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ANALYSIS OF PYRAMID EM WAVE ABSORBER BY FDTD METHOD AND COMPARING WITH CAPACITANCE AND HOMOGENIZATION METHODS

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Abstract—In this paper, we model an array of pyramid electromagnetic wave absorbers and calculate the return loss of this array using the FDTD method. For modeling the frequency dependent of the absorber, the Debye model is used. In doing so, a 3×3 structure of nine pyramid absorber is chosen instead of the array. The results are compared with capacitance and homogenization methods using average values for ε [10]. The results clearly show that the FDTD is an accurate method for calculating the return loss of an array of pyramid absorbers as compared with three other existing methods, and can be used to simulate the array of pyramid absorbers with different sizes in a wide range of frequencies.

1. INTRODUCTION

There are different structures for EM wave absorbers, such as wedge [1], pyramid [2] and honeycomb [3] used in anechoic chambers for reflectivity measurements [4–7]. In this paper we obtain the reflection of pyramid absorbers over the frequency range of 100–1000 MHz. To simulate pyramid absorbers, different models such as the capacitance model [8], the transmission line [4] and the homogenization method are used [9–11].

In this paper, the Finite Difference Time Domain (FDTD) is used to model the chambers. Since at low frequencies, the period of the array is small compared to the wavelength, in order to reduce the size of array of pyramid absorbers, nine pyramids (3×3) were used. Because the absorbent structure is frequency dependent, the Debye model [12] is used in the FDTD method. The results are compared with other existing methods.

2. FDTD METHOD FOR DISPERSIVE MEDIA

Numerical and semi-analytic methods for simulating electromagnetic wave absorbers use integral equations based on the MOM, the FEM, and the FDTD [13–16]. The FDTD is a time-domain technique that directly calculates the impulse response of an EM system. It can also be used for non-homogenization materials, because ε, μ and σ can be defined for each point of the area separately, and the results of the frequency-domain are calculated from the results of time-domain analysis.

3. MODELING THE PYRAMIDAL ABSORBER

In order to use the FDTD method, frequency dependence of ε and μ must be taken into account [17–23]. The standard procedure is using the convolution-integral approach. This approach becomes very complicated when incorporating the effective properties of a tapered structure. By using the concept of electric and magnetic susceptibility and the Debye model for the frequency dependence, the FDTD method can be modified to eliminate the need for using the convolution-integral approach. This scheme is described below.

The Debye media is characterized by a complex-valued, frequency-domain susceptibility function $x_p(w)$ that has one or more real poles at separate frequencies. For a single-pole Debye medium, we have

$$x_p(w) = \frac{\varepsilon_{sp} - \varepsilon_{\infty p}}{1 + jw\tau_p} = \frac{\Delta\varepsilon_p}{1 + jw\tau_p} \tag{1}$$

where ε_{sp} is the static or zero-frequency relative permittivity, $\varepsilon_{\infty p}$ is the relative permittivity at infinite frequency and τ_p is the pole relaxation time. The real-valued time-domain susceptibility function $x(t)$ is obtained by taking the inverse Fourier transformation of (1), which yields the following decaying exponential function

$$x_p(t) = \frac{\Delta\varepsilon_p}{\tau_p} e^{-t/\tau_p} U(t) \tag{2}$$

where $U(t)$ is the unit step. For a Debye medium having P poles, we extend (1) to express the relative permittivity by

$$\varepsilon(w) = \varepsilon_\infty + \sum_{p=1}^{p} 1 + \frac{\Delta\varepsilon_p}{1 + jw\tau_p} \tag{3}$$

3.1. Formulation for Multiple Debye Poles by ADE (Auxiliary Differential Equation)

Consider a multi term Debye dispersive medium having a total of P poles in its susceptibility response. At any particular E-field observation point, the Ampere's law in the time domain for this medium is

$$\nabla \times \vec{H}(t) = \varepsilon_0 \varepsilon_\infty \frac{d}{dt}\vec{E}(t) + \sum_{p=1}^{p} \vec{J}_p(t) \tag{4}$$

where $\vec{J}_p(t)$ is the polarization current associated with the Pth Debye pole. The goal of the ADE method is to develop a simple time-stepping scheme for $\vec{J}_p(t)$ which can be updated synchronously by (4). By using (2), a phasor polarization current is associated with each pole, which is:

$$\vec{J}_p(w) = \varepsilon_0 \Delta\varepsilon_p \left(\frac{jw}{1 + jw\tau_p}\right)\vec{E}(t) \tag{5}$$

or

$$\vec{J}_p(w) + jw\tau_p \vec{J}_p(w) = \varepsilon_0 \Delta\varepsilon_p jw \vec{E}(t) \tag{6}$$

After using the inverse Fourier transform, implementing it in an FDTD code and solving the result for $J_p^{\vec{n+1}}$, we obtain

$$J_p^{\vec{n+1}} = k_p J_p^{\vec{n}} + \beta_p \left(\frac{E^{\vec{n+1}} - E^{\vec{n}}}{\Delta t}\right) \tag{7}$$

where

$$k_p = \frac{1 - \dfrac{\Delta t}{2\tau_p}}{1 + \dfrac{\Delta t}{2\tau_p}} \tag{8a}$$

$$\beta_p = \frac{\dfrac{\varepsilon_0 \Delta\varepsilon_p \Delta t}{\tau_p}}{1 + \dfrac{\Delta t}{2\tau_p}} \tag{8b}$$

The second component of the ADE algorithm involves obtaining the $E^{\vec{n+1}}$. This requires knowledge of $J_p^{\vec{n+1/2}}$, which can be obtained from (7)

$$J_p^{\vec{n+1/2}} = \frac{1}{2}\left(J_p^{\vec{n}} + J_p^{\vec{n+1}}\right) = \frac{1}{2}\left[(1 + k_p)J_p^{n} + \frac{\beta_p}{\Delta t}\left(E^{\vec{n+1}} - E^{\vec{n}}\right)\right] \tag{9}$$

To evaluate (4) at time-step $n+1/2$, we have

$$\nabla \times \vec{H^{n+1/2}} = \varepsilon_0 \varepsilon_\infty \left[\frac{\left(\vec{E^{n+1}} - \vec{E^n} \right)}{\Delta t} \right] + \sigma \left[\frac{\left(\vec{E^{n+1}} - \vec{E^n} \right)}{2} \right] + \frac{1}{2} \sum_{p=1}^{p} \left[(1+k_p)\, J_p^n + \frac{\beta_p}{\Delta t} \left(\vec{E^{n+1}} - \vec{E^n} \right) \right] \tag{10}$$

Using all corresponding terms, we obtain the following explicit time-stepping relation for the E-field

$$\vec{E^{n+1}} = \left[\frac{2\varepsilon_0 \varepsilon_\infty + \sum_{p=1}^{p} \beta_p - \sigma \Delta t}{2\varepsilon_0 \varepsilon_\infty + \sum_{p=1}^{p} \beta_p + \sigma \Delta t} \right] \vec{E^n} + \left[\frac{2\Delta t}{2\varepsilon_0 \varepsilon_\infty + \sum_{p=1}^{p} \beta_p + \sigma \Delta t} \right] \times \nabla \times \vec{H^{n+1/2}} - \sum_{p=1}^{p} (1+k_p) \vec{J_p^n} \tag{11}$$

Thus, the ADE-FDTD algorithm for modeling a dispersive medium with P Debye poles is a three-step procedure.

3.2. Yee Algorithm

Numerical stability of the Yee algorithm [24] requires bounding of the time-step Δt relative to the space increments Δx, Δy and Δz. This Courant stability bound is given in three dimensions by

$$\Delta t \leq \frac{1}{c} \cdot \frac{1}{\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \tag{12}$$

The limit on Δt set by (12) enables successful application of the FDTD method to a wide variety of three-dimensional electromagnetic-wave-modeling problems of moderate electrical size and quality factor.

Note that the Yee cell size must be smaller than the minimum λ for each case, which in this case is $\frac{1}{10}\lambda_{\max}$. We use (13) to calculate cell size of the Yee lattice.

$$\Delta x,\, \Delta y,\, \Delta z \langle \frac{c}{K\sqrt{\varepsilon_r} f_{\max}} \tag{13}$$

where $f_{\max}$ is the maximum frequency used in each case, ε_r is the complex permittivity of the media and K is the accuracy coefficient of cells in Yee lattice.

In this study we used perfectly matched layers as the absorbing boundary condition in FDTD method.

3.3. Performance with FDTD Method

The values of a, b and c (Fig. 1) for the FDTD method on a pyramid absorbers are 90, 33 and 21 cm, respectively [6].

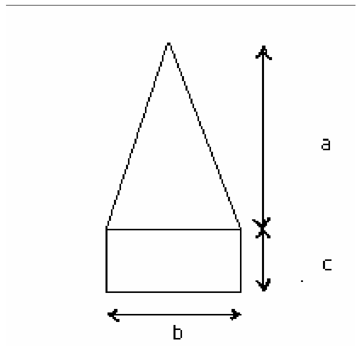


Figure 1. Electromagnetic wave pyramidal absorber.

To check the effect of adjacent pyramids in an array of pyramid absorbers (Fig. 2), 9 pyramids are considered in the PML space.

The pyramids are divided into cells taking into account these sizes in the FDTD method (Fig. 3). Each of these nine pyramids suffers from a frequency-dependent dielectric loss. Using the values of dielectric losses in the FDTD method and running the program, we obtain the reflection curve of the array.

4. SIMULATION RESULTS

The reflection loss of the pyramid absorber in the frequency range of 100–1000 MHz is shown in Fig. 4. We use these values to obtain the return loss of the pyramid absorbers shown in Fig. 5, where we also show the result of the capacitance and homogenization methods [8, 9].

To check the accuracy of the FDTD method for modeling the array of pyramid absorbers, the return loss of the array is calculated again for another dielectric material and the results are shown in Fig. 6.

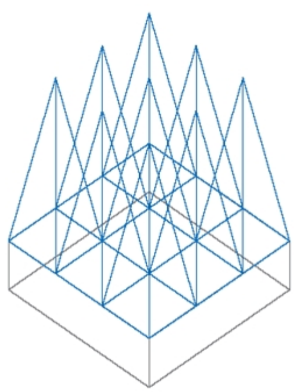


Figure 2. Nine pyramid absorbers (3×3).

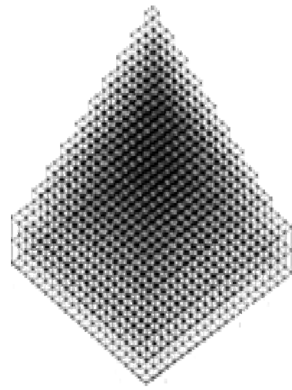


Figure 3. Cellular pyramid absorber.

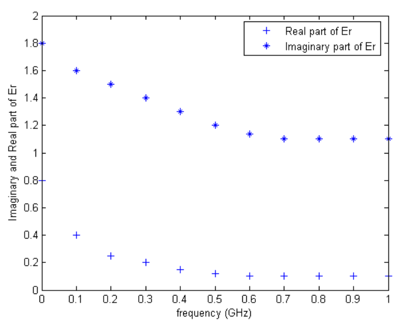


Figure 4. Real and imaginary parts of permittivity of pyramid absorber.

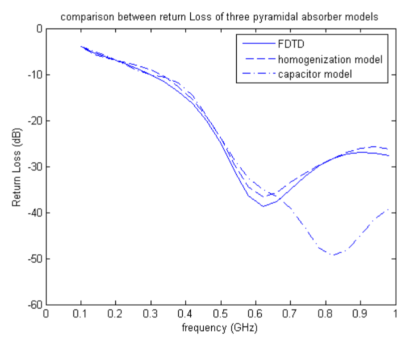
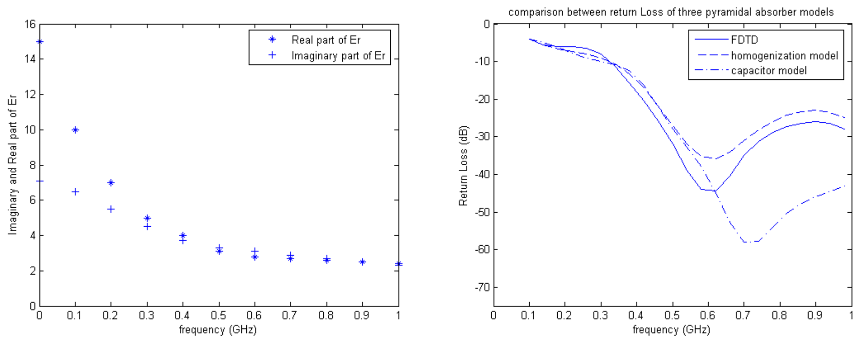


Figure 5. Return loss of pyramid absorber by FDTD method in comparison with the capacitance and the homogenization methods.

As shown in these figures, the FDTD method is in good agreement with the homogenization method. However, due to the model's approximation, the capacitance method has conformity at lower frequencies only.

Simulation results of the FDTD method obtained with the average value of ε are also compared with results of our study, as shown in Fig. 7.



(a) (b)

Figure 6. (a) Real and imaginary parts of permittivity of pyramid absorber; (b) Return loss of the pyramid absorber by the FDTD method as compared to those of the capacitance and homogenization methods.

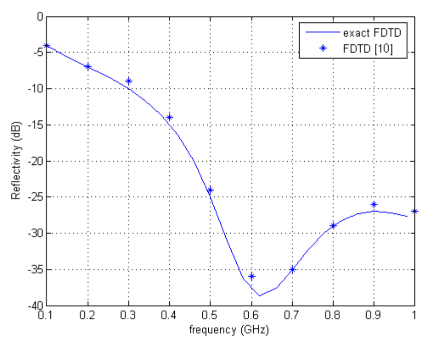


Figure 7. Return loss of a pyramid absorber by FDTD method as compared [10].

5. CONCLUSIONS

In this paper, the return loss of pyramid absorbers in an array structures for the 3D space by the FDTD method was obtained. By decreasing the cell size in the absorber, the accuracy of measurements will increase. The most suitable dimensions for cells in the above frequency band is 3 cm.

Simulation results using the FDTD method are in good agreement with the homogenization method using the average values of ε, and are more accurate than those of other existing methods.

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