International Journal of Scientific Research and Management (IJSRM)
||Volume||11||Issue||11||Pages||57-61||2023||
Website: www.ijsrm.net ISSN (e): 2321-3418
DOI: 10.18535/ijsrm/v11i11.p01

The Simulation of the Propagation of Electromagnetic Waves through a Material with Various Thicknesses Using Finite Difference Time Domain (FDTD)

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Abstract

A finite difference time domain method in one dimension (1D-FDTD) is employed to study the properties of the propagation of electromagnetic waves across a medium with finite thicknesses. In this paper, we simulated the propagation of a Gaussian pulse. Since we simulated in one dimension, the absorbing boundary condition (ABC) can be applied to minimize undesirable reflection which generated at the numerical boundaries. We also implemented total field / scattering field (TF/SF) to ensure the source propagated in only one direction. The analysis performed by inserting the object with both relative permittivity and permeability values higher than one decreased the pulse's amplitude.

Keyword: effect of object thickness, electromagnetic waves simulation, 1D-FDTD

Introduction

Finite difference time domain (FDTD) was the most popular method which was employed in simulating electromagnetic waves for handling various problems. This method had been used in analyzing many topics, such as designing antennas (Gao et al., 2005; Lee et al., 2004), simulation electromagnetic waves in a transducer (Xie et al., 2016), numerical modeling of ground penetration radar to detect landmines (Giannakis et al., 2016) and electromagnetic waves propagation in human tissues (Mirza, et al, 2015). This method was firstly proposed by Yee in 70's (Yee, 1966).

The basic concept of FDTD was solving Maxwell's equations, especially the Ampere law and Faraday law numerically. It required spatial discretization of both Electric and magnetic fields along with the temporal discretization of time propagation. Here, the Yee's lattices were based on second order of central difference. Depended on the requirement, we were able to derive the numerical equations for FDTD in 1D, 2D and 3D. Since the purpose of this paper was to analyzing of the effect of object thickness to the propagation of the electromagnetic waves here we derived the simple 1D FDTD numerical formulations. Then, we tried to analysis the propagation properties of the electromagnetic waves when the different medium with certain values of permittivity ε_r and permeability μ_r. We also looked at effect of the inserted medium's thickness when the electromagnetic propagates through that inserted medium.

The method and formulation

In this paper, since we focused on 1D, we had to reduce the 3D Maxwell equation to become only 1D Maxwell equation, such as

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon_x}\left(-\frac{\partial H_y}{\partial z}\right), \tag{1}$$

and

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu_x}\left(-\frac{\partial E_x}{\partial z}\right) \tag{2}$$

which was only involving field components E_x and H_y and pulse propagated at the $\hat{z}$ direction.

Based on that equations (Eq.(1)) and (Eq.(2)), the coding for basic simulation for updating E_x and H_y at the free space can be written as

```
for i = 1:Nz-1;
   Hy(i)=Hy(i)+(dt/mu)*(Ex(i+1) - Ex(i))/dz;
end                                                                    (3)
for i = 2:Nz
   Ex(i) = Ex(i) +(dt/ep)*(Hy(i) -Hy(i-1))/dz;
end
```

where N_z represented total spatial grid along the propagation. Spatial grid dz and temporal grid dt obeyed Courant condition with $dt = dz/(2c_0)$. Here *mu* and *ep* were permeability and permittivity of the medium where electromagnetic waves propagated.

Since we simulate 1D electromagnetic waves propagation, it was appropriate to only implementing absorbing boundary condition (ABC). Using also a gaussian pulse as a source, the coding in Eq.(3) should be add

```
A = -sqrt(ep/mu);
Esrc = exp(-((t-t0)/tau).^2);
Hsrc = A*exp(-((t-t0+delt)/tau).^2);                                   (4)
Ex(src)=Esrc;
Hy(src)=Hsrc;
```

for the source. Here, *E*src and *H*src were electric and magnetic fields source with *A* was the amplitude of magnetic source *H*src. Parameter *delt* was the delay between the electric and the magnetic pulses. Parameters *t0* and *tau* were time delay and the width of Gaussian pulse. Here, src was the grid location of the pulse's sources. The ABC was applied by adding the code

```
H2=0; H1=0; E2=0; E1=0;
Ex(1)=E2;
E2=E1;
E1=Ex(2);                                                              (5)
Hy(Nz)=H2;
H2=H1;
H1=Hy(Nz-1);
```

Here, N_z was the total number of spatial grids.

Unnecessary reflection was minimized using scattered/total field (TF/SF). Implementing this method, resulted in only one direction of the pulse's propagation. Then, we modified the update of H_y and E_x fields as

```
for s=1:Nz-1
    Hy(s)=Hy(s)+(dt/mu)*(Ex(s+1) - Ex(s))/dz;
end
   Hy(Nz) = Hy(Nz) + (dt/mu)*(E2 - Ex(Nz))/dz;
   Hy(src-1)=Hy(src-1)-(dt/mu)*Esrc(T)/dz;.
   Ex(1) = Ex(1) + (dt/mu)* (Hy(1) - H2)/dz;                           (6)
for s=2:Nz
   Ex(s) = Ex(s) + (dt/mu)*(Hy(s) -Hy(s-1))/dz;
end
   Ex(src)=Ex(src)- (dt/mu)*Hsrc(T)/dz;.
```

The simulation was performed by implementing ABC, Gaussian source and TF/SF source in FDTD as it was discussed above.

Results and Discussion

In this report, the medium surrounding was free space. Then, we inserted the object which had different values of permittivity and permeability. Here, we used $\varepsilon_m = 4$ and $\mu_m = 6$. The result with object thickness was 40 grids (around 78 nm) was presented in figure 1. The source was generated at grid's number 30 in free space.

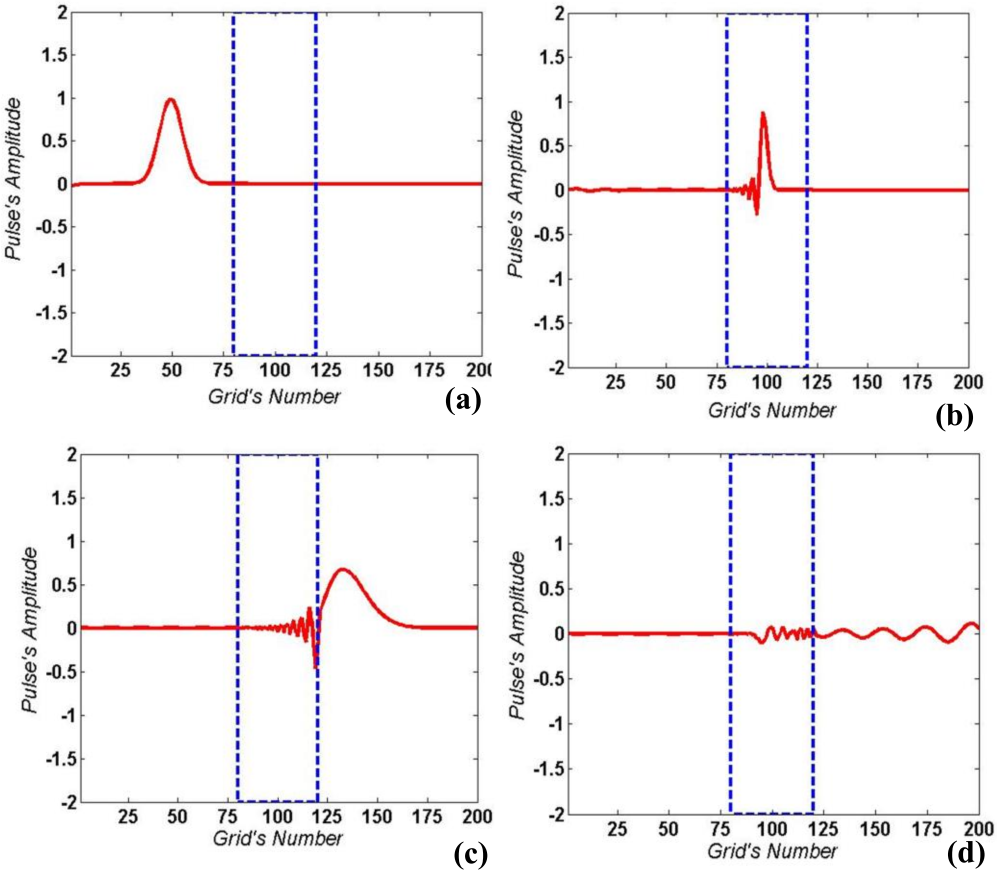

Figure 1. Propagation of the pulse at several time capture. In (a), propagation at 250 ps, In (b), propagation at 500 ps, In (c), propagation at 750 ps an (d) the propagation at 1000 ps.

The pulse propagation was represented by red line, while the boundaries of rectangle object were drawn using blue lines. The width of the object was 40 spatial grids (around 78 nm), from grid number 80 to 120. In Fig.(1a), when the simulation was captured at 250 ps, the Gaussian pulse propagate to the right direction. When we captured at 500 ps, the pulse had already propagate inside the object, as can be seen in Fig.(1b). It can be noticed from Fig.(1b), that the amplitude and the width of the Gaussian pulse decreased when it propagated through the object. This was because the medium of the inserted object had the values of permittivity and permeability higher than that that of its surrounding which was vacuum (free space). It meant that the density of the object was higher than the density of the free space. When the pulse propagation was captured at 750 ps (see Fig.(1c), the pulse left the object and started to propagate at the free space (less dense compare to the object), hence the amplitude and the width of the pulse increased. Then, when this pulse continued to propagate, it reached the numerical boundary and absorbed. This was shown in Fig.(1d), when the propagation was captured at 1000 ps. These results was expected.

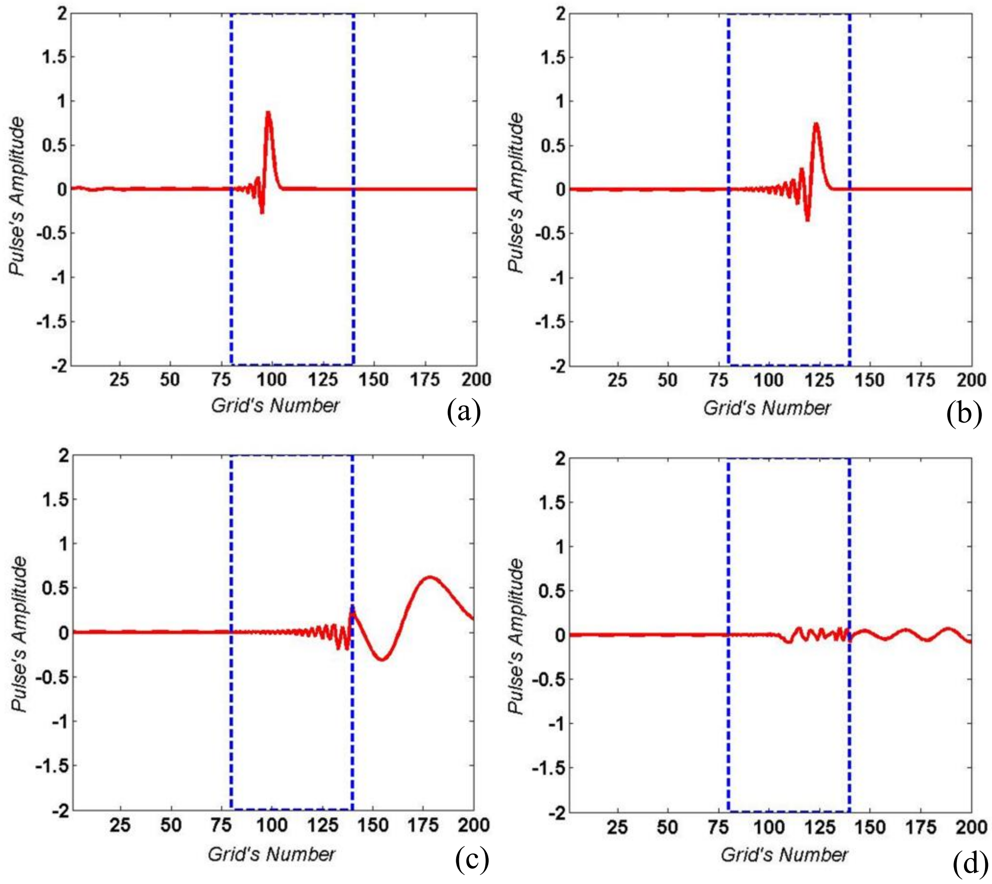

Figure 2. Propagation of the pulse at several time capture with the thickness of tectangular object was 60 grids. In (a), propagation at 500 ps, In (b), propagation at 750 ps, In (c), propagation at 1000 ps an (d) the propagation at 1125 ps.

Then we increased the thickness of the object to 60 spatial grids. The results was presented in Fig.(2a) to Fig.(2d). The pulse inside the object (see Fig.(2a) and Fig.(2b)) had similar trend compare to the previous result (Fig.(1b)). The amplitude and the width of the pulse decreased as the pulse propagated in the object. The other results (see Fig.(2c) and Fig.(2d)) was also having similar trends. It seem that increasing the width of the object was not significantly changing the profile of the pulse. We thought that this happened since we treated the object here as lossless materials. Hence, the thickness of the object became unimportant parameter.

Conclusion

The propagation of electromagnetic waves through the rectangular object had simulated using 1D-FDTD. We also noticed that the width of the rectangular object did not significantly affect the profile of the pulse of electromagnetic waves.

Acknowledgment

We highly acknowledge Physics Department, Faculty of Sciences and Mathematics, Diponegoro University for the support of this work .

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