Approximate Numerical Reflection Coefficient of Isotropic-Dispersion Finite-Difference Time-Domain(ID-FDTD) Scheme at the Planar Dielectric Interface for the TM Wave

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Abstract

This paper presents an analytical formulation of the numerical reflection coefficient of the ID-FDTD scheme at the planar dielectric boundary for a TM wave incidence. The reflection coefficient is formulated in an approximate manner, and the accuracy of this method is numerically verified. The effective dielectric constant for a grid on the interface is obtained, and then reduced to that of the Yee scheme for a small cell size.

Key words : ID-FDTD Scheme, Reflection Coefficient, Effective Dielectric Constant.

Ⅰ. Introduction

The standard finite-difference time-domain(FDTD) scheme, introduced by Yee in 1966, was the first technique in the direct time-domain solutions of Maxwell's differential equation on spatial grids or lattices, and has remained the subject of continuous development. The FDTD scheme employs the central finite difference equation to approximate the spatial and temporal derivatives in Maxwell's equations. It provides many advantages, such as low computational complexity, great flexibility, and easy implementation[1]. Since the modeling capabilities afforded by the FDTD scheme and related techniques have been recognizes, the interest in this area has expanded beyond defense technology. The FDTD method has been used intensively and widely to simulate electromagnetic wave phenomena. In recent decades, it has been applied in a variety of fields including electromagnetics, biology, materials science and optics[1].

However, the standard FDTD scheme(Yee scheme) undergoes "numerical dispersion" that causes numerical wave propagation at different phase velocities along different directions, which prevents the scheme from being applied to large scale or phase-sensitive problems. Several schemes have been proposed to rectify this numerical dispersion problem. A simple approach known as the ID-FDTD scheme has been proposed to drastically reduce the dispersion error[2]. It is based on a weighted summation of two different finite difference approximations for the spatial derivative, and can adjust the numerical phase velocity using the scaling factor[3].

Since more field sampling points on the Yee grid are used to reduce the anisotropy dispersion error for the ID-FDTD scheme, the fields on the material(dielectric or conductor) boundary should be calculated by using the fields inside and outside the material boundary as seen in Fig. 1. Therefore, the behavior of the ID-FDTD scheme is not clearly characterized at the material interface. The objective of this paper is to demonstrate that the ID-FDTD scheme can properly deal with the material boundary based on the analytical formulation of the numerical reflection coefficient of the ID-FDTD scheme for a TM polarized incidence wave.

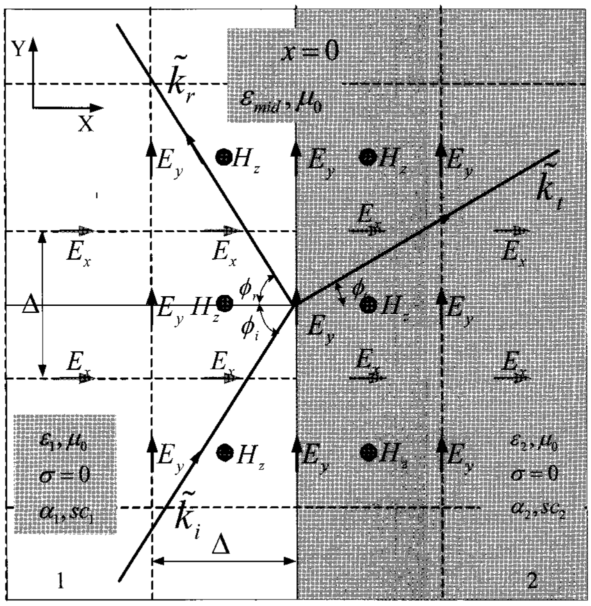

Fig. 1. Two-dimensional Yee grid for the TM mode with the planar dielectric boundary.

Manuscript received January 29, 2010 ; revised March 22, 2010. (ID No. 20100129-003J)
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Section Ⅱ, the numerical reflection coefficient is formulated and in. Section Ⅲ, the obtained coefficient is numerically verified and the accuracy of the coefficient is examined.

Ⅱ. Numerical Reflection Coefficient for the TM Polarized Wave

Fig. 1 shows two dielectric half-spaces in the FDTD grid for a TM wave with the numerical wave vector k_i and the frequency ω_0. Here, i=1 and 2 indicates the different dielectric half-spaces. The wave vectors of the reflected and the transmitted waves are given by k_r and k_t, respectively. The numerical dispersion equation [2] can be expressed in each half-space as

$$\frac{\varepsilon_i \mu_0 \Delta^2}{\Delta t^2}\sin^2\frac{\omega_0 \Delta t}{2} = \left(1-\alpha_i \sin^2\frac{\tilde{k}_{iy}\Delta}{2}\right)^2 \sin^2\frac{\tilde{k}_{ix}\Delta}{2} + \left(1-\alpha_i \sin^2\frac{\tilde{k}_{ix}\Delta}{2}\right)^2 \sin^2\frac{\tilde{k}_{iy}\Delta}{2}, \quad (1)$$

where $\tilde{k}_{ip}$ is the numerical wave number along p direction. Δ is the grid step for the x- and y-axes and Δt is the time step. k_{ix} and k_{iy} are the x- and y-components of the numerical wave vector. sc and μ_0 are the scaling factor and the free-space permeability, respectively. ε_i and α_i are the electrical permittivity and the weighting factor, respectively, in the material with the index i.

From the phase matching condition, it can be obtained that

$$\tilde{k}_{1y} = \tilde{k}_{2y} = \tilde{k}_1 \sin\varphi_i. \quad (2)$$

k_{1x} and k_{2x} can be numerically calculated using

$$\tilde{k}_{1x} = \tilde{k}_1 \cos\varphi_i, \ \tilde{k}_{2x} = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}\tilde{k}_1^2 - \tilde{k}_y^2}. \quad (3)$$

In each of the two media, the electromagnetic fields are denoted as H_{z1}, H_{z2}, E_{x1}, E_{x2}, E_{y1}, and E_{y2}. For a plane-wave incidence, the Isotropic-dispersion Finite-difference(ID-FD) of the electric field can be represented as

$$\tilde{\partial}_x \vec{E} = -j\frac{2}{\Delta}\sin\frac{\tilde{k}_x\Delta}{2}\left(1-\alpha_i \sin^2\frac{\tilde{k}_y\Delta}{2}\right)\vec{E} = -jK_x\vec{E},$$

$$\tilde{\partial}_y \vec{E} = -j\frac{2}{\Delta}\sin\frac{\tilde{k}_y\Delta}{2}\left(1-\alpha_i \sin^2\frac{\tilde{k}_x\Delta}{2}\right)\vec{E} = -jK_y\vec{E},$$

$$\tilde{\partial}_t \vec{E} = j\frac{2}{\Delta t}\sin\frac{\omega_0\Delta t}{2}\vec{E} = -j\Omega\vec{E}.$$

where $\tilde{\partial}_p$ is the ID-FD operator with $p = x, y,$ or t.

The Ampere's law and Faraday's law from a plane wave can be written as

$$j\Omega\varepsilon\vec{E} = -j\vec{K}\times\vec{H} = -j(K_y \times H_z)\hat{x} - j(K_x \times H_z)\hat{y},$$

$$j\Omega\mu\vec{H} = j\vec{K}\times\vec{E}. \quad (4)$$

where $\Omega = \frac{2}{\Delta t}\sin\frac{\omega\Delta t}{2}$ and $\vec{K} = K_x\hat{x} + K_y\hat{y}$. Therefore, the components of the electric and magnetic fields are related as

$$E_x = -\frac{K_y}{\Omega\varepsilon}H_z, \ E_y = \frac{K_x}{\Omega\varepsilon}H_z,$$

$$j\Omega\mu H_z = -\tilde{\partial}_x E_y + \tilde{\partial}_y E_x. \quad (5)$$

and the dispersion relationship is simply written as

$$\Omega^2\varepsilon\mu = K_x^2 + K_y^2.$$

Therefore, the fields in the discretized domain have similar expressions to those in the continuous domain. The numerical reflection coefficient can be easily formulated by following the procedure for the continuous domain using the FDTD update equation instead of Maxwell's equation itself[4].

The incident, reflected, and transmitted magnetic field can be written as

$$H_z^i = e^{-j(\tilde{k}_{1x}m\Delta + \tilde{k}_y n\Delta)},$$

$$H_z^r = -R_{TM}\, e^{-j(\tilde{k}_{1x}m\Delta + \tilde{k}_y n\Delta)},$$

$$H_z^t = T_{TM}\, e^{-j(\tilde{k}_{2x}m\Delta + \tilde{k}_y n\Delta)}.$$

where R_{TM} and T_{TM} are the numerical reflection and transmission coefficients, respectively.

Thus, the total field in medium 1 is the sum of the incidence and reflected waves represented as

$$H_{z1} = e^{-j\tilde{k}_y n\Delta}\left(e^{-j\tilde{k}_{1x}m\Delta} - R_{TM}\, e^{j\tilde{k}_{1x}m\Delta}\right),$$

$$E_{x1} = -\frac{K_{1y}}{\Omega\varepsilon_1} e^{-j\tilde{k}_y n\Delta}\left(e^{-j\tilde{k}_{1x}m\Delta} - R_{TM}\, e^{j\tilde{k}_{1x}m\Delta}\right),$$

$$E_{y1} = \frac{K_{1x}}{\Omega\varepsilon_1} e^{-j\tilde{k}_y n\Delta}\left(e^{-j\tilde{k}_{1x}m\Delta} - R_{TM}\, e^{j\tilde{k}_{1x}m\Delta}\right). \quad (6)$$

The total field in medium 2 is written in terms of the

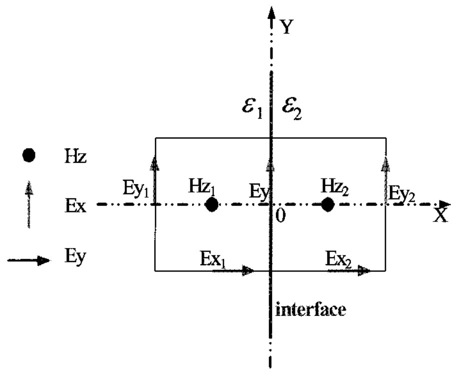

Fig. 2. Two-dimensional Yee grid for the TM mode.

transmitted field, as

$$H_{z2}=T_{TM}e^{-j(\tilde{k}_{2x}m\Delta x+\tilde{k}_{y}n\Delta)},$$

$$E_{x2}=-\frac{K_{2y}}{\Omega\varepsilon_{2}}T_{TM}e^{-j(\tilde{k}_{2x}m\Delta+\tilde{k}_{y}n\Delta)},$$

$$E_{y2}=\frac{K_{2x}}{\Omega\varepsilon_{2}}T_{TM}e^{-j(\tilde{k}_{2x}m\Delta+\tilde{k}_{y}n\Delta)}. \tag{7}$$

It can be observed that only E_y nodes are present at the interface. Thus, the tangential electric field(E_y) must be continuous:

$$E_{y1}\big|_{x=0}=E_{y2}\big|_{x=0}.$$

Using (6) and (7), the following relation can be obtained:

$$T_{TM}=\frac{\varepsilon_{2}K_{1x}}{\varepsilon_{1}K_{2x}}(1+R_{TM}). \tag{8}$$

To compute $H_{z1}\left(-\frac{\Delta}{2},0\right)$ or $H_{z2}\left(\frac{\Delta}{2},0\right)$, we need E_x and E_y both be present in the two media as seen in Fig. 2. However, it is difficult to solve H_z, E_x and E_y simultaneously based on the ID-FDTD update equation. So to calculate $H_{z1}\left(-\frac{\Delta}{2},0\right)$, for example, the dielectric constant of the Yee grid in Fig. 2 is assumed ε_1, and for $H_{z2}\left(\frac{\Delta}{2},0\right)$, ε_2 is assumed. Then, an approximate expression of R_{TM} can be obtained. For $H_{z1}\left(-\frac{\Delta}{2},0\right)$, (5) is discretized and (6), (7) and (8) are substituted into (5), and then (9) can be obtained.

$$j\Omega\mu_{0}H_{z}\big|_{x=-\frac{\Delta}{2}}=-\tilde{\partial}_{x}E_{y}\big|_{x=-\frac{\Delta}{2}}+\tilde{\partial}_{y}E_{x}\big|_{x=-\frac{\Delta}{2}}$$
$$=\frac{\left(1-\frac{\alpha_{1}}{2}\right)[E_{y1}(-\Delta,0)-E_{y1}(0,0)]+\frac{\alpha_{1}}{4}\left[\begin{array}{l}E_{y1}(-\Delta,-\Delta)-E_{y1}(0,-\Delta)\\+E_{y1}(-\Delta,\Delta)-E_{y1}(0,\Delta)\end{array}\right]}{\Delta}$$
$$+\frac{\left\{\begin{array}{l}\left(1-\frac{\alpha_{1}}{2}\right)\left[E_{x1}\left(-\frac{\Delta}{2},\frac{\Delta}{2}\right)-E_{x1}\left(-\frac{\Delta}{2},-\frac{\Delta}{2}\right)\right]\\+\frac{\alpha_{1}}{4}\left[\begin{array}{l}E_{x1}\left(-\frac{3\Delta}{2},\frac{\Delta}{2}\right)-E_{x1}\left(-\frac{3\Delta}{2},-\frac{\Delta}{2}\right)\\+E_{x2}\left(\frac{\Delta}{2},\frac{\Delta}{2}\right)-E_{x2}\left(\frac{\Delta}{2},-\frac{\Delta}{2}\right)\end{array}\right]\end{array}\right\}}{\Delta} \tag{9}$$

After simplifying (9), the magnetic field expression is obtained as

$$H_{z}\big|_{x=-\frac{\Delta}{2}}=\frac{1}{\Omega^{2}\mu_{0}\varepsilon_{1}}\left(e^{\frac{jk_{1x}\Delta}{2}}-R_{TM}e^{-\frac{jk_{1x}\Delta}{2}}\right)K_{1x}^{2}$$
$$+\left[\left(1-\frac{\alpha_{1}}{2}\right)\left(e^{\frac{jk_{1x}\Delta}{2}}-R_{TM}e^{-\frac{jk_{1x}\Delta}{2}}\right)+\frac{\alpha_{1}}{4}\left(e^{\frac{j3k_{1x}\Delta}{2}}-R_{TM}e^{-\frac{j3k_{1x}\Delta}{2}}\right)\right]\frac{K_{1y}^{2}}{\left(1-\alpha_{1}\sin^{2}\frac{k_{1x}\Delta}{2}\right)}$$
$$+\frac{\alpha_{1}}{4}e^{-\frac{jk_{2x}\Delta}{2}}\frac{K_{1x}}{K_{2x}}(1+R_{TM})\frac{K_{2y}^{2}}{\left(1-\alpha_{2}\sin^{2}\frac{k_{2x}\Delta}{2}\right)} \tag{10}$$

For $H_{z2}\left(\frac{\Delta}{2},0\right)$, a similar procedure to that for $H_{z1}\left(-\frac{\Delta}{2},0\right)$ can be used to obtain (11):

$$H_{z}\big|_{x=\frac{\Delta}{2}}=\frac{1}{\Omega^{2}\mu_{0}\varepsilon_{1}}e^{\frac{jk_{2x}\Delta}{2}}K_{1x}K_{2x}(1+R_{TM})$$
$$+\left[\left(1-\frac{\alpha_{2}}{2}\right)e^{-\frac{jk_{2x}\Delta}{2}}+\frac{\alpha_{2}}{4}e^{-\frac{j3k_{2x}\Delta}{2}}\right]\cdot\frac{K_{1x}}{K_{2x}}(1+R_{TM})\frac{K_{2y}^{2}}{\left(1-\alpha_{2}\sin^{2}\frac{k_{2x}\Delta}{2}\right)}$$
$$+\frac{\alpha_{2}}{4}\left(e^{\frac{jk_{1x}\Delta}{2}}-R_{TM}e^{-\frac{jk_{1x}\Delta}{2}}\right)\frac{K_{1y}^{2}}{\left(1-\alpha_{1}\sin^{2}\frac{k_{1x}\Delta}{2}\right)} \tag{11}$$

At the E_y node on the dielectric interface, the ID-FDTD update equation can be used, so that (12) can be formulated.

$$j\Omega\varepsilon_{mid}E_{y}\big|_{x=0}=-\tilde{\partial}_{x}H_{z}\big|_{x=0}$$
$$=-\frac{\left[\begin{array}{l}\left(1-\alpha_{1}\sin^{2}\frac{k_{y}\Delta}{2}\right)H_{z}\big|_{x=\frac{\Delta}{2}}\\-\left(1-\alpha_{1}\sin^{2}\frac{k_{y}\Delta}{2}\right)H_{z}\big|_{x=-\frac{\Delta}{2}}\end{array}\right]}{\Delta} \tag{12}$$

where ε_{mid} is the effective permittivity for the Yee grid on the interface.

After substituting (10) and, (11) into (12), and simplifying the equation, the numerical reflection coefficient is simply written as

$$R_{TM}=\frac{A}{B}$$

where

$$A=\left(e^{\frac{jk_{1x}\Delta}{2}}K_{1x}^{2}K_{2x}f_{2}-e^{-\frac{jk_{2x}\Delta}{2}}K_{2x}^{2}K_{1x}f_{4}\right)$$
$$+\left[\left(1-\frac{\alpha_{1}}{2}\right)e^{\frac{jk_{1x}\Delta}{2}}+\frac{\alpha_{1}}{4}e^{\frac{j3k_{1x}\Delta}{2}}-\frac{\alpha_{2}}{4}e^{\frac{jk_{1x}\Delta}{2}}\right]K_{2x}K_{1y}^{2}\frac{f_{2}}{f_{1}}$$
$$-\left[\left(1-\frac{\alpha_{2}}{2}\right)e^{-\frac{jk_{2x}\Delta}{2}}+\frac{\alpha_{2}}{4}e^{-\frac{j3k_{2x}\Delta}{2}}-\frac{\alpha_{1}}{4}e^{-\frac{jk_{2x}\Delta}{2}}\right]K_{1x}K_{2y}^{2}\frac{f_{4}}{f_{3}}$$
$$-j\Omega^{2}\mu_{0}\varepsilon_{mid}\Delta K_{1x}K_{2x},$$

$$B=\left(e^{-\frac{jk_{1x}\Delta}{2}}K_{1x}^{2}K_{2x}f_{2}+e^{-\frac{jk_{2x}\Delta}{2}}K_{2x}^{2}K_{1x}f_{4}\right)$$
$$+\left[\left(1-\frac{\alpha_{1}}{2}\right)e^{-\frac{jk_{1x}\Delta}{2}}+\frac{\alpha_{1}}{4}e^{-\frac{j3k_{1x}\Delta}{2}}-\frac{\alpha_{2}}{4}e^{-\frac{jk_{1x}\Delta}{2}}\right]K_{2x}K_{1y}^{2}\frac{f_{2}}{f_{1}}$$
$$+\left[\left(1-\frac{\alpha_{2}}{2}\right)e^{-\frac{jk_{2x}\Delta}{2}}+\frac{\alpha_{2}}{4}e^{-\frac{j3k_{2x}\Delta}{2}}-\frac{\alpha_{1}}{4}e^{-\frac{jk_{2x}\Delta}{2}}\right]K_{1x}K_{2y}^{2}\frac{f_{4}}{f_{3}}$$
$$-j\Omega^{2}\mu_{0}\varepsilon_{mid}\Delta K_{1x}K_{2x},$$

with

$$f_{1}=\left(1-\alpha_{1}\cdot\sin^{2}\frac{k_{1x}\Delta}{2}\right),\quad f_{2}=\left(1-\alpha_{1}\cdot\sin^{2}\frac{k_{y}\Delta}{2}\right),$$
$$f_{3}=\left(1-\alpha_{2}\cdot\sin^{2}\frac{k_{2x}\Delta}{2}\right),\quad f_{4}=\left(1-\alpha_{2}\cdot\sin^{2}\frac{k_{y}\Delta}{2}\right).$$

For real ε_1 and ε_2, R_{TM} should be real. From the requirement, is determined ε_{mid} as

$$\varepsilon_{mid}=\frac{\varepsilon_{1}+\varepsilon_{2}}{2}+\frac{(\alpha_{1}f_{2}-\alpha_{2}f_{4})(f_{1}f_{4}-f_{2}f_{3})\Delta t^{2}\sin^{2}\frac{k_{y}\Delta}{2}}{8\Delta^{2}\varepsilon_{0}\mu_{0}\sin^{2}\frac{\omega\Delta t}{2}f_{2}f_{4}}. \tag{13}$$

For this case, R_{TM} is simplified to

$$R_{TM}=\frac{\varepsilon_1\tan\frac{k_{2x}\Delta}{2}[1-H_1]-\varepsilon_2\tan\frac{k_{1x}\Delta}{2}[1-H_2]}{\varepsilon_1\tan\frac{k_{2x}\Delta}{2}[1-H_1]+\varepsilon_2\tan\frac{k_{1x}\Delta}{2}[1-H_2]} \quad (14)$$

where

$$H_1=\frac{f_1(\alpha_1 f_2+\alpha_2 f_4)\sin^2\frac{k_y\Delta}{2}}{4f_2\left(f_2^2\sin^2\frac{k_{1x}\Delta}{2}+f_1^2\sin^2\frac{k_y\Delta}{2}\right)},$$

$$H_2=\frac{f_3(\alpha_1 f_2+\alpha_2 f_4)\sin^2\frac{k_y\Delta}{2}}{4f_4\left(f_2^2\sin^2\frac{k_{1x}\Delta}{2}+f_1^2\sin^2\frac{k_y\Delta}{2}\right)}.$$

For $\alpha_1=\alpha_2=0$(Yee scheme), the effective dielectric constant (13) and the reflection coefficient (14) are reduced to those of the Yee scheme[4] as

$$\varepsilon_{mid_{(Yee)}}=\frac{\varepsilon_1+\varepsilon_2}{2},$$

$$R_{TM_{(Yee)}}=\frac{\varepsilon_1\tan\frac{k_{2x}\Delta}{2}-\varepsilon_2\tan\frac{k_{1x}\Delta}{2}}{\varepsilon_1\tan\frac{k_{2x}\Delta}{2}+\varepsilon_2\tan\frac{k_{1x}\Delta}{2}} \quad (15)$$

For small $\triangle$, it can be observed that

$$R_{TM}\rightarrow\frac{\frac{k_{2x}}{\varepsilon_2}-\frac{k_{1x}}{\varepsilon_1}}{\frac{k_{2x}}{\varepsilon_2}-\frac{k_{1x}}{\varepsilon_1}}=\frac{\eta_2\cos\phi_t-\eta_1\cos\phi_i}{\eta_2\cos\phi_t+\eta_1\cos\phi_i}=R_{exact}.$$

The effective dielectric constants for the ID-FDTD and Yee schemes are different as (13) is a function of the FDTD parameters such as incidence angle, $\triangle$ and $\triangle t$. However, $\varepsilon_{mid}=\frac{\varepsilon_1+\varepsilon_2}{2}+O(\triangle)$ can be simply proven.

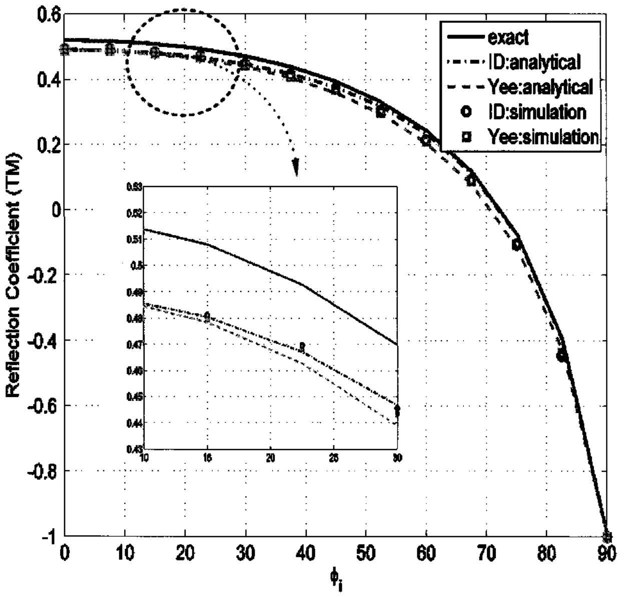

Fig. 3. Comparison of the reflection coefficients when CPW =25, $\varepsilon_1=1$ and $\varepsilon_2=10$.

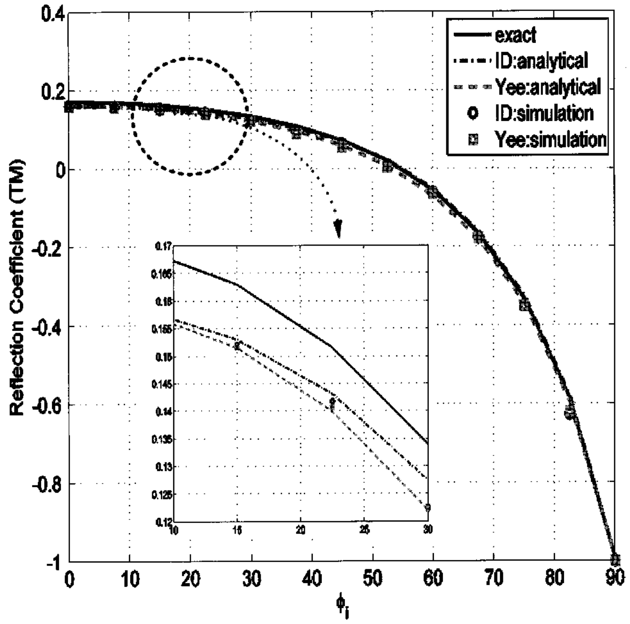

Fig. 4. Comparison of the reflection coefficients when CPW =15 and $\varepsilon_1=1$ and $\varepsilon_2=2$.

Hence, for real FDTD simulation situations, ε_{mid} can be approximated as $\frac{\varepsilon_1+\varepsilon_2}{2}$, which is that for the Yee scheme.

Ⅲ. Numerical Results

Fig. 3 and 4 give the comparison of the reflection coefficients calculated by two formulations, (13) for the ID-FDTD scheme and (14) for Yee scheme. For Fig. 3, *S*(courant number)=0.5, CPW(Cell Per Wavelength)=25, $\varepsilon_1=1$, and $\varepsilon_2=10$ are assumed. For Fig. 4, CPW=15, $\varepsilon_1=1$, and $\varepsilon_2=2$ are used. The results of the ID-FDTD and Yee schemes are very close to the exact results: however, it can be seen that the ID-FDTD scheme will provide slightly more accurate results than the Yee scheme. Fig. 5 gives the comparison of the absolute error of effective dielectric constants between the ID-FDTD and Yee schemes. The error is defined as $error=|\varepsilon_{mid}-\varepsilon_{mid_{(Yee)}}|$. In Fig. 5, it can be seen that the error is very small and decreases with increasing dielectric constant, as expected.

Ⅳ. Conclusions

Analysis of the numerical properties of the ID-FDTD scheme for a material interface was performed. The approximate analytical expression is obtained for the reflection coefficient of the ID-FDTD scheme in a TM wave. The formulated coefficient can be reduced to that of the Yee scheme for $\alpha_1=\alpha_2=0$. The formulated re-

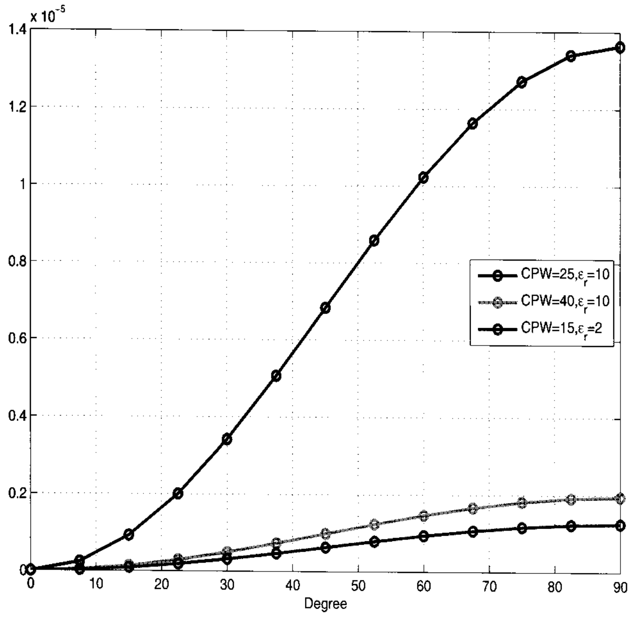

Fig. 5. Comparison for the effective dielectric constants.

flection coefficient is verified numerically based on two simulations. The ID-FDTD scheme can provide slightly more accurate results than the Yee scheme. In addition, the effective dielectric coefficient for the grid on the interface is formulated, which can be approximated by that of the Yee scheme.

This work was supported by Inha University Research Grant.

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