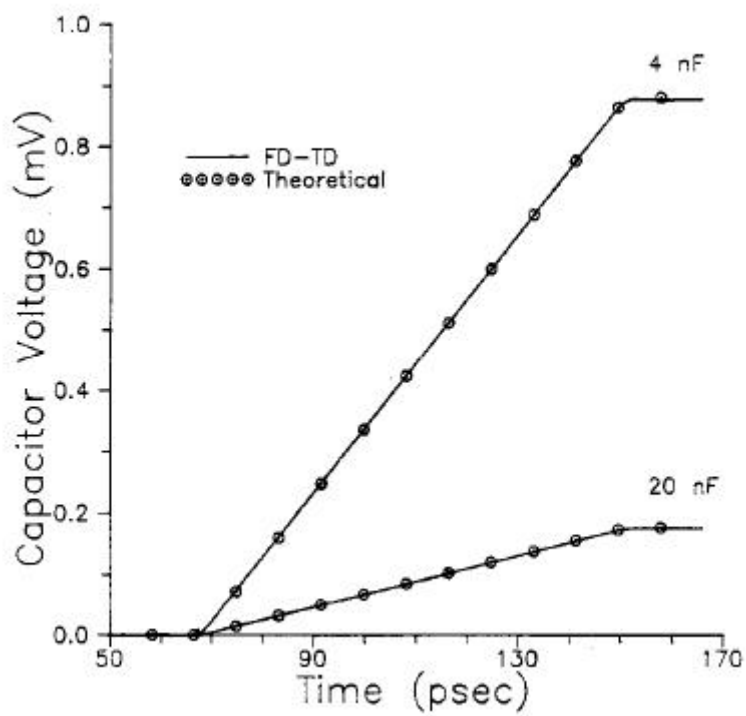
$$\begin{aligned}
I_z \Big|_{i,j,k}^{n+1/2} = & \frac{C \Delta z}{\Delta t} (E_z \Big|_{i,j,k}^{n+1} - E_z \Big|_{i,j,k}^n) \\
J_L = & \frac{I_z \Big|_{i,j,k}^{n+1/2}}{\Delta x \Delta y}
\end{aligned} \tag{2.88}$$

$$, C \quad . \tag{2.83} \quad E_z \Big|_{i,j,k}^n$$

$$E_z \Big|_{i,j,k}^{n+1} = E_z \Big|_{i,j,k}^n + \left[ \frac{-\frac{\Delta t}{\varepsilon_0}}{1 + \frac{C \Delta z}{\varepsilon_0 \Delta x \Delta y} \frac{\Delta t}{\Delta y}} \right] \nabla \times H \Big|_{i,j,k}^{n+1/2} \tag{2.89}$$

가

$$E_z \Big|_{i,j,k}^{n+1} = \left[ \frac{1 - \frac{\Delta z}{2R\epsilon_0\Delta x\Delta y}\Delta t + \frac{C\Delta z}{\epsilon_0\Delta x\Delta y}}{1 + \frac{\Delta z}{2R\epsilon_0\Delta x\Delta y}\Delta t + \frac{C\Delta z}{\epsilon_0\Delta x\Delta y}} \right] E_z \Big|_{i,j,k}^n + \left[ \frac{\frac{\Delta t}{\epsilon_0}}{1 + \frac{\Delta z}{2R\epsilon_0\Delta x\Delta y}\Delta t + \frac{C\Delta z}{\epsilon_0\Delta x\Delta y}} \right] \nabla \times H \Big|_{i,j,k}^{n+\frac{1}{2}} \quad (2.90)$$



2- 22 FDTD

(2.90) FDTD

2- 22 가 가 50Ω

# FDTD

5.

$$I_d = I_0 [e^{(qV_d/kT)} - 1] \quad (2.91)$$

$$\begin{aligned} & \text{, } q \quad \text{, } V_d \quad \text{, } k \quad \text{, } T \\ & \text{가} \quad \text{가 } z \\ & 2 \end{aligned} \quad (2.92)$$

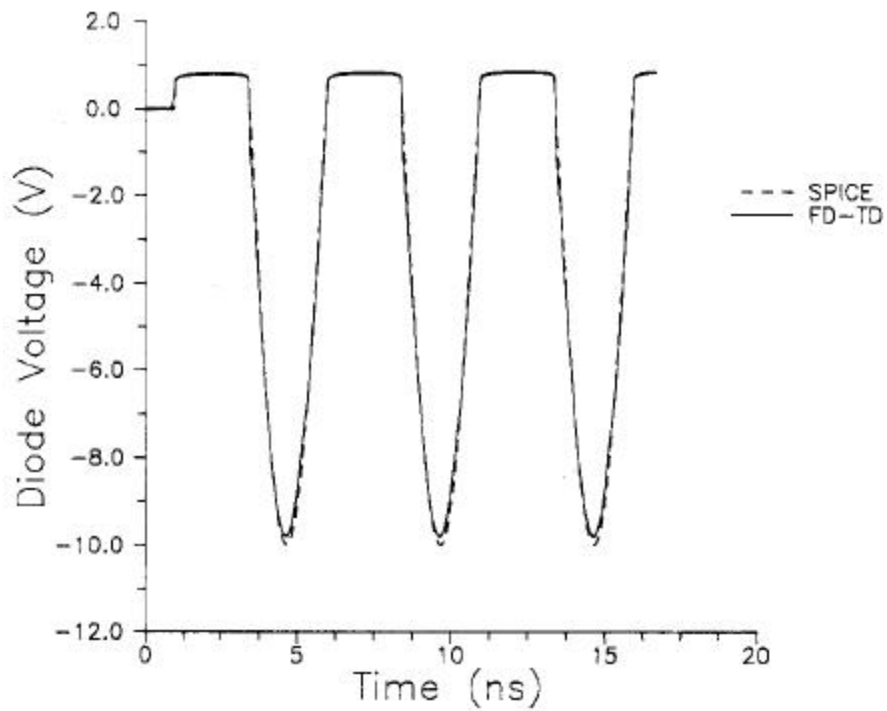
$$\begin{aligned} E_z \big|_{i,j}^{n+1} = E_z \big|_{i,j}^n & I_0 [e^{(-qE_z \big|_{i,j} \Delta t / kT)} - 1] \\ & + \frac{\Delta t}{\epsilon_0} \nabla \times H \big|_{i,j}^{n+1/2} - \frac{\Delta t}{\epsilon_0 \Delta x \Delta y} \end{aligned} \quad (2.92)$$

$$(2.93) \quad (2.92) \quad \text{FDTD}$$

$$E_z \big|_{i,j,k}^{n+1/2} = \frac{1}{2} (E_z \big|_{i,j,k}^{n+1} + E_z \big|_{i,j,k}^n) \quad (2.93)$$

$$(2.92) \quad (2.93) \quad 3$$

$$E_z \big|_{i,j,k}^{n+1} = E_z \big|_{i,j,k}^n + \frac{\Delta t}{\epsilon_0} \nabla \times H \big|_{i,j,k}^{n+1/2} - \frac{\Delta t}{\epsilon_0 \Delta x \Delta y} I_0 [e^{(-q(E_z \big|_{i,j,k}^{n+1} + E_z \big|_{i,j,k}^n) \Delta t / 2kT)} - 1] \quad (2.94)$$



2- 23

FDTD

SPICE

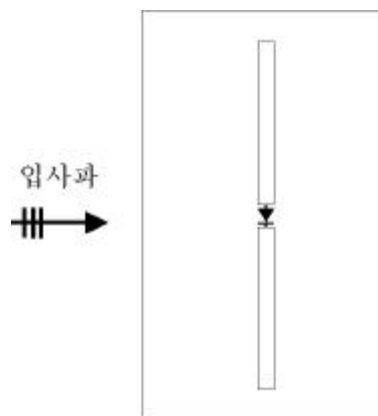
(2.94)

Newton- Rapshon

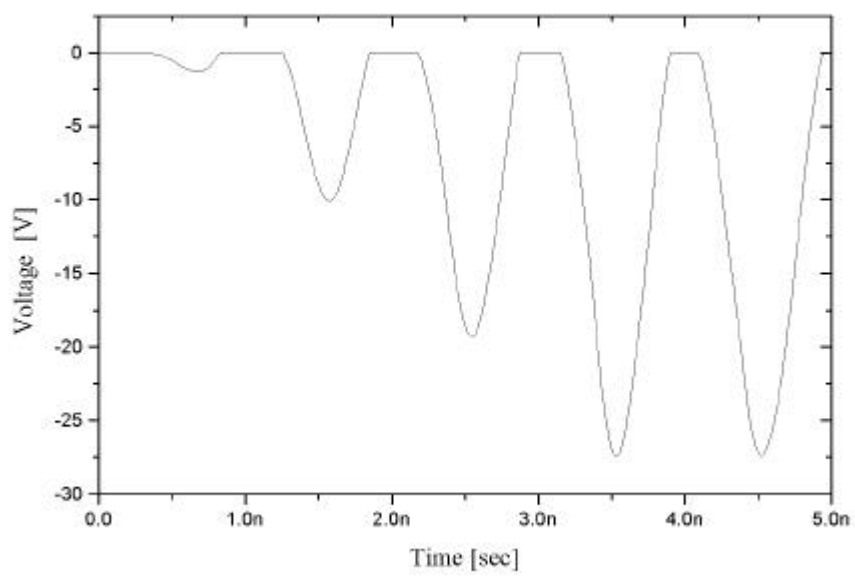
가

. NR

, NR  
 ,  
 . 10V, 200MHz 가 가 ,  $I_0 = 1 \times 10^{-14} A$  가  
 가  $50\Omega$  FDTD  
 SPICE  
 .  
 2- 24  
 가 . 2- 24 가  
 2- 25 .



2- 24  
 가 ,  
 가 . 가  
 가 2- 25  
 .



2- 25

2- 24

## 8 (sub- grid)

FDTD

가

1/10

1/20

가

가

. FDTD

가

. , 가

가

가

가

가 가

( )

가

1981 Kunz Simpson expansion  
FDTD

[12]. 1990 Kim Hoefer

(interpolation)

[13]. , 1991 Zivanovic

(homogeneous traveling wave)

[14]. , 1992 Prescott Zivanovic

0.65%

[15]. Chevalier

가

가

가

가

가

[16].

가.

2- 11

가

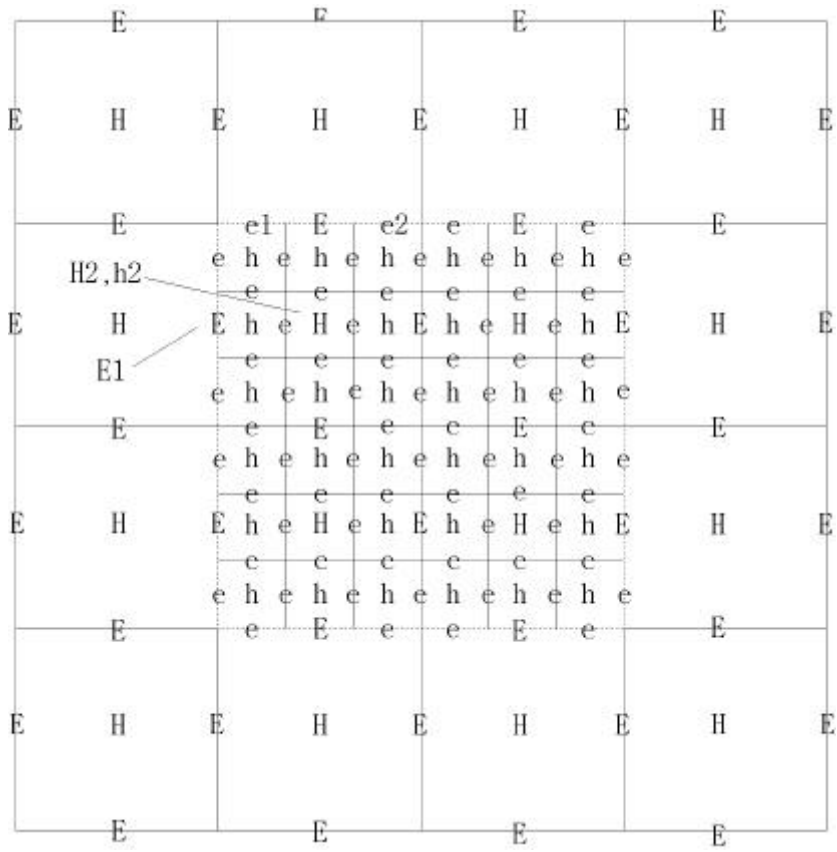
Chevalier

1/3, 1/5, 1/7



가 가

. 1/3 .



2- 26

$(E^{n+1})$

$(H^{n+1/2})$

. , 2- 26 E1 -

가

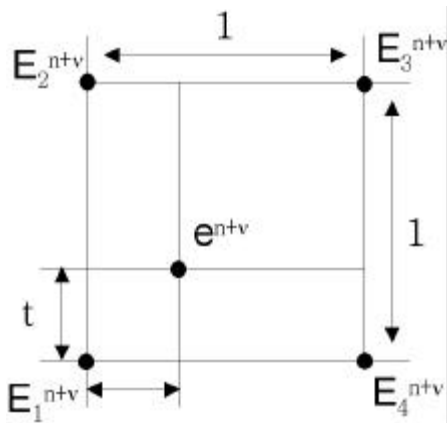
Taylor

2

.

$$E^{n+\nu} = E^n + \frac{E^{n+1} - E^{n-1}}{2} \nu + \frac{E^{n+1} + E^{n-1} - 2E^n}{2} \nu^2 \quad (2.95)$$

$1/3, 2/3, 1$  가  $3$  가  $3$  ,  
 $1$   $1/3$   $3$   $1/3, 2/3$   
 (2.95)



2- 27 bilinear

, 2- 26 - e1, e2

bilinear . 2- 11

$$E_1^{n+\nu}, E_2^{n+\nu}, E_3^{n+\nu}, E_4^{n+\nu} \quad e^{n+\nu}$$

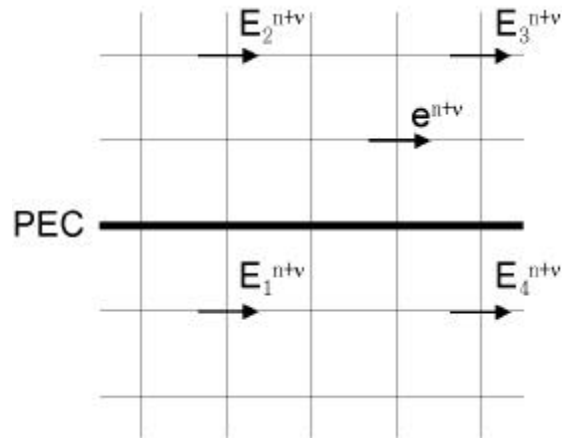
.

$$(2.96)$$



2- 28

$$(2.97)$$



2- 29

, 2- 29

0

(2.96)

$$e^{n+\nu} = \frac{(1-s)}{l} (1-t) E_1^{n+\nu} + \frac{(1-s)}{l} t E_2^{n+\nu} \quad (2.98)$$

(2.95) (2.98) -

1

가 .

가

CFL

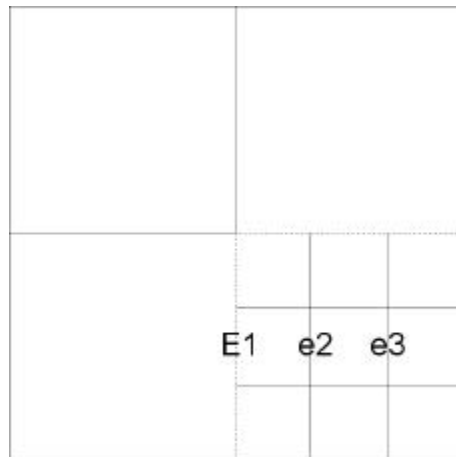
$\Delta t$

$\Delta t$

$\Delta t$

$\Delta t$

1.2



2-30 - 가

$\Delta t$

, -  
가 2-30 -  
E1 가 e1, e2  
. E1 Yee FDTD  
E1 가 E1 Yee FDTD  
,  
. e1  
E1 e2 e1 가  
. e1  
E1 Yee e2 Yee  
e1<sub>Local</sub> 가

$$e1 = 0.95 e1_{Local} + 0.05 \frac{E1 + e2}{2} \quad (2.99)$$

가 0.95 0.05 .  
 가 - 2000  
 (2.99) 가 20000  
 .  
 - .

t=n :

$$\begin{aligned} & \cdot H^{n+1/2} E^{n+1} . \\ & \cdot - E^{n+1} . \end{aligned}$$

t=n+1/6 :

$$\cdot h^{n+1/6} .$$

t=n+2/6 :

$$\begin{aligned} & \cdot - e^{n+2/6} \\ & \cdot \\ & \cdot - e^{n+2/6} \\ & \cdot \\ & \cdot e^{n+2/6} . \\ & \cdot \text{가} , - \text{가} . \end{aligned}$$

t=n+3/6 :

$$\begin{aligned} & \cdot h^{n+3/6} . \\ & \cdot h^{n+3/6} H^{n+1/2} . \end{aligned}$$

t=n+4/6 :

· -  $e^{n+4/6}$   
·  
· -  $e^{n+4/6}$   
·  
·  $e^{n+4/6}$  ·  
· 가 , - 가  
·

t=n+5/6 :

·  $h^{n+5/6}$  ·

t=n+6/6 :

· -  $e^{n+6/6}$   
·  
· -  $e^{n+6/6}$   
·  
·  $e^{n+6/6}$  ·  
· 가 , - 가  
·  
·  $e^{n+6/6}$   $E^{n+1}$  ·  
·

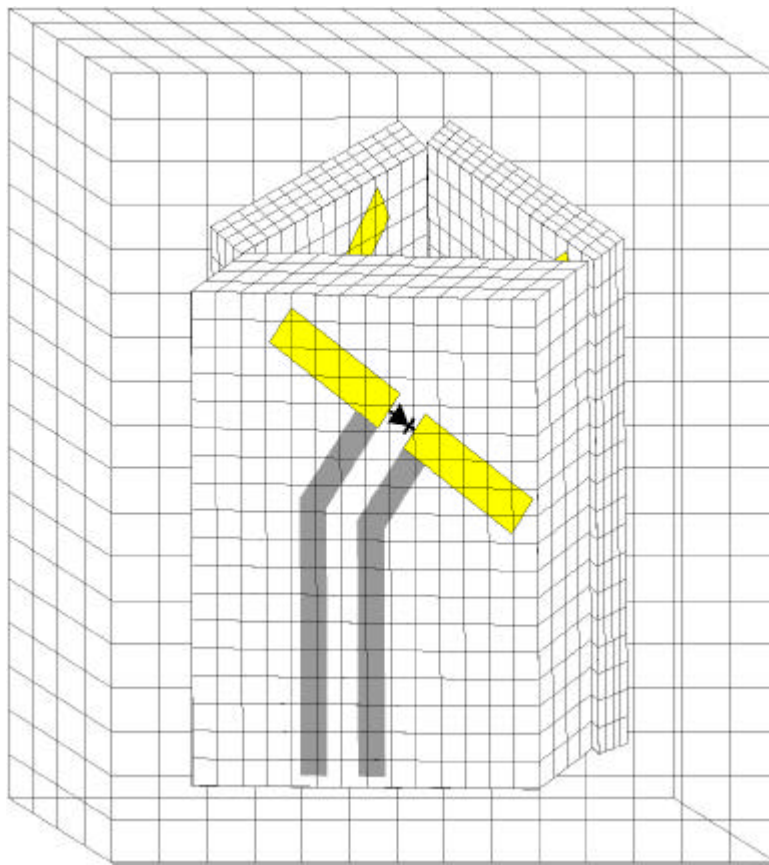
가 2- 31 3  
60 ° .

FDTD  
FDTD

가

가

2-31



2-31



가

,

2- 31

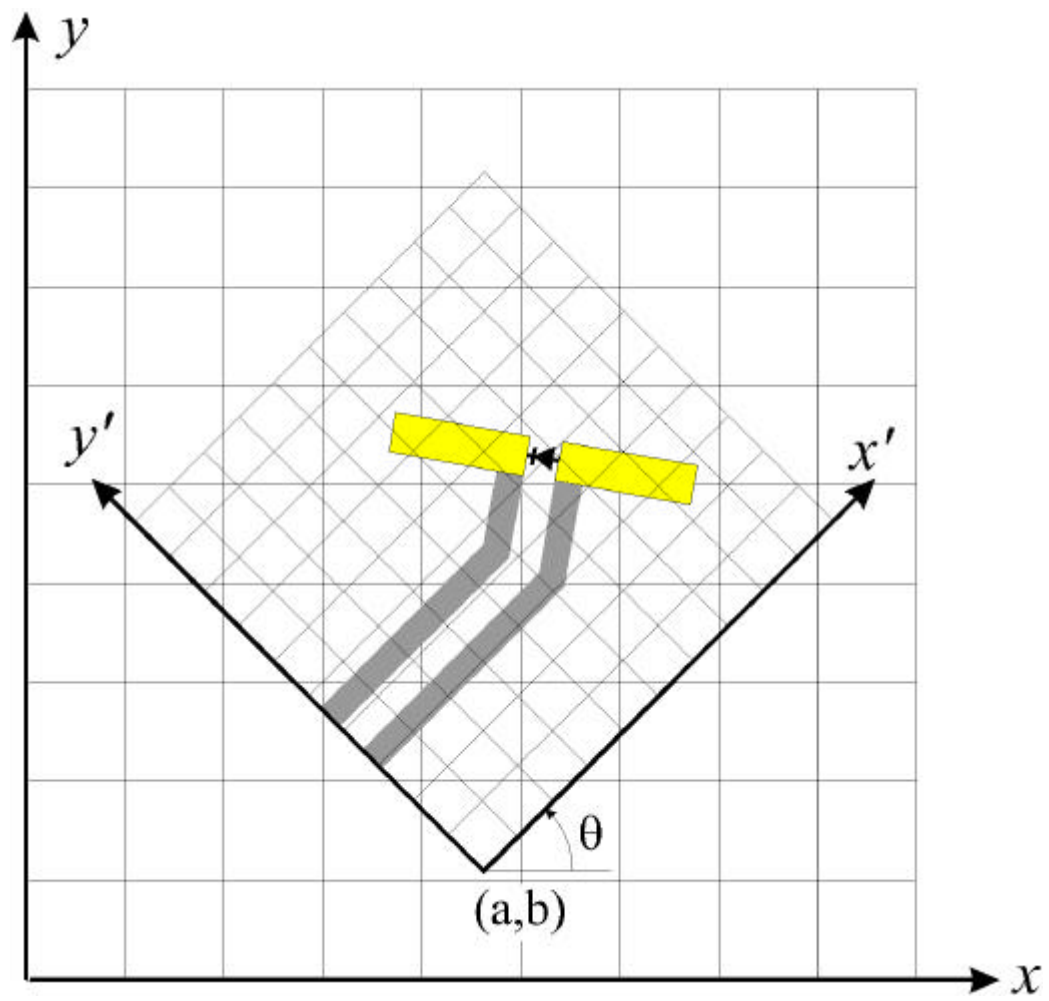
3

2- 31

3

2- 32

2



2- 32 2

가

bilinear

,

Taylor

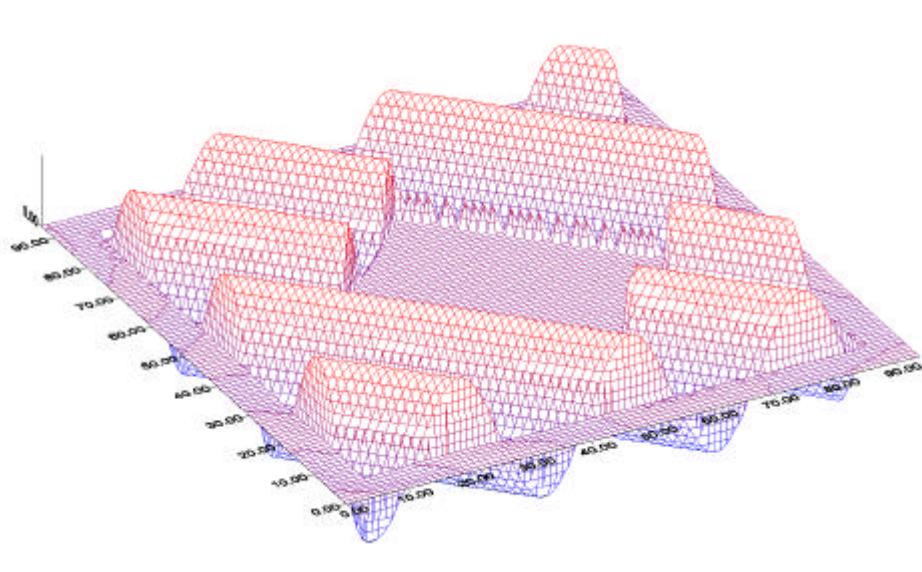
2

.

x, y 가

x, y

.



2- 33

TEz

2- 32

가

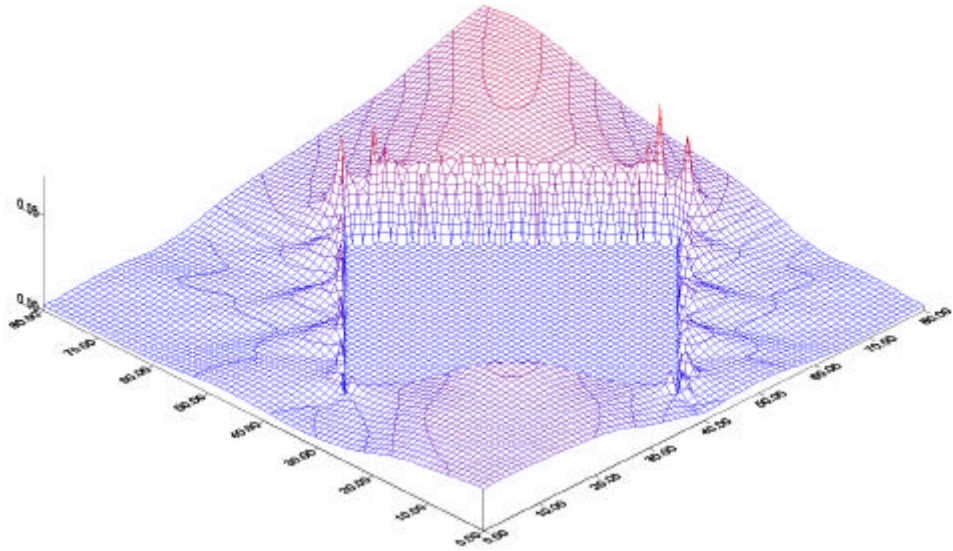
(a,b)

(x',y')

(x,y)

.

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x'/D \\ y'/D \end{pmatrix} + \begin{pmatrix} a \\ b \end{pmatrix} \quad (2.100)$$



2- 34

D  
가  
(x,y)

5 D 5가  
(x',y')

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} D \cdot \cos \theta & D \cdot \sin \theta \\ -D \cdot \sin \theta & D \cdot \cos \theta \end{pmatrix} \begin{pmatrix} x - a \\ y - b \end{pmatrix} \quad (2.101)$$

2- 32 ( )가 1.5 cm  
가 0.5 cm, t= 17 ps , 가 a=10.1 , b=47.2  
=45 ° , 가 1 TEz  
가 45 °  
가 2- 32

5%

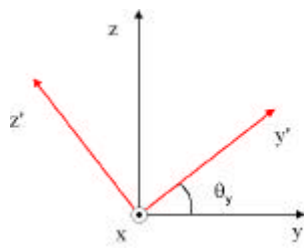
1 GHz

3

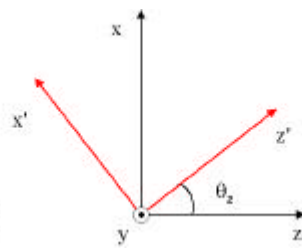
2

3

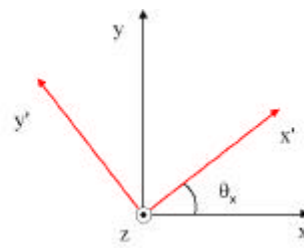
3



(a)  $T_x$



(b)  $T_y$



(c)  $T_z$

2-35 3

x,y,z

x',y',z'

2-35

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \mathbf{T}_\theta \begin{pmatrix} x - a \\ y - b \\ z - c \end{pmatrix} \quad (2.102)$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \mathbf{T}_\theta^{-1} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad (2.103)$$

,

$$\mathbf{T}_{\theta_x} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & D \cdot \cos \theta & D \cdot \sin \theta \\ 0 & -D \cdot \sin \theta & D \cdot \cos \theta \end{pmatrix} \quad (2.104)$$

$$\mathbf{T}_{\theta_y} = \begin{pmatrix} D \cdot \cos \theta & 0 & -D \cdot \sin \theta \\ 0 & 1 & 0 \\ D \cdot \sin \theta & 0 & D \cdot \cos \theta \end{pmatrix} \quad (2.105)$$

$$\mathbf{T}_{\theta_z} = \begin{pmatrix} D \cdot \cos \theta & D \cdot \sin \theta & 0 \\ -D \cdot \sin \theta & D \cdot \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2.106)$$

$$\mathbf{T}_{\theta_x}^{-1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & D \cdot \cos \theta & -D \cdot \sin \theta \\ 0 & D \cdot \sin \theta & D \cdot \cos \theta \end{pmatrix} \quad (2.107)$$

$$\mathbf{T}_{\theta_y}^{-1} = \begin{pmatrix} D \cdot \cos \theta & 0 & D \cdot \sin \theta \\ 0 & 1 & 0 \\ -D \cdot \sin \theta & 0 & D \cdot \cos \theta \end{pmatrix} \quad (2.108)$$

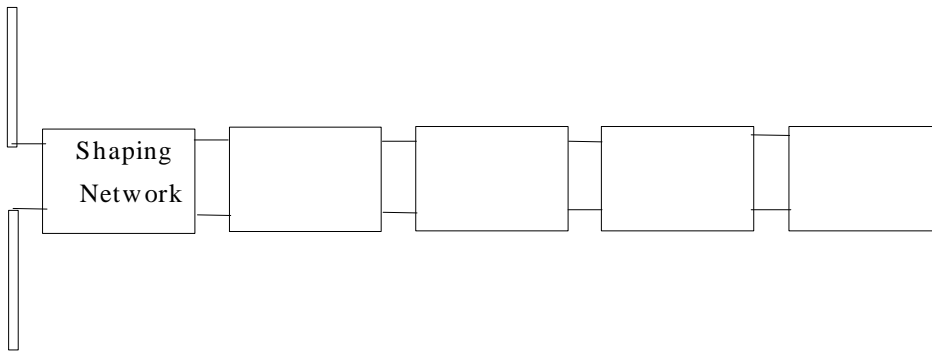
$$\mathbf{T}_{\theta_z}^{-1} = \begin{pmatrix} D \cdot \cos \theta & -D \cdot \sin \theta & 0 \\ D \cdot \sin \theta & D \cdot \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2.109)$$

### 3 FDTD

2 FDTD  
 FDTD . 가 3 mm  
 FDTD 0.25 mm  
 .

1

가



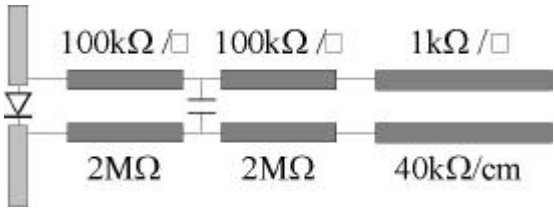
3- 1

3- 1

, , ,  
 . 가  
 가

DC . DC

ET 3DV5



3- 2 ET 3DV5 가

3- 2 가

Schottky

1.

가 (  $\beta_o h = 2\pi h / \lambda_o \ll 1$  )

$V_{oc} \approx h E_z^i(0, \omega) \quad ;$

가

가

가

2.

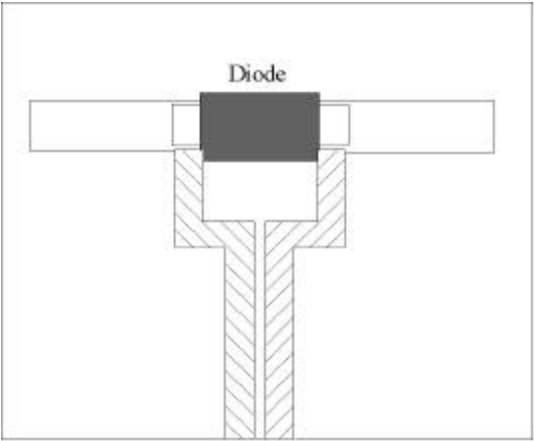
DC

Schottky

가

가

Schottky



3-4 Schottky



Schottky

Hewlett Packard 社

HSCH- 5331

， 가

.

3.

.

.

가

.

.

$$r^i = \frac{R_s}{W_L} \quad [ \Omega/\text{m} ]$$

(3.1)

,

$R_s$  :

$W_L$  ;

$r^i$  :

(3.1) 3- 2 ,

.

100k $\Omega$  / □



2M $\Omega$

1k $\Omega$  / □



40k $\Omega$ /cm

$W_L = .25$  mm

$r^i = 400$  M $\Omega$ /m

$W_L = .25$  mm

$r^i = 4$  M $\Omega$ /m

2

1.

2

2

가

가

가

가

2

ET 3DV5

1  
 $K \Omega$   
 Thin Film      Thick  
 가  
 가

2.

가

가

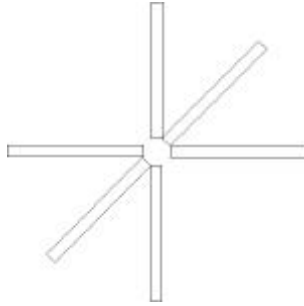
가

가

3.

3

3-5



3- 5

가 가 .

$$\vec{E} = E_x \hat{x} + E_y \hat{y} + E_z \hat{z} \quad (3.2)$$

3- 5

.

$$V_{dc} = C [ |E_x|^2 + |E_y|^2 + |E_z|^2 ] = C |\vec{E}|^2 \quad (3.3)$$

(3.3)

3

.

ET3DV5

3- 6

.

54.74 °

가 가

가 .

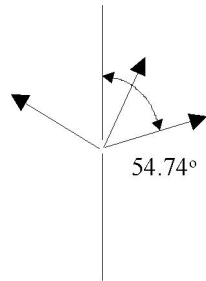
가

.

가

가

가



3- 6

3

가

가

3- 7

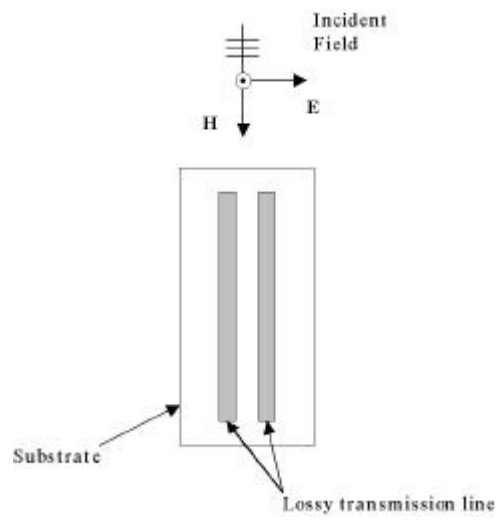
1 mm

100 kΩ/

가

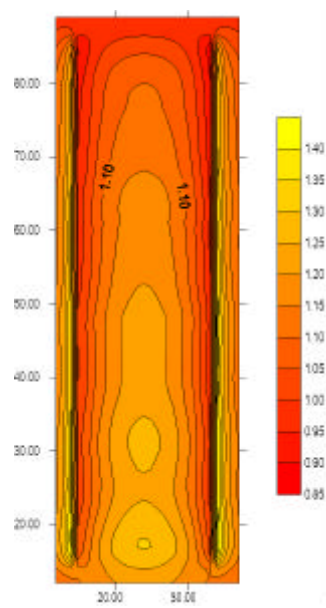
3- 8

3- 8

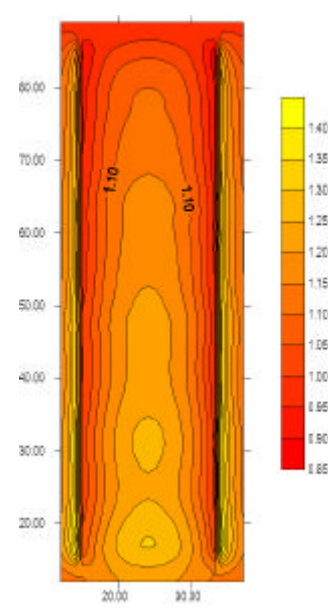


3- 7

가



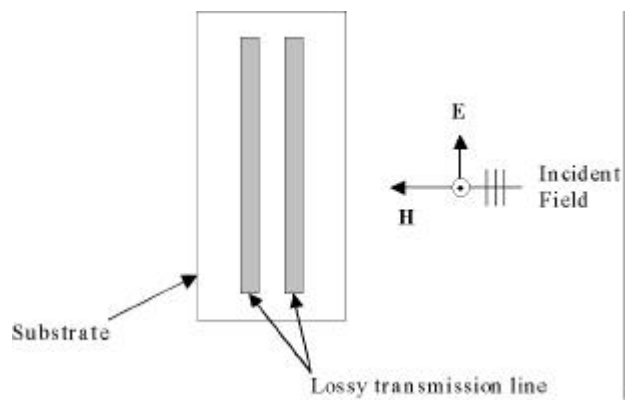
(a)



(b)

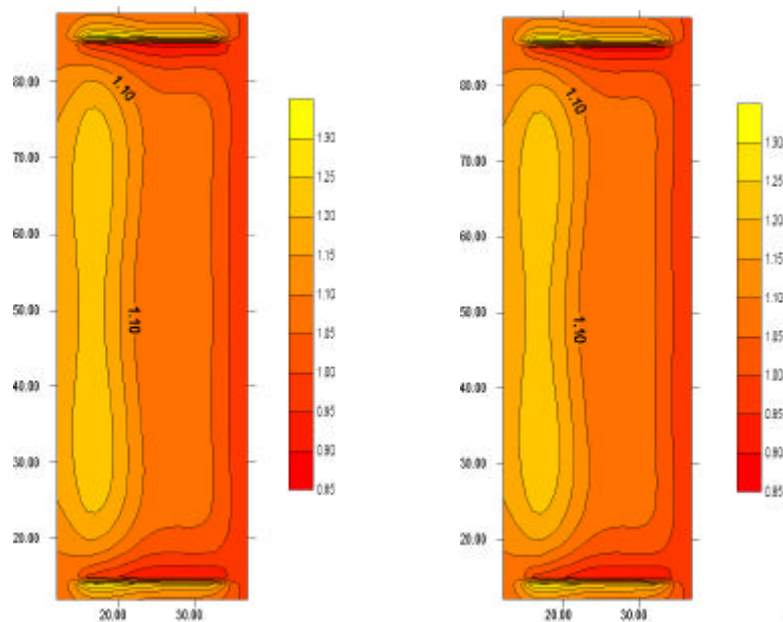
3- 8

가



3- 9

가



3- 10

가

3- 9

가

3- 10

.

3- 10

3- 8

.

.

4

FDTD

가

.

1.

3- 11

가

가

.

3

3

. 3- 11

가

54.74 ° 가

90 ° .

가

가

.

3- 11

1

. ,

2

, 100 k $\Omega$ /

1 k $\Omega$ /

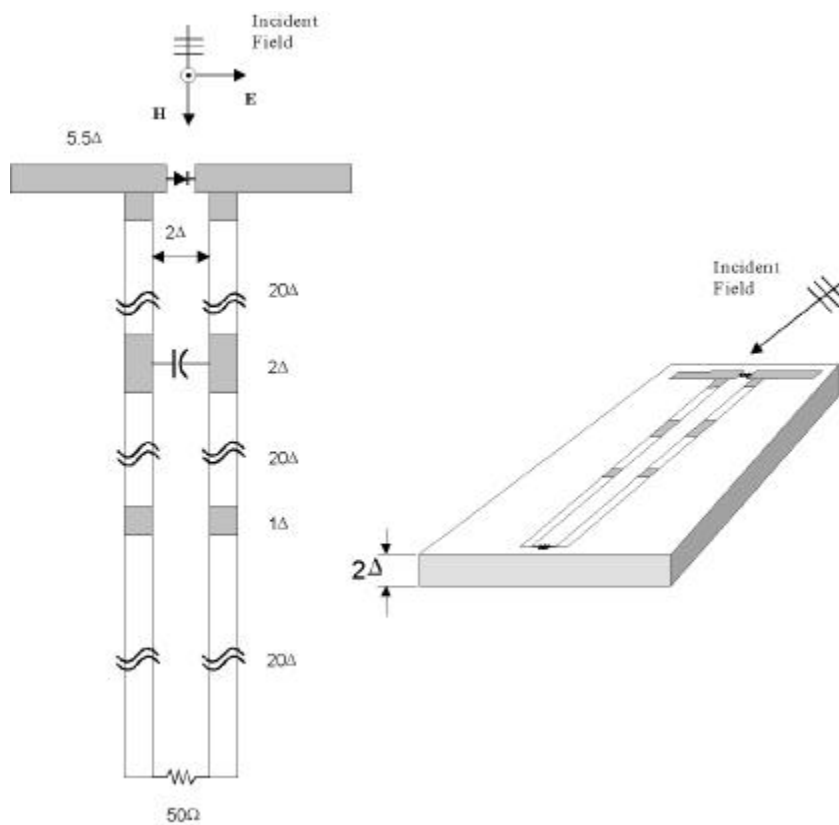
1

.

50

.

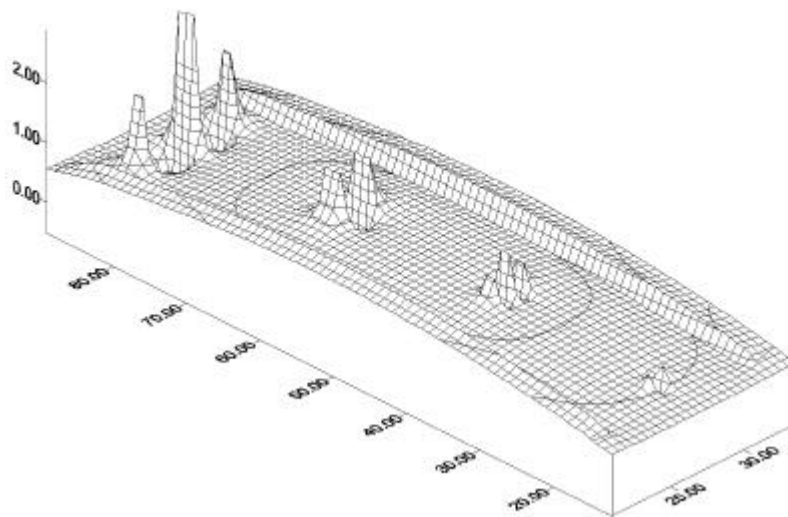
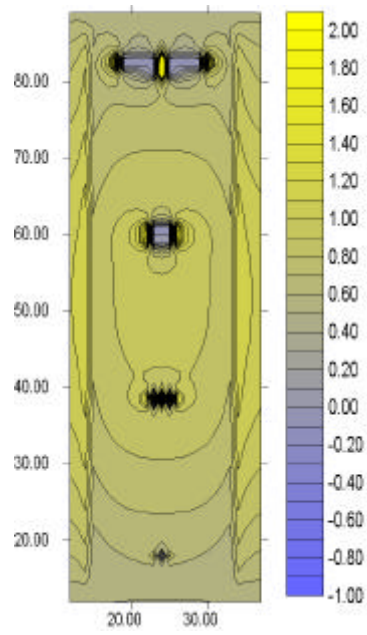




3- 11

3- 12

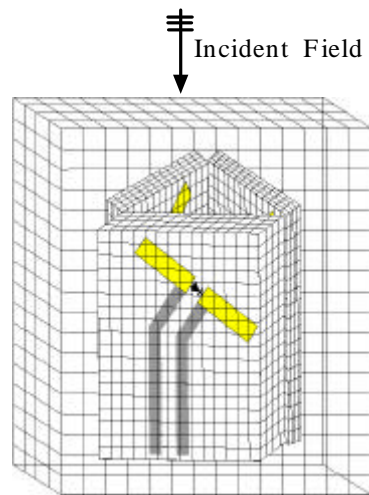
가



3- 12

2.

3- 13



3- 13

3- 13

2

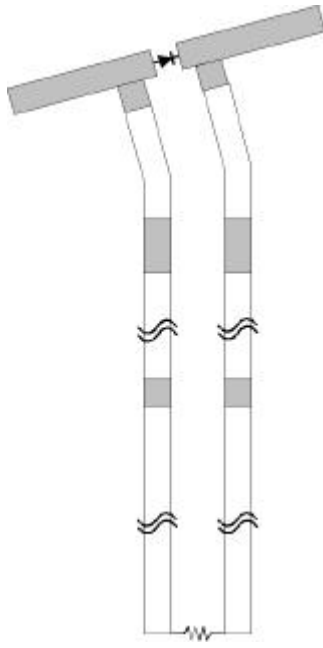
3- 14

3.14 (b)

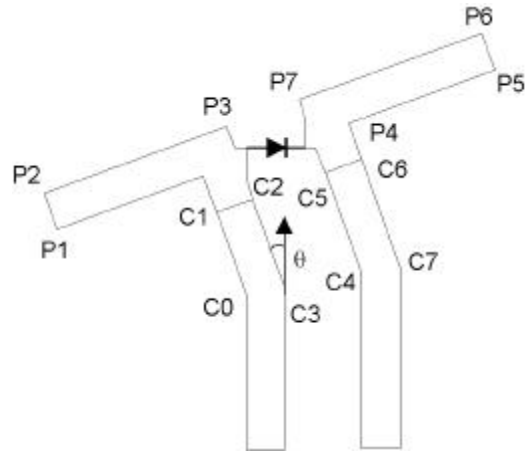
2 conformal

3.14

(b)



(a)



(b)

3- 14

FDTD

3- 14

3- 15

3- 14

50

DC

AC

DC

가

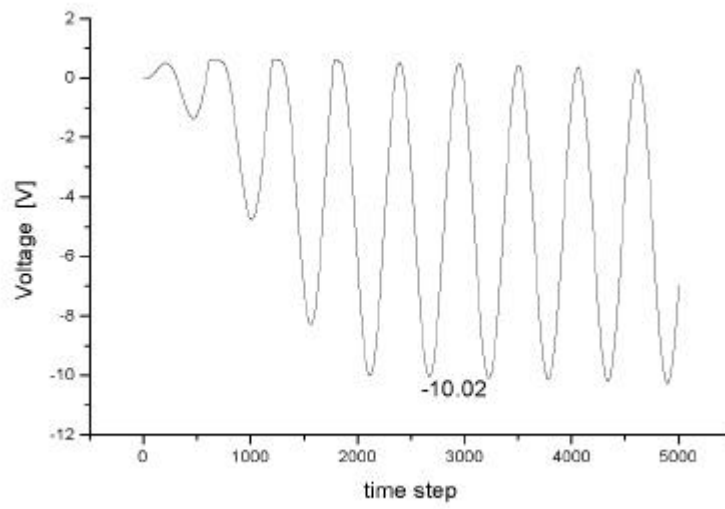
DC

DC

DC

DC

FDTD



3- 15

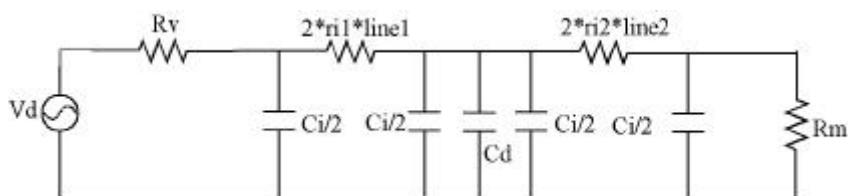
FDTD

FDTD

FDTD

가

가



3- 16

가

$R_v$  (video resistance)

$$V_d \qquad \qquad \qquad V_d$$

(open)

$$Vm \qquad \qquad \qquad .$$

$$Vm \; = \; \frac{R_m V_d}{R_v \; + \; 2 \; r^i l_L \; + \; R_m} \tag{3.4}$$

$$,$$

$$R_v = 94.68 \; K \; \Omega \; (\text{HSC} \text{-} 5331 \qquad \qquad R_j)$$

3.

가 가

3- 17

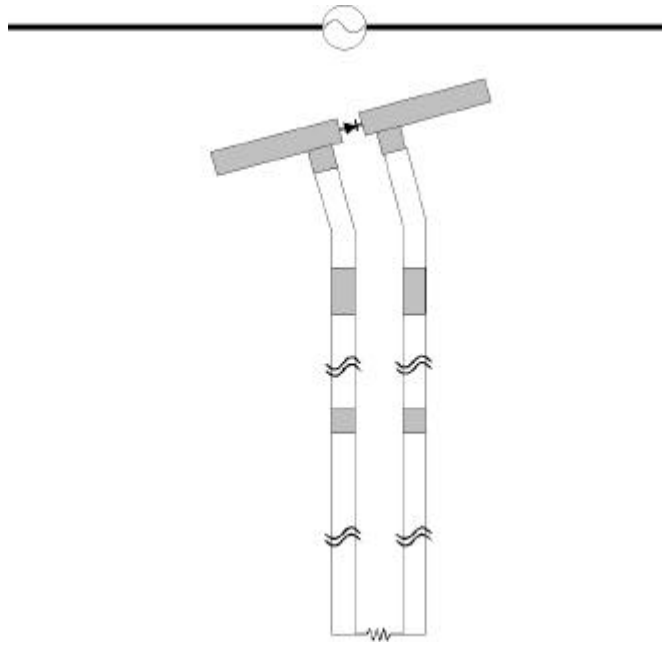
가

가

가 가

3- 17

.



3- 17

가

3- 17

3- 18

.

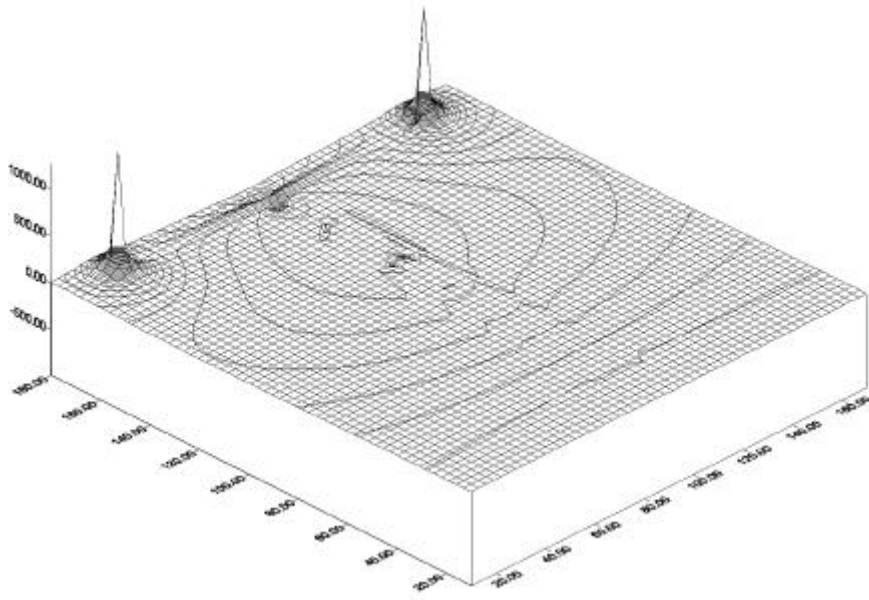
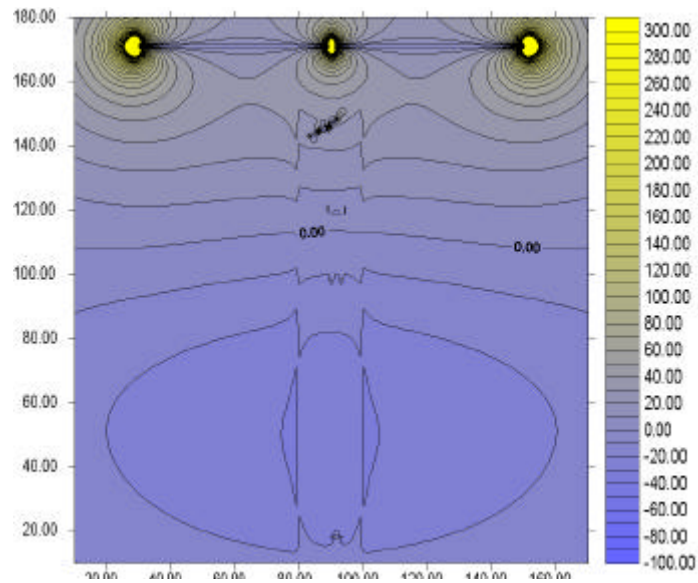
1 cm

.

3- 19

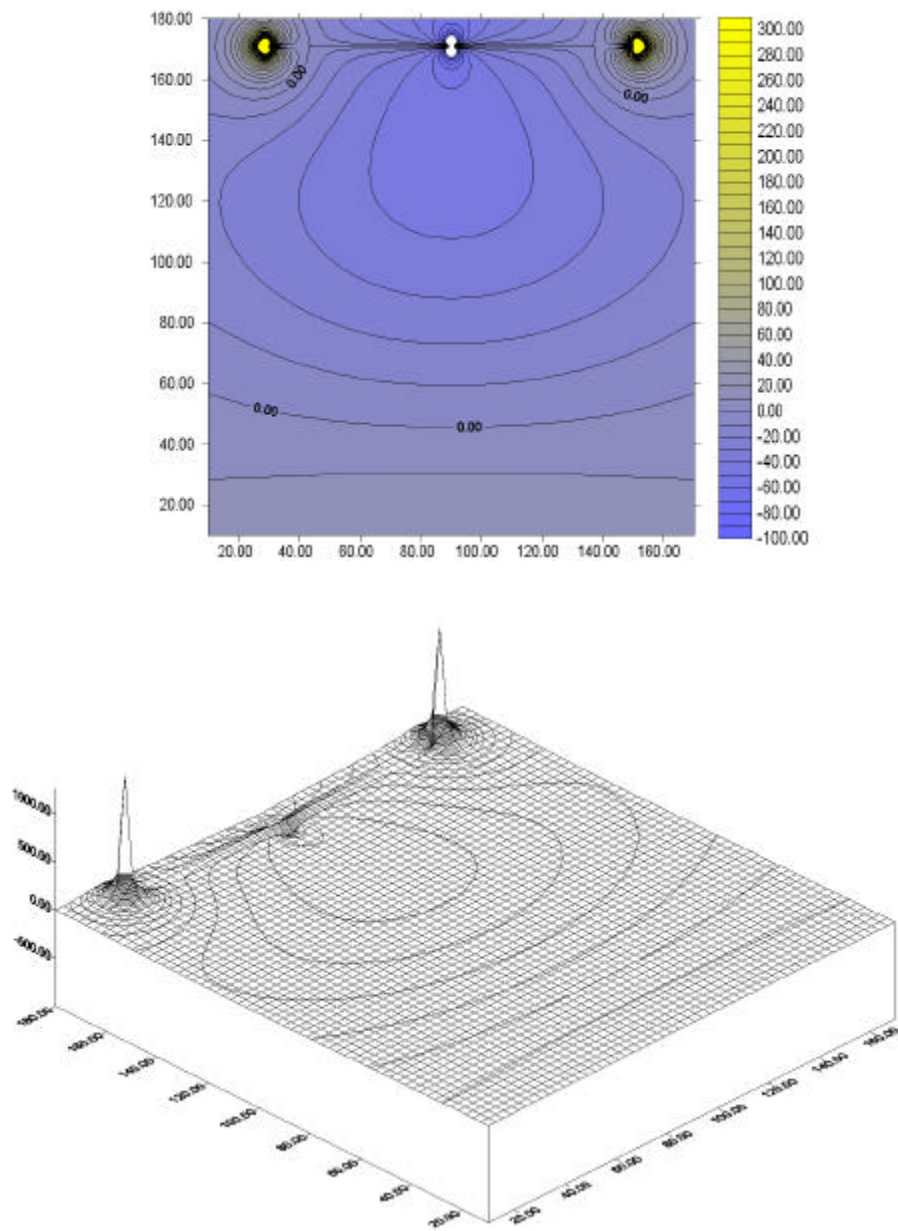
가

.



3- 18 가 가





3- 19

## 4

Probe  
FDTD Yee  
Yee , PML  
FDTD  
Conformal Diode  
Sub-grid  
가

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