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Numerical Solutions of Maxwell's Equations to Calculate Waves Propagation in Dielectric Material using Finite Difference Time Domain (FDTD) Technique

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ABSTRACT

This paper presents the numerical solutions of Maxwell's time dependent curl equations by using finite difference time domain (FDTD) technique for simulating the electromagnetic waves propagation in a dielectric medium designed in different shapes in two dimensional system. The waves propagated in the dielectric slab, which can be studied to show that for the example, a dielectric medium can use to guide the waves in a material. The results of the calculations indicated that the performance of a dielectric slab model acted as a guide of the signals. The impact of a dielectric slab orientation variation can be studied. The results demonstrated that each change in the shape structure of a dielectric could result into the different distributions, as an example two different distributions generated when the dielectric slabs oriented in the *x*-direction compared with *y*-direction. Moreover, the propagations of the waves can be studied when varying the phase. The first simulation the dielectric slabs placed in free space and the second the dielectric slab placed between two parallel strips made of the perfect electric conductors (PECs). The result of the first simulation demonstrated that the signal updated on the dielectric as well as free space while the result of the second simulation, the signal only updated in the dielectric slab between the strips. In one dimensional (1-D) as an example of the propagation of electromagnetic wave in a dielectric constant compared with PEC. The results have shown that it is possible to study two different types of materials in a one simulation. Therefore, the results obtained clearly demonstrated that electromagnetic wave completely reflected back into a domain when the pulse is striking with the PEC while in a region of dielectric, the pulse propagated in a dielectric constant and the other parts reflected back into a domain.

Keywords: Maxwell's curl equations, finite difference time domain (FDTD), and transverse magnetic (TM_z) wave.

1. Introduction

There are a number of electromagnetic problems should be studied to describe the behavior of electromagnetic waves in many fields such as interaction of electromagnetic with a dielectric material [1] and also interactions of radio frequency (RF) with the human tissue such as in MRI [2]. It is very important point to study the propagation of electromagnetic wave in a dielectric material. This can be described by solving Maxwell's curl equations analytically but sometimes, there are many problems that make finding the exact solution analytically difficult. To overcome this problem, we usually use the numerical technique to solve Maxwell's curl equations to make prediction of an approximation solution. Several numerical computational techniques have been developed such as the finite difference time domain (FDTD) method that can provide very good accurate results [2]. This technique has been widely utilized to solve electromagnetic problems by modelling a variety of electromagnetic problems in one (1-D), two (2-D) and three dimensional (3-D). Therefore, the aim of this work is to study the electromagnetic wave propagation direction in a dielectric material by applying the FDTD method in one (1-D) and two (2-D) dimensional systems in order to make a comparison between the simulations. We will generate the distributions of the wave propagation in a one and two dimensional with the purpose of demonstrating the effect of adding a dielectric material in a domain and an electromagnetic interacts with a material. For example in a one dimensional system can study the interactions of electromagnetic waves with the dielectric material and perfect electric conductor (PEC) that can be compared when simulating simultaneously together to study the behavior of electromagnetic waves when striking with different media in a one simulation. The free space, dielectric and perfect electric conductor (PEC) will be included in the computational domain and the space will excite by using the Gaussian pulse in order to make a comparison when the wave interact with material. Because this type of pulse has a symmetry distribution and this is explained in the result section in a one dimensional simulation system. Moreover, the TM mode Maxwell's equations solved in two dimensional system and a number of different shapes can be constructed in the computational domain such as added a dielectric slab, circular and ring shapes filled with a relative dielectric constant of 2.1. We can consider and prove that the distributions of the fields rely on the geometry of the guide. For examples, we study a dielectric slab placed along *x*-direction compared with a dielectric slab with the same thickness but it placed along y-direction. The purpose of the examples is to investigate the propagation direction of the TM_z waves when flipping the slab 90 degrees. It is very important to observe what occurs when adding different dielectric shapes in the space. Therefore, the reason of including different shapes in a computational domain is to study the distributions by producing many patterns based on the structure. This can be described by solving Maxwell's curl equations numerically so that the partial derivatives can be approximated by applying a central finite difference method. The equations will be converted into discrete update equations to implement on a computer program language as the MATLAB program have written to perform the FDTD simulations in one and two dimensional. The numerical calculations can be performed by applying the following method.

2. Methods

This section presents an overview of the computational method that is used in this research. We will introduce the basic concepts of the finite difference time domain (FDTD) method to compute electromagnetic wave propagation in a free space when including a dielectric material in a computational domain. The FDTD method was firstly introduced by Yee K. S. in the paper published in 1966 [3] and then developed by many researchers to model various complicated problems. The electromagnetic field components will produce in a computational domain in every time step by solving Maxwell's equations numerically, which can be given by [4]:

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\varepsilon_r \varepsilon_o} \nabla \times \mathbf{H} \tag{1.a}$$

$$\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu_o} \nabla \times \mathbf{E} \tag{1.b}$$

Where the **E** is the electric field, **H** is the magnetic field, ε_o is the permittivity and μ_o is the permeability of free space and ε_r is a relative dielectric constant of medium, the following equations demonstrate the system in three-dimensional [5]:

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon_r \varepsilon_o} \left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) \tag{2.a}$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon_r \varepsilon_o} \left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right) \tag{2.b}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_r \varepsilon_o} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) \tag{2.c}$$

$$\frac{\partial H_x}{\partial \mathrm{t}} = -\frac{1}{\mu_o} \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right) \tag{2.d}$$

$$\frac{\partial H_y}{\partial \mathrm{t}} = -\frac{1}{\mu_o} \left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right) \tag{2.e}$$

$$\frac{\partial H_z}{\partial \mathrm{t}} = -\frac{1}{\mu_o} \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right) \tag{2.f}$$

The paper is organized as the following, the next section will explain the reduction of equation (2) into two dimensional system and then a one dimensional system, because the work in this paper is divided into two parts, simulations in a one dimensional (1D) and two dimensional (2D) systems.

2.1. FDTD simulations of two-dimensional (2-D) system

The equation (2) describes the system in 3-D and it can be reduced from the 3-D to 2-D systems by setting this condition, the partial derivatives in equation (2) with respect to *z* must be equal zero. In this case two groups will be obtained, the first one is called transverse electric (TE) and the second is called transverse magnetic (TM) modes. The latter will be implemented in the calculation and the Maxwell's equations in two-dimensional system will be solved as the TM_z-FDTD which introduced by Yee K. S. [3]:

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_r \varepsilon_o} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) \tag{3.a}$$

$$\frac{\partial H_x}{\partial \mathrm{t}} = -\frac{1}{\mu_o} \frac{\partial \mathrm{E_z}}{\partial \mathrm{y}} \tag{3.b}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu_o} \frac{\partial E_z}{\partial x} \tag{3.c}$$

The equation (3) is called the transverse magnetic (TM_z) wave which consists of three components and the electric field is polarized along the z-axis.

The transverse magnetic wave will generate in the *x-y* plane, and the fields will propagate in this plane in two-dimensional system. To generate the field components, we need to produce three updating equations by using the central finite difference on the space and time as the following [5]:

$$\frac{\partial F^n(i,j)}{\partial t} = \frac{F^{n+\frac{1}{2}}(i,j) - F^{n-\frac{1}{2}}(i,j)}{\Delta t} \tag{4.a}$$

$$\frac{\partial F^n(i,j)}{\partial x} = \frac{F^n(i+\frac{1}{2},j) - F^n(i-\frac{1}{2},j)}{\delta x} \tag{4.b}$$

The central finite difference approximation is applied into equation (3) in order to generate three discrete updating equations, since the finite difference equations approximation for Maxwell's equations in 2-D provided by [3]:

$$H_x^{n+\frac{1}{2}}(i,j+\tfrac{1}{2}) = H_x^{n-\frac{1}{2}}(i,j+\tfrac{1}{2}) - \frac{\delta t}{\mu_0\,\delta}(E_z^n(i,j+1) - E_z^n(i,j)) \qquad (5.a)$$

$$H_y^{n+\frac{1}{2}}\left(i+\tfrac{1}{2},j\right) = H_y^{n-\frac{1}{2}}\left(i+\tfrac{1}{2},j\right) + \frac{\delta t}{\mu_0\,\delta}(E_z^n(i+1,j) - E_z^n(i,j)) \qquad (5.b)$$

$$E_z|_{i,j}^{n+1} = E_z|_{i,j}^{n} + \frac{\delta t}{\delta\,\varepsilon_r\varepsilon_o}((H_y|_{i+\frac{1}{2},j}^{n+\frac{1}{2}} - H_y|_{i-\frac{1}{2},j}^{n+\frac{1}{2}}) - (H_x|_{i,j++\frac{1}{2}}^{n+\frac{1}{2}} - H_x|_{i,j-\frac{1}{2}}^{n+\frac{1}{2}})) \qquad (5.c)$$

Where δ is the spatial increment and δt is the time increment. Based on the equation (5), the 2-D TM_z wave will be generated in a space by using the positioning of the field components as can be seen in figure 1, it can be noted that each electric field component will calculate by surrounding magnetic components as well as each magnetic field components will calculate by surrounding the electric field components. The program can be written based on the flowchart as illustrated in figure 2. This will demonstrate in the 2-D FDTD result section.

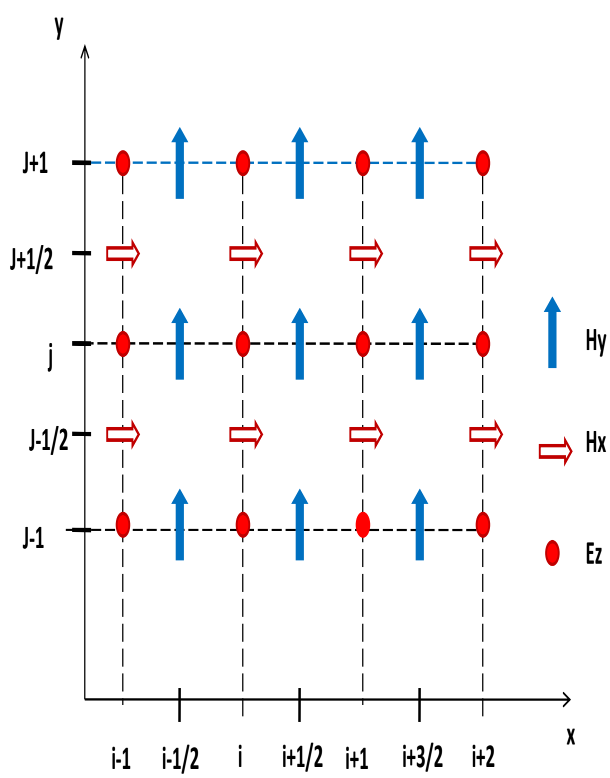

Fig. 1. Two-dimensional-FDTD, Positions of the field components, the electric (E_z) and magnetic (H_x and H_y) in the transverse magnetic (TM_z) mode [1].

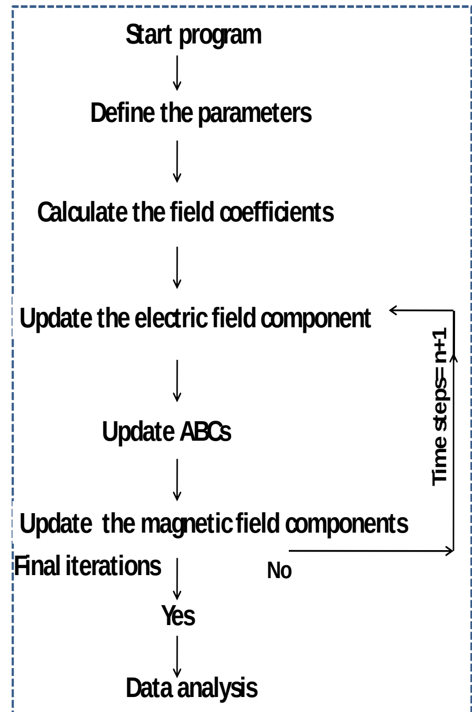

Fig.2.The flow chart of the FDTD program uses to generate the TM_z field components in the computational domain in the *x-y* plane.

2.2. FDTD simulations of one-dimensional (1-D) system

In this section, it will be explained how the FDTD method solves the problem in a one dimensional system and the results of simulations will describe the behavior of electromagnetic wave when the waves propagate and strike a dielectric material and also the wave propagates through a dielectric which means that the wave incident and penetrated through a dielectric slab. Therefore, the purpose of this simulation is to study the behavior of electromagnetic wave when interacting with dielectric and perfect electric conductor. Therefore, Maxwell's equations will be solved numerically in 1-D FDTD by setting the equations (2) as there is no variations in electromagnetic fields in the *z* and *y* directions. It can be normalized Maxwell's equations by using this relation form: $\breve{E} = \sqrt{\varepsilon_o/\mu_o}\ E$ [6]. It in this case, it can be obtained two field components normalized as the following:

$$\frac{\partial E_y}{\partial t} = -\frac{1}{\varepsilon_r\sqrt{\varepsilon_o\mu_o}}\frac{\partial H_z}{\partial x} \qquad (6.a)$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\sqrt{\varepsilon_o\mu_o}}\frac{\partial E_y}{\partial x} \qquad (6.b)$$

When applying a central difference approximation on the equation (6), we will obtain the discrete updating equations (7) which will be implemented in the computer program to calculate two field components as the E_y and H_z:

$$E_y^{n+1}(i) = E_y^n(i) - \frac{\Delta t}{\varepsilon_r\sqrt{\varepsilon_o\mu_o}}\left(\frac{H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2}\right) - H_z^{n+\frac{1}{2}}\left(i-\frac{1}{2}\right)}{\delta x}\right. \qquad (7.a)$$

$$H_z^{n+1/2}(i+1/2) = H_z^{n-\frac{1}{2}}(i+1/2) - \frac{\Delta t}{\sqrt{\varepsilon_o\mu_o}}\left(\frac{E_y^n(i+1) - E_y^n(i)}{\delta x}\right. \qquad (7.b)$$

Where δx and Δt are the spatial step and time increment, respectively. As seen in the equation (7), the fields normalized and the wave propagation along *x*-direction which can be classified to the *x*-directed and *y*-polarized.

3. Results and discussion

The research in this paper is divided into two parts to demonstrate the results of the simulations. The first part of the result dealt with a one-dimensional simulation and the second part of the result dealt with two-dimensional simulations of electromagnetic waves.

3.1. Numerical results of a one dimensional (1-D FDTD) system

This section presents the simulation of electromagnetic field in a one-dimensional in order to study the interactions of electromagnetic waves with the relative dielectric constant of 2.1 including in the domain. First, we will start to simulate a one-dimensional system based on discrete form, which is expressed in equations (7) in the previous section. The example in a one-dimensional case, the computational domain can be divided into 200 points. In the showed problem, a dielectric constant equals of 2.1 placed from the point number five until point number ten and the perfect electric conductor (PEC) is placed in the last ten points from point 190 to 200 by setting the electric fields equal zeros in this region during the calculation in each time step [7]. The computational domain was excited by a Gaussian pulse and it sets as a hard source [8], this type of pulse generates a symmetry distribution in a space. This is allow us to make a comparison when the electromagnetic wave interacts with different materials in a computational domain as explained in the 1D-FDTD result section. Furthermore, the grid is terminated by the truncation condition at the left side of a domain. This means that it opens to infinity in order to reduce the reflections in the computation domain and the pulse should be disappeared at the boundary. The snapshot can be generated to observe the behavior of electromagnetic field when the wave hits the dielectric material.

The example provided in figure 3 demonstrates the normalized field calculated at snapshot of 70 time step, the pulse produced in the middle of a domain as can be noted that it consists of two peaks, the pulse is propagated in free space on the left and right sides which is called propagating bilaterally as shown in figure 3. It can be studied the interaction of TM_z wave with different media as the example demonstrated in figure 4. This simulation is explained a comparison of the FDTD simulation when interacting of the wave with a PEC and a dielectric material in a one simulation. The difference is expected as appeared in the calculations, at 300 time step the right side of the pulse reached the perfect electric conductor (PEC) and the pulse completely reflected back into the left side of a simulation domain as shown in figure 4 as appeared in a peak (1).

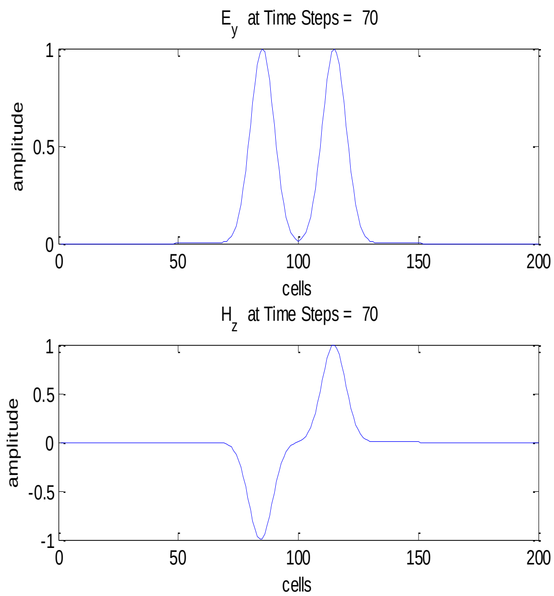

Fig.3. The Gaussian pulse is placed in the middle of the domain and the pulse generated and bilaterally propagated in the positive and negative directions.

At the same time steps, the electromagnetic fields reached the locations of the dielectric and propagated inside a dielectric constant medium and the pulse interacted with the dielectric medium as shown in figure 4. It can be observed that at this time step the part of the pulse is reflected back on the opposite directions in a free space as shown in figure 4 which is appeared in a peak (2) which generates by the interface between air and dielectric when interacting the pulse with a dielectric and other part of the pulse continues propagated in the dielectric medium until the end of the slab. The pulse reached the end of the dielectric and then the pulse continues to propagate in free space and also the portion of the pulse is reflected back to propagate along the *x* direction again on the right side which is appeared in peak (3). This is due the interface between the dielectric and air. The peak (2) appeared in figure 4 generated by the interface between air and dielectric and peak 3 appeared in figure 4 generated at the interface between the dielectric and air. Therefore, the peak (2) and adjacent peak (3) generated when the pulse travels between two different boundaries. It means that this effect is occurred when the signal propagate between two different media. The aim of this example is to make comparison in a one simulation between two media such as a dielectric material and perfect electric conductor (PEC) as shown in figure 4. This can be done by applying a Gaussian pulse, which is propagating bilaterally as shown in figure 3. It was found that the pulse is completely reflected when a PEC was placed at the right side of a domain while when a dielectric material was placed at the left side of a domain, a one portion of the pulse is reflected and other parts are propagated through the media.

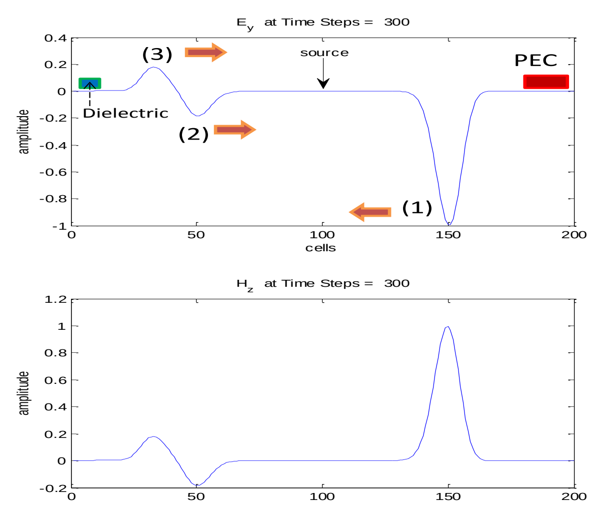

Fig.4. Comparison calculation between two types of media.

The Gaussian pulse is reflected completely back by the perfect electric conductor (PEC) on the right side as illustrated in peak (1) compared with the FDTD result on the left side of a computational domain, the pulse is striking the relative dielectric of 2.1 and then propagated in a dielectric medium. The part of pulse is reflected which is appeared as a peak (2) and other part is penetrated to propagate inside dielectric medium until the pulse reached the end of the dielectric then a part of the pulse is propagated in free space and other part is reflected back into the right side which is appeared in a peak (3) at 300 time step.

3.2. Numerical Results of two-dimensional (2-D FDTD) system

This section presents the simulation of electromagnetic field in two-dimensional. We wrote the computer programs to calculate the electric and magnetic field components iteratively based on the use of updating equation (5) which was described in 2-D FDTD method section. We have calculated the field components in the FDTD problem space that consists of 200-by-200 cells in *x* and *y* directions, respectively. A dielectric constant can be constructed as the slabs in many shapes in the middle of a simulation domain as shown in figure 5. Many different shapes have been simulated to demonstrate the effect of changing the shape on the distributions of fields. We set a dielectric constant of 2.1 in each shape and surrounded the dielectric slab set as a free space. The purpose of designing different shapes is to make a comparison when the TM_z waves propagate in different shapes, which leads to consider the effect on the distributions of the propagation. For example in figure 5 (A), the dielectric slab is placed and oriented in the *x*-direction while the dielectric slab in figure 5 (B) is placed and oriented in the *y*-direction. figure 5 (C and D), the dielectric material can be constructed as the L-shaped and T-junction shaped. In this case, it can be considered the wave propagation direction and the distributions. The last example shown in figure 5 (E and F) are used to study the propagations of TM_z waves inside the ring and circular shapes. We expect to see that the dielectric slabs can behavior as a waveguide to concentrate the fields to propagate from a one cell to next cell in the dielectric slab as the source of excitation placed inside a dielectric. The computational domain can be excited by a sinusoidal source operated at one GHz as this is ultra-high frequency. The grid size is equal to fourteen cells per wavelength in order to obtain very good stability in the calculations and the Courant condition can be applied as mentioned in the paper published in [9]. Therefore, based on the figure 1, figure 2 and equations (5), the three field components are calculated in each cell and every time step. Moreover, the absorbing boundary condition (ABC) should be included in the calculations and the grid is terminated by the first order MUR approximation absorbing boundary condition (ABC) [10] in order to save a computational time and also to avoid the reflections produced from the boundaries. In this case the problem can be treated as an open computational domain. For the example shown in figure 6, the snapshots of TM_z wave generated in free space without including any obstacle in a computational domain. The comparisons can be made between the simulations in the next examples as many shapes made of dielectric material are placed in a space. As the example, the waves can be guided to propagate inside a dielectric material in the *x* direction as shown in figure 7 and when the source operated out of phase 90 degree as shown in figure 8. It can be seen that the phase of the field components has changed when compared the results of two simulations. The TM_z waves can be guided to propagate inside a dielectric material in the *y* direction as shown in figure 9. The purpose of the examples is to compare the result of simulations when the dielectric slabs oriented in the *x* and *y* directions as shown in figure 7 and figure 9, respectively. It can be clearly noted that the field components such as H_x and H_y appeared in different patterns. Therefore, it can be guided the wave to propagate in the *x* and *y* directions, this can lead to vary the patterns of the fields and this take place when rotating the dielectric slab 90 degree. Furthermore, TM_Z wave propagated between the strips (PECs) as the waves updated in each cell exactly inside dielectric. Because, we placed the dielectric medium between the strips as shown in figure 10. This simulation can be compared with result of the simulation shown in figure 7. It can be seen that the wave propagates in a dielectric medium and free space in figure 7 while in figure 10, the waves only propagated in the dielectric between two parallel stripes, it means that there are reflections between the PECs strips. In this case, the field components can be controlled to propagate in the dielectric medium without penetrating outside the structure. Moreover, the TM_z waves can be guided to propagate in different shapes as the examples in the L-shaped and T-shaped structures as illustrated in the results of the simulations that demonstrated in figure 11 and figure 12, respectively. It can be obviously observed that the signals propagated and distribution appeared identical when placed a dielectric as T-junction shape in a domain. The similar result was obtained as shown in figure 3, as was illustrated in a one dimensional simulation, this due to fact that the signal produced and propagated bilaterally in the positive and negative directions. The snapshots generated in different shapes demonstrated that the field distributions changed when the TM_z wave produced in different shapes.

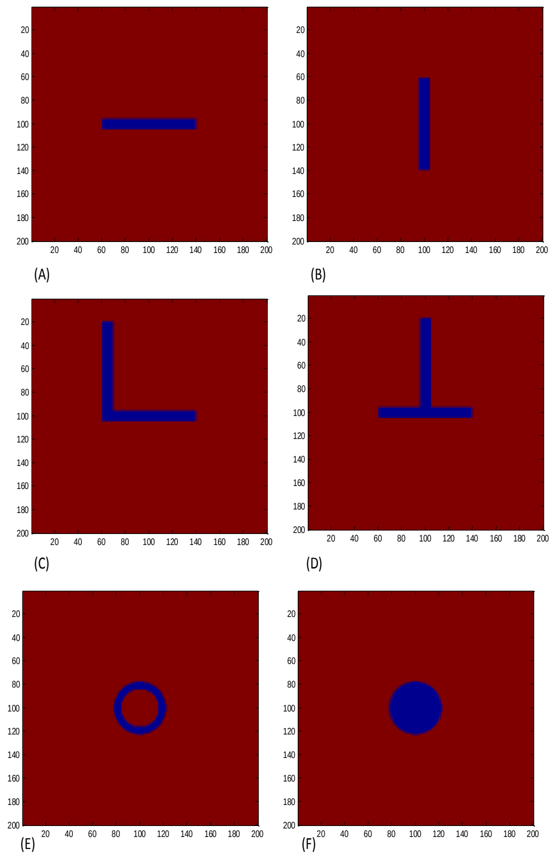

Fig. 5. Many different types of shapes were constructed and filled with the dielectric constant of 2.1 in the middle of the computational domain.

Furthermore, it can be simulated the propagation of wave inside a dielectric medium as the example, the point source of excitation was placed in a circular shape dielectric medium as shown in figure 13. The TM_z wave propagated from a dielectric medium to free space and the distributions of the field components appeared uniform and the fields covered all the circular shape. The result of simulation indicated that the distributions appeared very good as well as the circular patterns generated in the image. Because, we used the first order MUR ABC in the calculation as shown in figure 13. This numerical study in the following example demonstrates that the waves will be guided in a dielectric which is designed as a ring shape when the source placed in a dielectric as shown in figure 14 (A). This can be compared with a ring dielectric surrounded by the perfect electric conductors (PECs) as shown in figure 14 (B) as the aim of this example is to assess the performance of the strips when constructed as a ring-shaped structure. The results of simulations demonstrated that the waves generated in a dielectric medium as provided in the snapshot in figure 14 (A). It can clearly be noted that the wave propagated in a dielectric and when the wave reached at the end of ring shape, the wave propagated in free space while in figure 14 (B) the waves guided in a dielectric medium as it placed between the strips made of perfect electric conductors (PECs). The difference between the results of two simulations is that many reflections generated between the strips and also the wave is controlled to keep the propagation inside the structure. This effect was presented in the result section in a one dimensional when the pulse hits the PEC, this example demonstrated the behavior of electromagnetic wave when adding PEC in a space, the pulse completely reflected back in the domain. In the same case in two-dimensional, the pulse reflected between the strips and propagated between strips as demonstrated in different shapes. Comparison can be made between the parallel strips and the circular strips in the two simulations. The results of the simulations indicated that in the two cases, the waves updated every time step, controlled and guided between the strips in the computational domains.

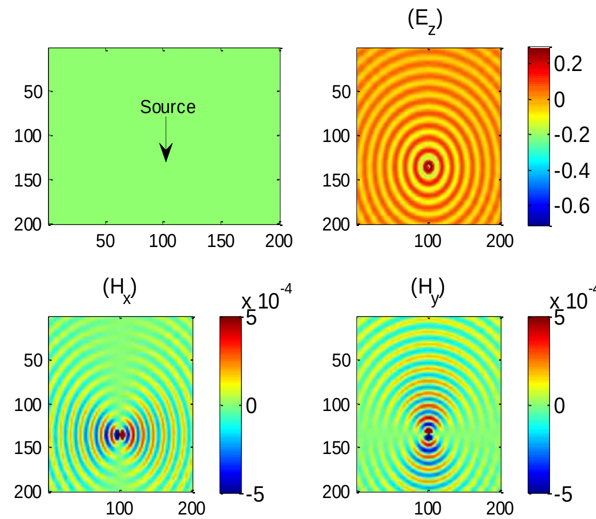

Fig.6. The TM$_z$ wave, electric field component (V/m) and magnetic components (A/m) generated in a free space.

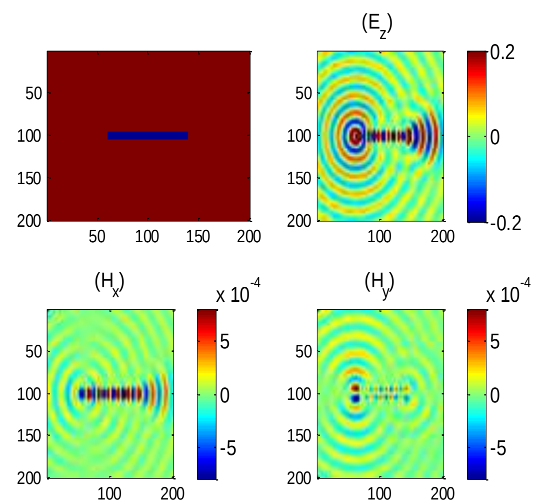

Fig.7. The TM$_z$ wave, the electric field component (V/m) and magnetic fields (A/m) propagated inside the dielectric in the *x* direction.

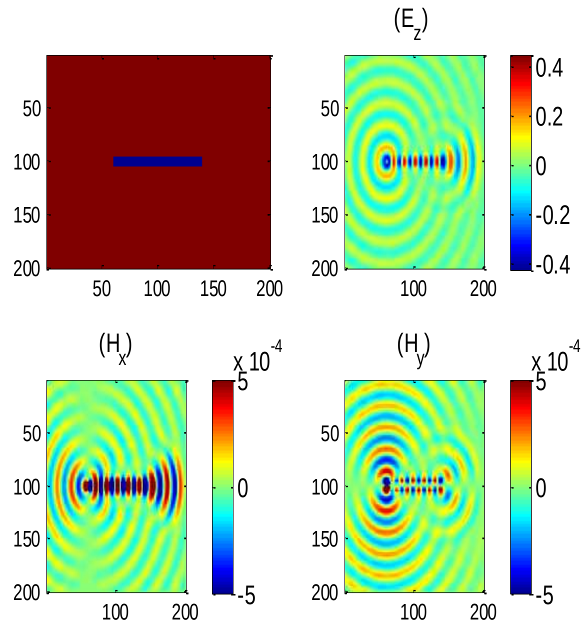

Fig. 8. The TM$_z$ wave, electric field component (V/m) and magnetic fields (A/m) propagated inside the dielectric in the *x* direction and TM$_z$ wave generated out of phase 90 degrees.

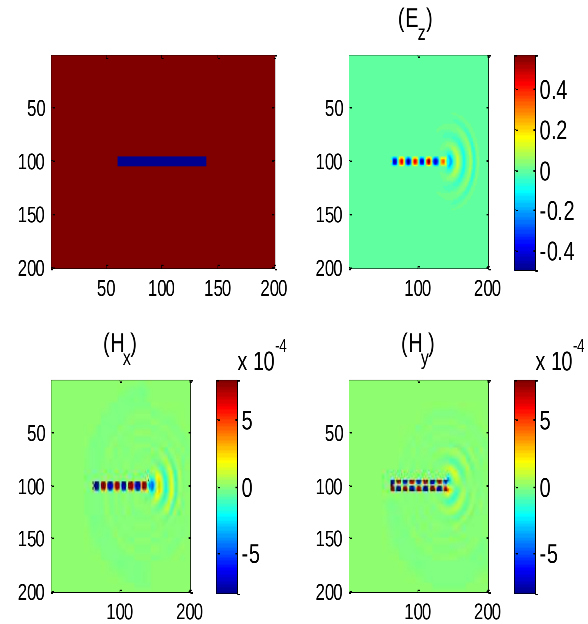

Fig.10. The TM$_Z$ wave, Electric field component (V/m) and magnetic fields (A/m) and wave propagated in a dielectric permittivity of 2.1 as a dielectric slab located between two parallel strips made of the PECs.

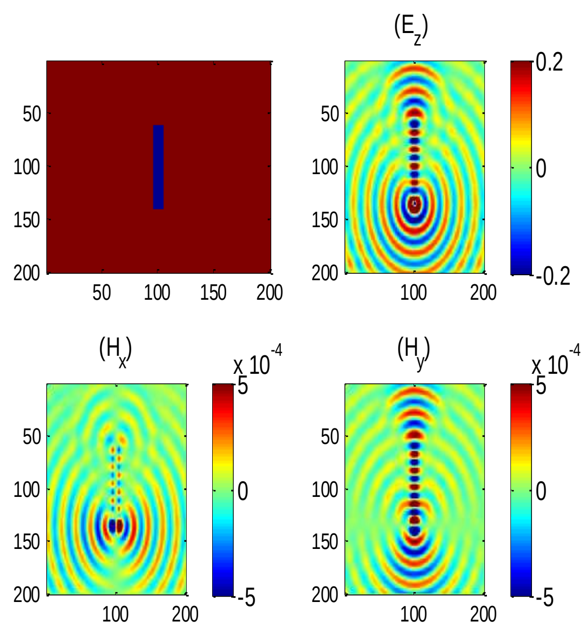

Fig. 9. The TM$_Z$ wave, Electric field component (V/m) and magnetic fields (A/m) propagated inside the dielectric in the *y* direction.

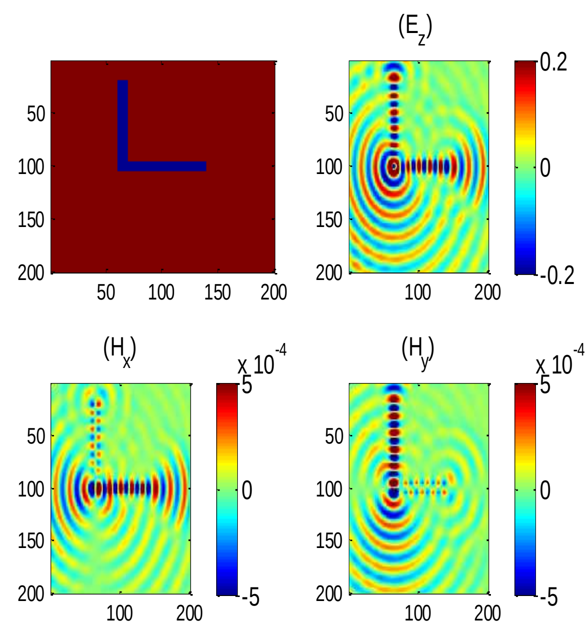

Fig. 11. The TM$_Z$ wave, Electric field component (V/m) and magnetic fields (A/m) and wave propagated inside a dielectric designed as the L-shaped structure.

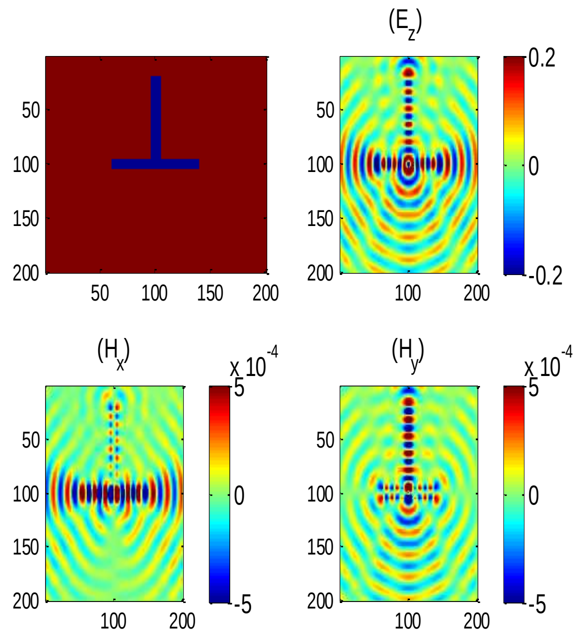

Fig. 12. The TMz wave, Electric field component (V/m) and magnetic fields (A/m) and wave propagated inside a dielectric designed as T-junction shaped structure.

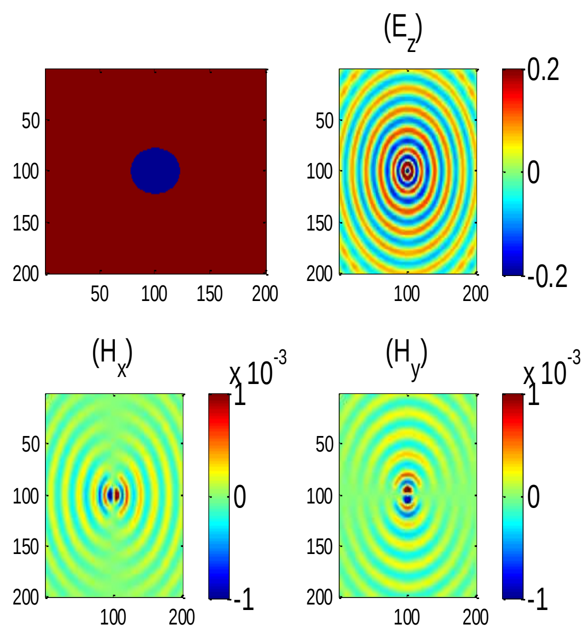

Fig. 13. The TMz wave, Electric field component (V/m) and magnetic fields (A/m), the excitation source is placed inside circular shape, which is filled with a dielectric in the middle of a domain and snapshot generated at 250 time step.

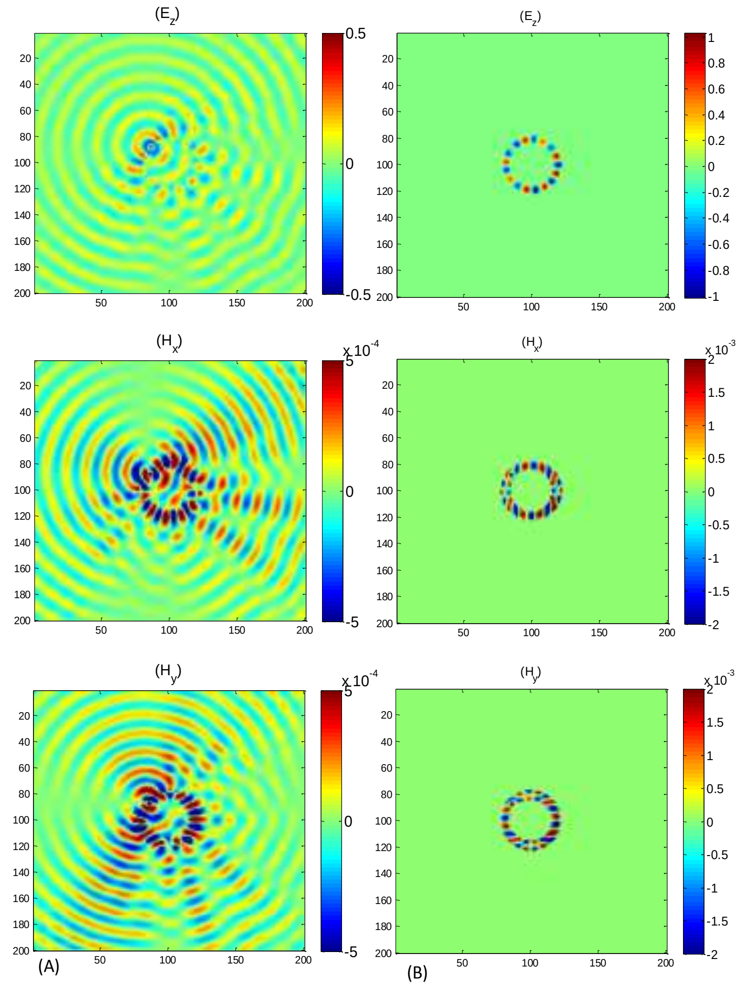

Fig.14. The TM$_z$ wave, electric field component (V/m) and magnetic components (A/m) generated at 250 time step: (A) inside the ring-shaped structure filled with a dielectric and (B) the dielectric surrounded by the PECs.

4. Conclusion

The article in the paper described the FDTD technique, which was implemented for solving the transverse magnetic mode of Maxwell equations in order to study the propagation of the TM$_z$ wave inside a relative dielectric medium. Comparison between two media such as a dielectric material and PEC have been studied to demonstrate how the 1D-FDTD is an efficient method to simulate and describe the behavior of electromagnetic wave when studying two media in a one simulation. It was found that the method is extremely powerful for solving Maxwell's equations to study the distributions of electromagnetic waves when propagating in one and two dimensional systems in dielectric media that are designed in a complex geometries. It was obtained that the FDTD method can compute the electric and magnetic fields in each point in a domain at every time step when included the dielectric material in a space. The TM_z waves were guided in space in one and two dimensional systems. The patterns of the fields can be changed when varying the shape and the TM_z waves can be guided in different shapes even in the T-shaped and L-shaped sharp bend structure that have filled with a dielectric material placed in the computational domain.

5. References

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