# 마이크로 스트립에 기초한 불연속 선로의 모델링 및 해석을 위한 유한차분법의 적용

## Applications to the FDTD Technique for Modeling and Characterization of Microstrip Based Discontinuity Structure

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요 약

불연속 전송선로를 해석하기 위한 유용한 방법으로서 유한요소법이나 공간도메인법등과 같은 주파수영역 해석법과 선로제작에 기초한 파라미터 측정법등이 사용된다. 시간영역의 유한차분법은 한번의 모의실험을 통해 주파수 의존적인 파라미터값을 구할수있어 불연속선로를 해석하는데 매우 효과적이다. 본 논문에서는 마이크로 스트립에 기초한 몇가지 형태의 2 포트 불연속 회로망 즉, 케스케이된 스텝 불연속 선로와 레이스트렉 지연선 및 단일 스터브 필터에 대한 정확한 모델링과 해석을 위하여 시간영역의 유한차분법의 적용방법이 논의된다. 2 포트 회로망으로 구성된 평면형 마이크로 스트립 불연속선로를 해석하기 위하여 일반적으로 분산 파라미터에 기초한 해석절차가 사용된다. 주파수 의존적인 분산 파라미터는 시간영역의 유한차분법에 의해 모니터된 입사, 반사 및 투과된 전압으로 부터 고속 푸리에 변환을 통해 얻어지고, 또한 그 결과를 공간-스펙트랄 방법 및 모멘트 방법의 결과와 비교함으로써 시간영역의 유한차분법이 다양한 형태의 불연속 선로에 성공적으로 적용됨을 볼수있다.

## 1. INTRODUCTION

Accurate characterization of planar microstrip discontinuities is the basis for industrial applications of computer aided design(CAD) of microwave integrated circuits(MIC), monolithic microwave integrated circuits(MMIC) and miniature hybrid microwave integrated circuits (MHMIC). In general, these circuits are composed of cascaded planar transmission lines which are interconnected by circuit discontinuities. The difficulties in describing the scattering parameters of these discontinuities are accentuated by the possibility of the presence of a multi-layered substrate structure. For planar microstrip discontinuities of arbitrary shape, accurate frequency-dependent characterization of the reflection and transmission properties of these discontinuities is of great importance

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and is a continuing area of interest in microwave CAD.

Up to now, discontinuity problems in microstrip lines have been studied for many years, where discontinuities typically were analyzed using most quasi-static or approximate full-wave techniques [1~3].

More recently, a number of full-wave techniques have been presented for the analysis of microstrip discontinuities including the open-end[3], and step-in-width[2]. All the above mentioned investigations, however, were done in the frequency-domain, that is, a new simulation was performed for each frequency point. For broadband characterization of discontinuities, many frequency points and, hence, many simulations may be needed.

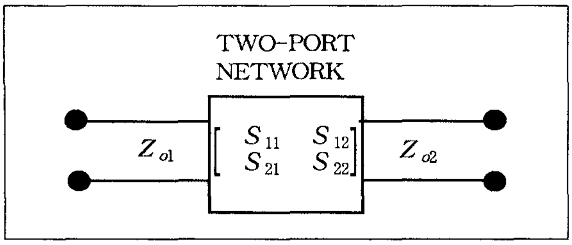
In 1988, Zhang and Mei have first used the FDTD technique to analyze several types of microstrip discontinuities including T-junction and cross-junction[6]. Sheen et al. applied the FDTD technique to characterize microstrip low pass filters and branch line couplers[7].

There are so many methods for the analysis and characterization of discontinuity transmission line structure such as FEM(Finite Element Method), SDM(Spectral Domain Method), and parameter measurement method for the fabricated structure over the experimental equipment as the vector network analyzer. Many researchers have been used the above technique for analysis of discontinuity structure. However, the FDTD method is very useful to get the scattering parameters for the various discontinuity structure because we can get frequency-dependent scattering parameters over one time simulation.

In this paper, the FDTD method is applied to determine the broadband characteristics for the planar microstrip discontinuities such as cascaded step-in-width[8], race-track delay[9], and single stub filter structure[10]. Results of frequency-dependent scattering parameters for the structures mentioned above with variable lengths(L) such as line length(L) between the both steps for cascaded step-in-width, variable length L1 for race-track delay line, and variable stub length L1 for the single stub filter are presented and compared to space spectral domain method and moment method. This paper begins with the general two port network formulation for discontinuity. This is followed by the description of time domain simulation and results for some types of discontinuity including a brief review of the FDTD method. Finally, at the last chapter, conclusion of the paper for the above mentioned discontinuity structure is presented.

## 2. TWO PORT NETWORK FORMULATION FOR DISCONTINUITY

Discontinuities can be conveniently characterized in terms of the scattering parameters. The scattering parameters for a




[Fig. 1] A general two-port network for the scattering parameters.

general two port network are defined as

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{1}$$

An abrupt change in microstrip line width, commonly named microstrip step-in-width, is a discontinuity frequently appearing in microwave integrated circuits such as low-pass filters, stepped impedance transformers and impedance matching networks[5].

As shown in Figure 2, two orthogonal excitations for the two port network are needed at port 1 and port 2, respectively, to calculate the two port scattering parameters. Generalized scattering parameters for the two port network of the any discontinuity structure shown in Figure 1 and 2 are found from

$$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{Z_{01}}} & 0 \\ 0 & \frac{1}{\sqrt{Z_{02}}} \end{bmatrix} \begin{bmatrix} V_{i1} & 0 \\ 0 & V_{i2} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{Z_{01}}} & 0 \\ 0 & \frac{1}{\sqrt{Z_{02}}} \end{bmatrix} \begin{bmatrix} V_{r11} & V_{t12} \\ V_{t21} & V_{r22} \end{bmatrix} \tag{3}$$

$$S_{11}(\omega) = \frac{V_{r11}(\omega)}{V_{i1}(\omega)} \tag{4}$$

$$S_{21}(\omega) = \frac{\dfrac{V_{t21}(\omega)}{\sqrt{Z_{02}(\omega)}}}{\dfrac{V_{i1}(\omega)}{\sqrt{Z_{01}(\omega)}}} \tag{5}$$

$$S_{12}(\omega) = \frac{\dfrac{V_{t12}(\omega)}{\sqrt{Z_{01}(\omega)}}}{\dfrac{V_{i2}(\omega)}{\sqrt{Z_{02}(\omega)}}} \tag{6}$$

$$S_{22}(\omega) = \frac{V_{r22}(\omega)}{V_{i2}(\omega)} \tag{7}$$

Here $Z_{01}(\omega)$ and $Z_{02}(\omega)$ are the characteristic impedances of the microstrip lines connected to port 1 and port 2, respectively. The voltages $V_{r11}(\omega)$ and $V_{r22}(\omega)$, $V_{i1}(\omega)$ and $V_{i2}(\omega)$, and $V_{t12}(\omega)$ and $V_{t21}(\omega)$ are the Fourier-transformed reflected, incident and transmitted voltages at ports 1 and 2, respectively. Here, $V_{tjk}$ is the voltage of the wave transmitted to port j when port k is excited.

## 3. TIME DOMAIN SIMULATION AND RESULTS

### 3.1 FDTD METHOD

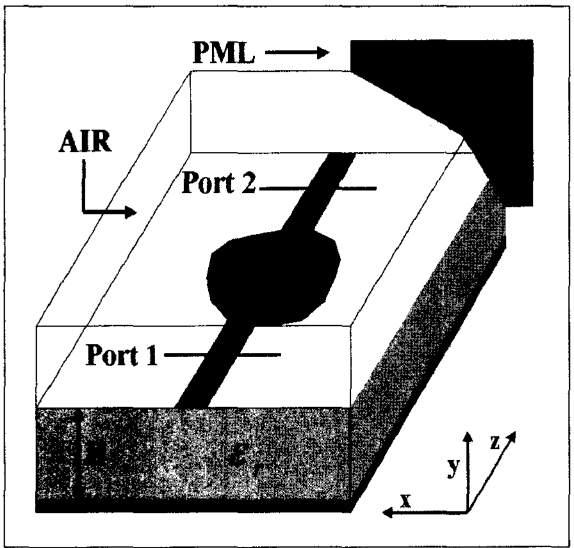
Recently, the FDTD method has been widely extended to analyze microstrip based structures for various type of microswave system[6,7,11-12].

Application of the FDTD method to simulate the characteristics of the transmission lines provides broadband frequency information in one time simulation. Basically, in this method, the two Maxwell's curl equations are discretized both in time and space and the field values on the nodal points of the space-time mesh are calculated.

$$\nabla\times\vec{E} = -\mu\frac{\partial\vec{H}}{\partial t} \tag{8}$$

$$\nabla\times\vec{H} = \varepsilon\frac{\partial\vec{E}}{\partial t}+\sigma\vec{E} \tag{9}$$

The entire computational domain is discretized into a number of cells of size $\Delta x$, $\Delta y$ and $\Delta z$ in x, y and z directions, respectively. As an input excitation, a Gaussian pulse is desirable because its frequency spectrum also being Gaussian, provides frequency domain information from DC to the desired cutoff frequency by adjusting the width of the pulse. Figure 2 shows the total computational domain for the FDTD simulation of the two-port network structrue with PML (Perfectly Matched Layer) absorbing boundary conditions.



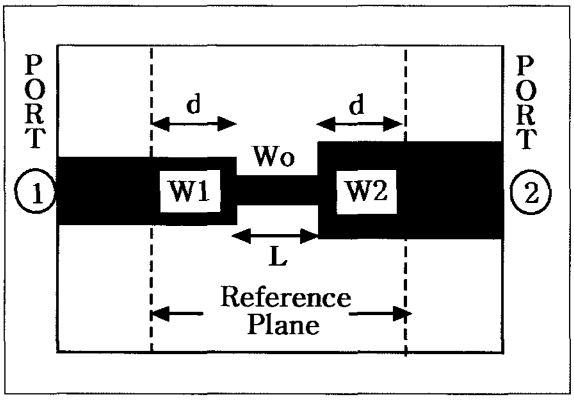

[Fig. 2] Entire computational domain for the FDTD simulation of the two-port network discontinuities with PML absorbing boundary cells.

3.2 CASCADED-STEP DISCONTINUITY

For a general two-port network as the cascaded step-in-width with different characteristic impedances of conductor width W1, W2, Wo, and the step length L, as illustrated in Figure 3.

As the first example, the specification of the cascaded step-in-width structure is adopted from [8] with widths, W1=0.4mm, W2=0.8mm, and Wo=0.2mm, stub lengths L=0.15mm, 0.3mm, 0.6mm and 1.2mm between the two conductors W1 and W2, substrate thickness, H=0.25mm and dielectric constants, $\varepsilon_r = 3.8$, are considered shown in Figure 3. The metal strips and the ground plane are assumed to be perfectly conducting and infinitely thin, and are defined by setting the tangential component of the electric field to zero. The conductor lines are simulated on an $N_x\Delta x$ by $N_y\Delta y$ by $N_z\Delta z$ computational domain with $\Delta x=\Delta y=\Delta z=50\mu m$.

This corresponds to a conductor width of W1=8$\Delta x$, W2=16$\Delta x$ and Wo=4$\Delta x$, substrate




[Fig. 3] The planar microstrip structure of the cascaded step-in-width with variable length L.

heights of H=5$\Delta y$. The width, $N_x$, and height, $N_y$, of the simulation box are chosen to be large enough to not disturb the field distributions near the strips. In all, the entire computational domain including the PML (Perfectly Matched Layer) absorbing boundary conditions of 6 cells for each side is divided into 88 by 40 by 220 grid cells.

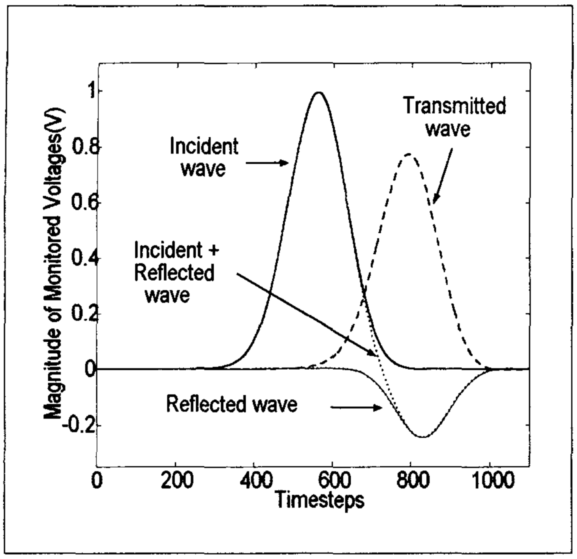
A time step of $\Delta t$=0.087 $ps$ is used and the total number of time steps is 1500. The input is excited with a Gaussian pulse with T=9.24 $ps$ and $t_0$=27.7 $ps$. To obtain the transient time response under the strips of the discontinuity structure, each port is excited and then voltages of each port are recorded at the reference plane shown in Figure 3 with the actual length of conductor, d=1mm. Quantitative frequency-domain information contained in the time-domain data is extracted via the Fast Fourier Transform (FFT).

To obtain the effective monitored voltages such as incident wave, reflected wave, and transmitted wave, we should take enough timesteps on the FDTD simulation. In this simulation, running time of simulation is totally 1100 timesteps. Figure 4 shows the normalized monitored voltage waveforms and figure 5 represents the variation of the characteristic impedances as a function of frequency. Here, we can see that the characteristic impedance slowly increase following frequency for the single line of different conductor width, W1 and W2, respectively. And also, Figure 5 represents that characteristic impedances are exactly same between the two different numerical approach such as FDTD and MoM.

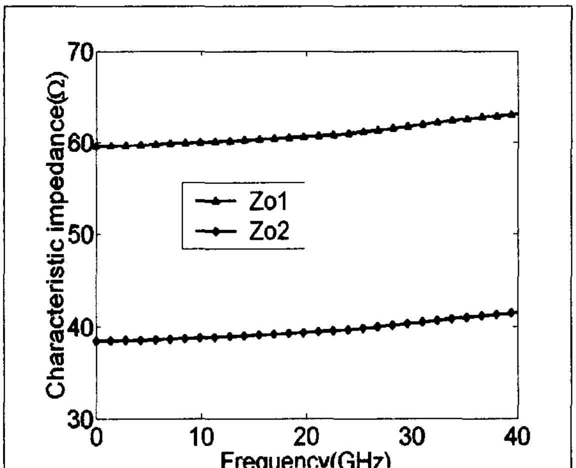
And Figures 6 to 8 show the frequency-dependent scattering parameters including the result of normalized step length for the structure. The figures say that return and insertion losses for the given structure are getting bigger and smaller at high frequency, respectively. Because there is a strong interaction between both steps since the separation of both steps is less than half the guided wavelength.

Interestingly, a tighter coupling of both stpes leads to a lower reflection coefficient over the frequency. From Figure 6, the results for the two types of approaches show very good agreement over the entire broadband frequency range excepting for the DC value and around low frequency.

But, there are small amount of differences

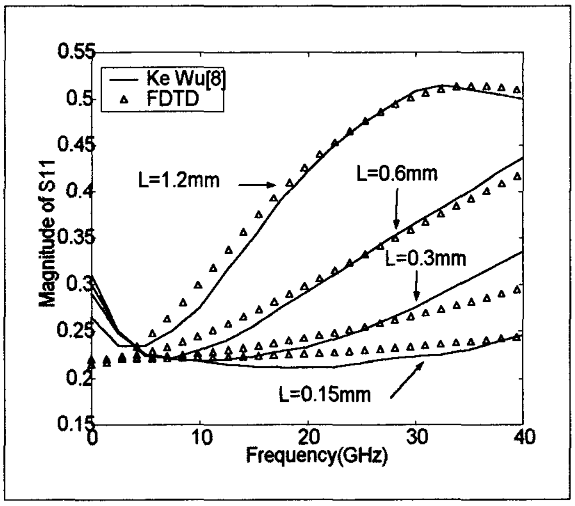



[Fig. 4] Magnitude of monitored voltages at the reference planes for the cascaded step-in-width with the specification of W1=0.4mm, Wo=0.2mm, W2=0.8mm and L=0.15mm

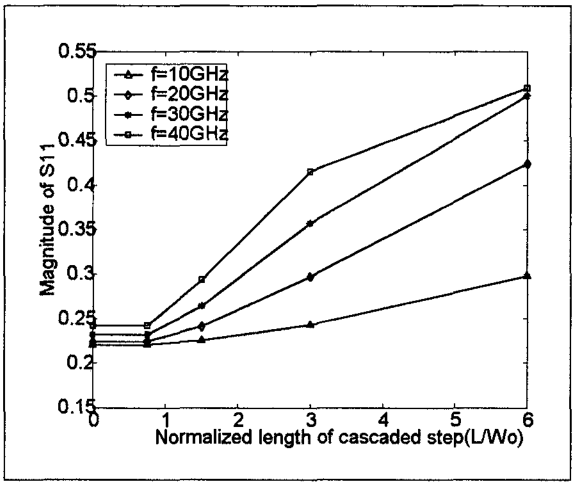



[Fig. 5] Characteristic impedances for the cascaded step-in-width with the specification of W1=0.4mm and W2=0.8mm, H=0.25mm(Solid line : FDTD, △ and ◇ : MoM)

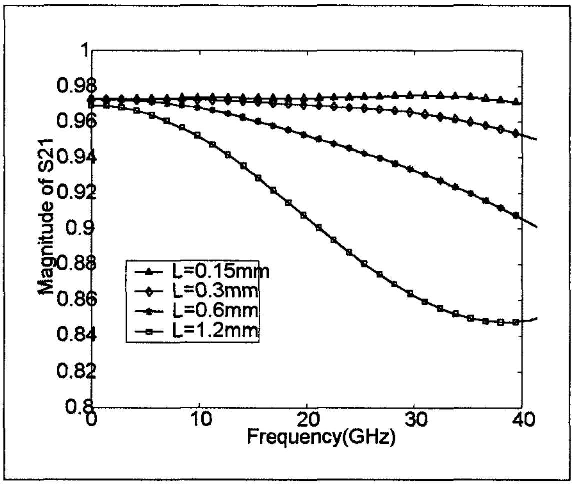
between the two methods. First, magnitude of the scattering parameters of static value solution ofclosed form expression for step discontinuity is about 0.2 at DC value and around low frequency and second, a little bit differences are due to grid cell size of the FDTD method. While the FDTD simulation tool is running, we also get the electric field waveform beneath the strip conductor of the given discontnuity structure for each timesteps. Figure 9 shows the electric field waveform along the z-axis at 1000 timesteps as the results of each timestep. for the cascaded step-in-width under the specification of W1=0.4mm, W2=0.8mm, Wo=0.2mm, and L=0.3mm.




[Fig. 6] Magnitude of scattering parameter S11 for the cascaded step-in-width with the specification of W1=0.4 mm, Wo=0.2mm, W2=0.8mm and L=0.15mm, 0.3mm, 0.6mm, 1.2mm, respectively.(Solid line : Ke Wu[8], △ : FDTD)



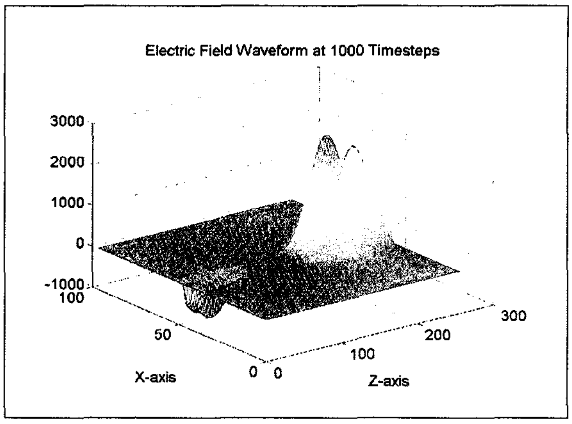

[Fig. 7] Magnitude of scattering parameter S11 in dB scale for the cascaded step-in-width with the normalized step length (L/Wo : mm)




[Fig. 8] Magnitude of scattering parameter S21 for the cascaded step-in-width with the specification of W1=0.4mm, Wo=0.2mm, W2=0.8mm and L=0.15mm, 0.3mm, 0.6mm, 1.2mm, respectively.

### 3.3 RACE TRACK DELAY LINE

As the second example, microstrip circuit which will be analyzed is a "race track" delay

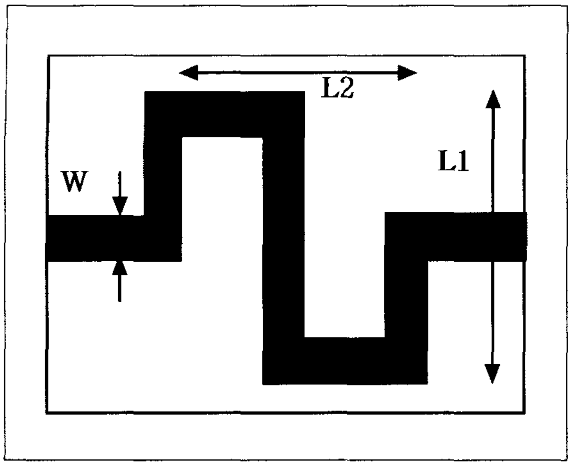



[Fig. 9] Electric field waveform along the z-axis at 1000 timesteps for the cascaded step-in-width with the specification of W1=0.4mm, W2=0.8mm, Wo=0.2mm, and L=0.3mm

line shown in Figure 10. This type of microstrip circuit is often used in the clock distribution system of an electronic device when a clock signal requires some amount of delay for timing purposes.

It consists of alternating traces tightly routed on the substrate whose overall length provide the desired delay time. Since this circuitry is often used on high-speed, fast edge-rate signals, one concern a designer might have is the effects on the quality of the intended signal. From the 90° bend, a discontinuity is introduced by the angled traces of the microstrip circuit due to the additional capacitance at the corners of the bend. In order to determine the effects of this racetrack, it is modeled using the FDTD method.

As the specification of the racetrack delay line, W=2.438mm(6$\Delta x$), L1=16.256mm (42$\Delta x$),

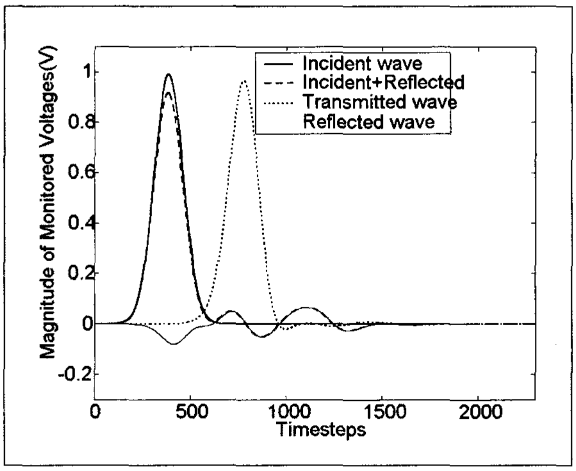



[Fig. 10] Race-track delay line with the conductor width W=2.438mm, the substrate height of H=0.795mm, dielectric constant of $\varepsilon_r = 2.2\ \varepsilon_0$ and variable length L1

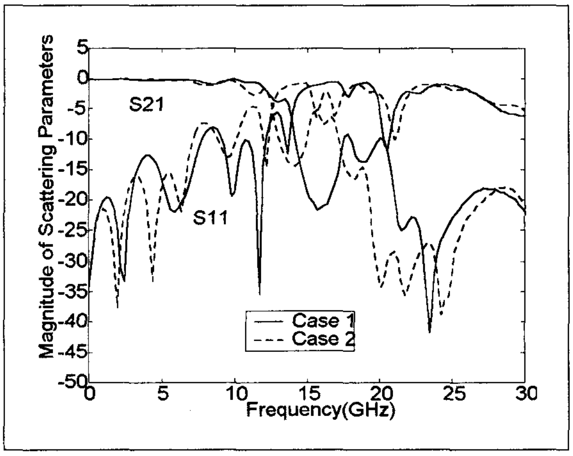
L2=12.7mm(32 $\Delta z$), and substrate thickness, h=0.795mm(3 $\Delta y$) and dielectric constants, $\varepsilon_r = 2.2\ \varepsilon_0$, shown in Figure 10 is considered.

Figure 11 shows the monitored voltages at the reference planes such as incident, incident and reflected, transmitted, and reflected waveforms.

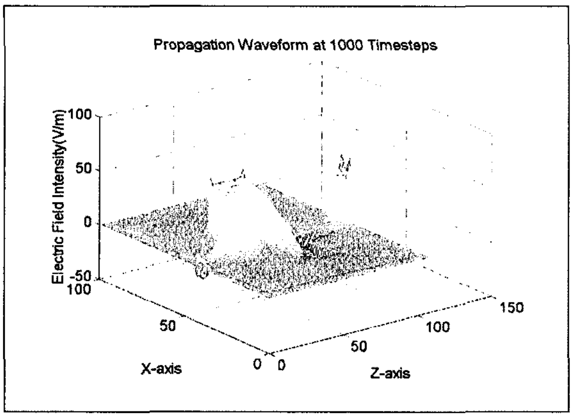
The result of scattering parameters for the two cases is found in Figure 12 and it is seen that as the frequency increases from 0 to approximately 10 GHz, the S11 paramter is increasing while S21 remains fairly flat for both cases. Above 10 GHz, S21 decreases rapidly. This is again due to the discontinuity introduced by the capacitance associated with the sharp corners of the racetrack. For higher frequencies where this becomes a problem, this capacitance can be reduced by mitering or rounding the corners of the racetrack. Also Figure 13 represents propagation of electric field waveform along z-direction at 1000 timesteps.




[Fig. 11] Magnitude of monitored voltages at the reference planes for the race-track delay line with the specification of W=2.438mm, L1=16.256, L2=12.7mm




[Fig. 12] Magnitude of scattering parameter S11 and S21 of the race-track delay line for the two different cases (Case 1 : W=2.438 mm, L1=12.7 mm, L2=16.256 mm. Case 2 : W=2.438 mm, L1=18.699mm, L2=16.256mm)

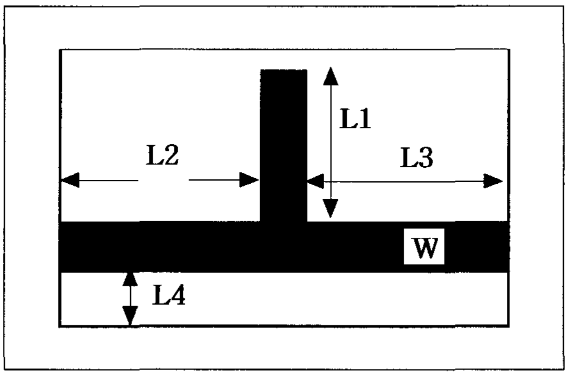



[Fig. 13] Electric field waveform along the z-axis at the 1000 timesteps for the race track delay line with the specfication of W=2.438mm, L1=16.256mm, L2=12.7mm.

### 3.4 SINGLE STUB FILTER

As the final example circuit, the shielded microstrip single stub filter structure is considered. The structure has been analyzed by G. Eleftheriades[10] using the method of moment(MoM). In this paper, we consider the same structure as adopted in[10] with the variable stub length L1 for the three cases(Case 1 : L1=13.8 mm, Case 2 : 18.4 mm, Case 3 : 23 mm) as shown in Figure 14 using the FDTD technique.

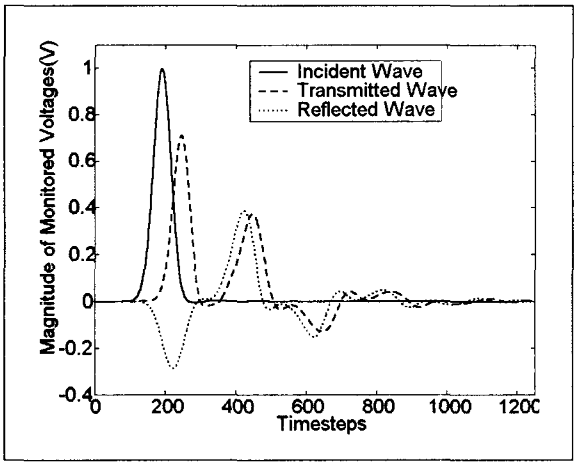
This corresponds to a conductor width of W=8 $\Delta x$, and variable stub lengths L1=24 $\Delta x$, 32 $\Delta x$, 40 $\Delta x$, substrate height of h=3 $\Delta y$. The entire computational domain including the PML (Perfectly Matched Layer) absorbing boundary conditions of 6 cells for each side is divided into 112 by 35 by 164 grid cells. A time step of $\Delta t$ =0.96 *ps* is used and the total number of time steps is 1800. The input is excited with a Gaussian pulse with T=34.2 *ps* and $t_0$=102.8 *ps*.



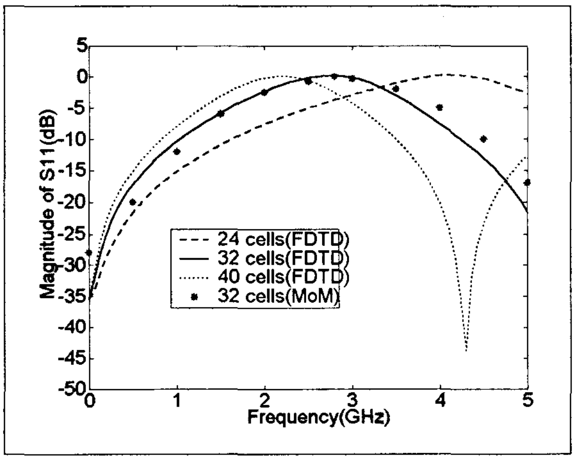

[Fig. 14] Single stug filter with the conductor width W=4.6mm, conductor length, L2=L3=41.4mm, L4=23mm, the substrate height of H=1.57mm, dielectric constant of $\varepsilon_r = 2.33\ \varepsilon_o$ , and variable stub length L1 (Case 1 : 13.8mm, Case 2 : 18.4mm, Case 3 : 23.0mm)

Figure 15 shows the monitored voltages such as incident, incident and reflected, transmitted, and reflected waveforms for the single stub filter at the reference planes. The results of scattering parameters S11 and S21 in dB scale for the three cases are found and compared to the result of moment method for 32 cell stub length in Figure 16 and 17. From the results, We can see that the two approaches have very good agreement but there are so small amount of differeces between the two methods for magnitude of the given structure. It may be due to the cell size of the FDTD grid as mentioned above. Thus the FDTD method should be very useful to analyze microstrip based discontinuity structure.

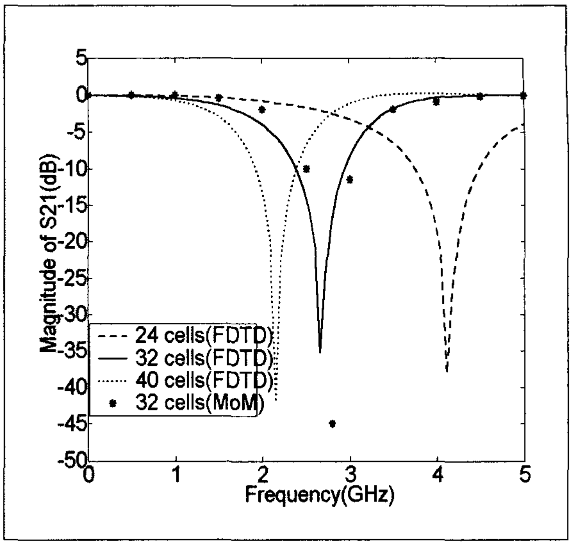
And Figure 18 represent the propagation waveform of electric field along z-direction at 400 timesteps.



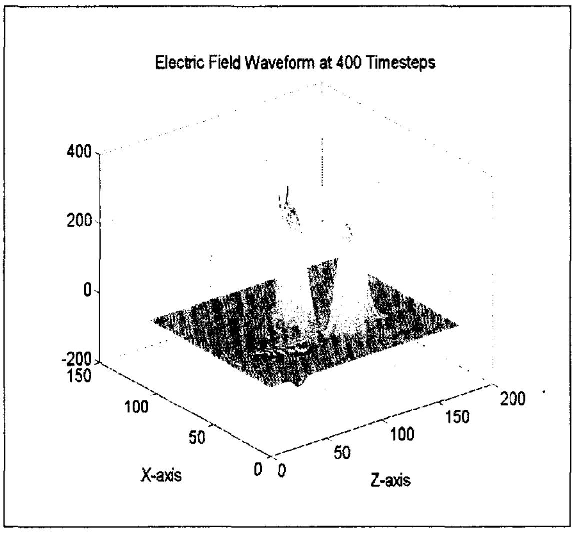

[Fig. 15] Magnitude of monitored voltages at the reference planes for the single stub filter with the specification of W=4.6mm, h=1.57mm, L1=18.4mm, L2=46.0mm, L3=46.0mm




[Fig. 16] Magnitude of scattering parameter S11 in dB scale for the single stub filter with conductor width W=2.438mm, and the variable stub lengths.




[Fig. 17] Magnitude of scattering parameter S21 in dB scale for the single stub filter with the variable stub lengths, L1=13.8mm(24 cells), 18.4mm(32 cells), 23.0mm(40 cells) for the fixed conductor width W=2.438mm




[Fig. 18] Electric field waveform along the z-axis at the 400 timesteps for the single stub filter with the specfication of W=2.438mm, L1=16.256mm, L2=12.7mm

## 4. CONCLUSION

Many researchers have been used frequency domain techniques for analysis of discontinuity structure. However, the FDTD method is very useful to get the scattering parameters for the discontinuity structure because we can easily get frequency-dependent scattering parameters over one time simulation.

In this paper, the FDTD method has been applied to accutrately model and find the scattering parameters for the microstrip based two port network such as cascaded step-in-width, racetrack delay line, and single stub filter of planar type discontinuity structure.

The result of the FDTD technique for frequency-dependent scattering parameters has been compared to the space-spectral domain method for the cascaded step-in-width and the method of moment for the single stub filter. For the cascaded step-in-width, two approaches show good agreement over the entire broadband frequency range excepting for the DC value and around low frequency. As we seen that the compared results between the methods are very good agreement for the three example structures. Thus, we can see that the FDTD technique is successfully applied to microstrip based various types of discontinuity structure to analyze. The scattering parameters for the mentioned discontinuity structures above show a frequency-dependence which would not be obtained with quasi-static methods.

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