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Signal Integrity Analysis of Modified Coplanar Waveguide Structure Using ADI-FDTD Method

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Abstract

Very Large Scale Integration (VLSI) technology shrinks to Deep Sub Micron (DSM) geometries, interconnect is becoming a limiting factor in determining circuit performance. High speed interconnect suffers from signal integrity effects like crosstalk, and propagation delay thereby degrading the entire system operation. In order to reduce the adverse signal integrity effects, if is necessary for the interconnect to have accurate physical dimensions. The interconnection and packaging related issues are main factors that determine the number of circuits that can be integrated in a chip as well as the chip performance. In this paper, it is proposed to simulate high speed interconnect structures using Alternate Direction Implicit Finite-Difference Time-Domain Method (ADI-FDTD) method. The electrical parameters such as mutual inductance and mutual capacitance were calculated from E and H fields for Coplanar waveguide (CPW) and Stacked Grounded Coplanar waveguide (SGCPW).

Keywords: Interconnects, ADI-FDTD Method, Coplanar Waveguide, Crosstalk and Signal Integrity

I.Introduction

Coplanar waveguides and slot lines are important planar transmission line in microwave and millimeter wave integrated circuits. In 1966, Yee proposed a technique to solve Maxwell's curl equations using the finite-difference time-domain (FDTD) technique. Yee's method has been used to solve numerous scattering problems on microwave circuits, dielectrics, and electromagnetic absorption in biological tissue at microwave frequencies. Since FDTD requires that the entire computational domain be gridded, and these grids must be small compared to the smallest wavelength. Models with long, thin features, (like wires) are difficult to model in FDTD because of the excessively large computational domain required. FDTD finds the E/H fields directly everywhere in the computational domain. However, as the traditional FDTD method is based on an explicit finite-difference algorithm, the Courant–Friedrich–Levy (CFL) condition must be satisfied when this method is used. Therefore, a maximum time-step size is limited by minimum cell size in a computational domain, which means that if an object of analysis has fine scale dimensions compared with wavelength, a small.

In this work, a new algorithm is proposed in order to eliminate the restraint of the CFL condition. This new algorithm is based on the alternating-direction implicit (ADI) method and is applied to the Yee's staggered cell to solve Maxwell's equation. The ADI method is known as the implicit-type finite-difference algorithm, which has the advantage of ensuring a more efficient formulation and calculation than other implicit methods in the case of multidimensional problems.

2. ADI-FDTD Method

2.1 Introduction

Finite Difference Time-Domain Method (FDTDM) is a popular electromagnetic modeling technique. It is easy to understand, easy to implement in software, and since it is a time-domain technique it can cover a wide frequency range with a single simulation run. In 1966, Yee proposed a technique to solve Maxwell's curl equations using the finite-difference time-domain (FDTD) technique. Yee's method has been used to solve numerous scattering problems on microwave circuits, dielectrics, and electromagnetic absorption in biological tissue at microwave frequencies. Since FDTD requires that the entire computational domain be gridded, and these grids must be small compared to the smallest wavelength and smaller than the smallest feature in the model, very large computational domains can be developed, which result in very long solution times. However, as the traditional FDTD method is based on an explicit finite-difference algorithm, the Courant–Friedrich–Levy (CFL) condition must be satisfied when this method is used. Therefore, a maximum time-step size is limited by minimum cell size in a computational domain, which means that if an object of analysis has fine scale dimensions compared with wavelength, a small time-step size creates a significant increase in calculation time. In this work, a new algorithm is proposed in order to eliminate the restraint of the CFL condition. This new algorithm is based on the alternating-direction implicit (ADI) method and is applied to the Yee's staggered cell to solve Maxwell's equation. The ADI method is known as the implicit-type finite-difference algorithm, which has the advantage of ensuring a more efficient formulation and calculation than other implicit methods in the case of multidimensional problems.

2.2 Numerical Formulation

The numerical formulation of the ADI FDTD method is presented in Equation (2.1)–(2.13). In order to simplify the problem, it is assumed that the medium in which the wave propagates is a vacuum. In addition, all cells in a computational domain have the same size. The electromagnetic-field components are arranged on the cells in the same way as that using the conventional FDTD method. The calculation for one discrete time step is performed using two procedures. The first procedure is based on Equation (2.1)–(2.6) and the second procedure is based on Equation (2.7)–(2.12).

2.2.1 First Procedure

$$\mathrm{Ex}(i+1/2,j,k) = \mathrm{Ca}(i+1/2,j,k).\,\mathrm{Ex}(i+1/2,j,k) + \mathrm{Cb}(i+1/2\ ,j,k)\ .[\{\mathrm{Hz}(i+1/1,j+1/2,k) - \mathrm{Hz}(i+1/2,j-1,k)\}/y(i) - \{\mathrm{Hy}(i+1/2,j,k+1/2) - \mathrm{Hy}(i+1/2,j,k-1/2)\}/z(k) \tag{2.1}$$

$$\mathrm{Ey}(i,j+1/2,k) = \mathrm{Ca}(i,j+1/2,k).\,\mathrm{Ey}(i,j+1/2,k) + \mathrm{Cb}(i\ ,j+1/2,k)\ .[\{\mathrm{Hx}(i,j+1/2,k+1/2) - \mathrm{Hx}(i,j+1/2,k-1/2)\}/z(k) - \{\mathrm{Hz}(i+1/2,j+1/2,k) - \mathrm{Hz}(i-1/2,j+1/2,k)\}/x(i) \tag{2.2}$$

$$\mathrm{Ez}(i,j,k+1/2) = \mathrm{Ca}\ (i,j,k+1/2.\,\mathrm{Ez}(i,j,k+1/2) + \mathrm{Cb}(i,j,k+1/2).[\{\mathrm{Hy}(i+1/2,j,k+1/2) - \mathrm{Hy}(i-1/2,j,k+1/2)\}/x(i) - \{\mathrm{Hx}(i,j+1/2,k+1/2) - \mathrm{Hx}(i,j+1.k-1/2)\}/y(i) \tag{2.3}$$

$$\mathrm{Hx}(i,j+1,k+1/2) = \mathrm{Hx}(i,j+1/2,k+1/2)\mathrm{Cb}(i,j+1/2,k+1/2).[\{\mathrm{Ey}(i,j+1/2,k+1) - \mathrm{Ey}((i,j+1/2,k)\}/z(k) - \{\mathrm{Ez}(i,j+1,k+1/2) - \mathrm{Ez}(i,j,k+1/2)\}y(i) \tag{2.4}$$

$$\mathrm{Hy}(i+1/2,j,k+1/2) = \mathrm{Hy}(i+1/2,j,k+1/2) + \mathrm{Db}\ (i+1/2,j,k+1/2).[\{\mathrm{Ez}\ (i+1,j,k+1/2) - \mathrm{Ez}\ (i,j,k+1/2)\}/x(i) - \{\mathrm{Ex}\ (i+1/2,j,k+1) - \mathrm{Ex}(i+1/2,j,k)\}/z(k) \tag{2.5}$$

$$\mathrm{Hz}(i+1/2,j+1/2,k) = \mathrm{Hz}(i+1/2,j+1/2,k) + \mathrm{Db}(i+1/2,j+1/2,k)^{\wedge\prime}\ [\{\mathrm{Ex}(i+1/2,j+1,k) - \mathrm{Ex}(i+1/2,j,k)/y(i) - \{\mathrm{Ey}(i+1,j+1/2,k) - \mathrm{Ey}(i,j+1/2,k)/x(i) \tag{2.6}$$

2.2.2 Second Procedure

$$\mathrm{Ex}(i+1/2,j,k) = \mathrm{Ca}(i+1/2,j,k).\,\mathrm{Ex}(i+1/2,j,k) + \mathrm{Cb}(i+1/2,j,k).[\{\mathrm{Hz}(i+1/2,j+1/2,k) - \mathrm{Hz}(i+1/2,j-1/2,k)/y(i) - \{\mathrm{Hy}(i+1/2,j,k) - \mathrm{Hy}(i+1/2,j,k-1/2)\}z(k) \tag{2.7}$$

$$\mathrm{Ey}(i,j+1/2,k) = \mathrm{Ca}(i,j+1/2,k).\,\mathrm{Ey}(i,j+1/2,k) + \mathrm{Cb}(i,j+1/2,k).[\{\mathrm{Hx}(i,j+1/2,k+1/2) - \mathrm{Hx}(i,j+1/2,k-1/2)\}/z(k) - \{\mathrm{Hz}(i+1/2,j+1/2,k) - \mathrm{Hz}(i-1/2,j+1/2,k)\}/x(i) \tag{2.8}$$

$$\mathrm{Ez}(i,j,k+1/2)\ \ \mathrm{Ca}(i,j,k+1/2).\mathrm{Ez}(i,j,k+1/2)\ \ .[\{\mathrm{Hy}(i=1/2,j,k+1/2)-\mathrm{Hy}(i-1/2,j,k+1/2)\}]/x(i)\ -\mathrm{Hx}(i,j+1/2,k+1/2)-\mathrm{Hx}(i,j-1/2,k-1/2)\}/y(i) \quad (2.9)$$

$$\mathrm{Hx}(i,j+1/2,k+1/2)=\mathrm{Hx}(i,j+1/2,k+1/2)+\mathrm{Db}(i,j+1/2,k+1/2).[\{\mathrm{Ey}(i,j+1/2,k+1)-\mathrm{Ey}(i,j+1/2,k)\}/z(k)\ -\{\mathrm{Ez}(i,j+1,k+1/2)-\mathrm{Ez}(i,j,k+1/2)\}/y(i) \quad (2.10)$$

$$\mathrm{Hy}(i+1/2,j,k+1/2)=\mathrm{Hy}(i+1/2,j,k+1/2)+\mathrm{Db}(i+1/2,j,k+1/2).[\{\mathrm{Ez}(i+1,j,k+1/2)-\mathrm{Ez}(i,j,k+1/2)\}/x(i)\ -\{\mathrm{Ex}(i+1/2,j,k+1)-\mathrm{Ex}(i+1/2,j,k)\}/z(k) \quad (2.11)$$

$$\mathrm{Hz}(i+1/2,j+1/2,k)=\mathrm{Hz}(i+1/2,j+1/2,k)+\ \mathrm{Db}(i+1/2,j+1/2,k).[\{\mathrm{Ex}(i+1/2,j+1,k)-\mathrm{Ex}(i+1/2,j+1,k)\}/y(i)\ -\{\mathrm{Ey}(i+1,j+1/2,k)-\mathrm{Ey}(i,j+1/2,k)\}/x(i) \quad (2.12)$$

where

$$\mathrm{Ca}(i,j,k)=2\varepsilon(i,j,k)-\sigma(i,j,k)\Delta t/2\varepsilon(i,j,k)\ +\sigma(i,j,k)\Delta t \quad (2.13)$$

$$\mathrm{Cb}(i,j,k)=2\Delta t/2\varepsilon(i,j,k)\ +\sigma(i,j,k)\Delta t \quad (2.14)$$

$$\mathrm{Db}(i,j,k)=\Delta t/\mu(i,j,k) \quad (2.15)$$

3. Proposed Structure

There are two loss mechanisms in the CPW structure. One is the signal line resistive loss and the other is the silicon substrate loss. In the low frequency range under 10GHz, the signal line resistive losses dominate. The electric (E) field for the CPW structure is distributed evenly on the top and the bottom of the signal line while that for the SGCPW structure there is a higher concentration on the bottom of the signal line. This increases the current crowding in the SGCPW structure to the bottom half of the signal line and hence increasing its effective resistance and the associated losses. On the other hand, substrate losses for the CPW structure increase with frequency such that at frequencies greater than 10GHz its loss is greater than for the GCPW structure. Coplanar waveguide (CPW), Stacked Grounded Coplanar Waveguide (SGCPW)

The S-GCPW structure was created by taking a CPW design and then filling in the other levels of metal in an elliptical arc. It is interesting to note that providing the additional metal layers does not substantially lower the characteristic impedance of the line. This is because the electric field for the GCPW structure is already spread between the coplanar ground lines and the bottom ground line. Dielectric substrate 1, which is below the central conductor, is of Droid with dielectric constant 2.2 and dielectric substrate 2, which is below the dielectric substrate 1, is of silicon with dielectric constant 4. So adding the additional metal layers does not perturb this field substantially. This assumption was validated via ADI FDTD simulations where the per unit capacitance for the GCPW structure is 4 pF while the per unit capacitance for the S-GCPW structure is 6 pF. Figure 1 and Figure 2 show the proposed structures. Table 1 gives the dimensions of SGCPW.

4. Results and Discussion

Numerical simulations are done using ADI-FDTD method. The parameters for simulations are shown in Table 2. Simulations are run in Pentium IV (3 GHz) processor. The signal applied has a frequency of 50 GHz. Time step for FDTD method is calculated using the equation

$$\Delta t_{FDTD}=\frac{\Delta X}{2\times c}$$

Where Δt_{FDTD} denotes time step in ordinary FDTD method.

$$\Delta t_{FDTD} = 0.0833\times 10^{-14} \text{ sec.}$$

For ADI FDTD method time step is taken as twice as that of normal FDTD method.

$$\Delta t_{ADI\text{-}FDTD} = 2 \times \Delta t_{FDTD} = 0.1666 \times 10^{-14} \text{ sec.}$$

Both ADI-FDTD and FDTD algorithms are used for simulating the CPW structure, simulation are run for 1500 iterations and CPU run time is compared.

Table 3 shows that CPU run time saved in analysis of CPW interconnect using ADI FDTD method is 77.4465 sec. So it is nearly 1.765 times faster than the traditional FDTD method.

The following are the ADI-FDTD simulation results for CPW and SGCPW. The result shows that for SGCPW electric and magnetic fields are more confined under the signal line as compared to the other structure (CPW). Simulations are run for 1500 iterations and results are given in Figure3 and Figure 4..

There is no much variation in inductance value between CPW and SGCPW. Since electric field is more confined for SGCPW, the value capacitance is slightly higher than CPW. As compared with CPW, SGCPW has low mutual inductance and mutual capacitance value. So crosstalk with the adjacent will be lesser for SGCPW. By comparing induced voltage and induced current for CPW and SGCPW it is found that SGCPW has lower value. So at higher frequencies SGCPW can be used for better performance.

5.Conclusion

This work introduces a new structure based on the ADI method. As this method is free from CFL condition restraint, it requires fewer computer resources, such as CPU time, if the minimum cell size in the computational domain is much smaller than the wavelength. Numerical simulation shows that the new method is very efficient, and the results agree very well with that of the conventional FDTD method. In this work the ADI- FDTD method this work provides low-loss transmission line structure that is crucial for such designs. As compared to all other structures SGCPW has low mutual inductance and mutual capacitance value. So cross talk with adjacent interconnects will be lesser for SGCPW.

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Table 1 Dimension of SGCPW

Layer	Dimension
M8,M7	1.2 µm
M6,M5	0.6 µm
M4-M1	0.3 µm
Dielectric thickness	7.8 µm
Dielectric constant	4
Substrate resistivity	15 ohm-cm

Table 2 CPU time comparison for FDTD and ADI FDTD

FDTD	ADI-FDTD
178.5790 sec	101.1325 sec

Table 3 Comparison of CPW and SGCPW

Parameters	**CPW**	**SGCPW**
Inductance	1.59 µH	1.58 µH
Capacitance	5 pF	7 pF
Mutual Inductance	0.1 nH	1 pH
Mutual Capacitance	$0.3\text{x}10^{-13}$ F	$0.2\text{x}10^{-16}$ F
Induced Voltage	2 mV	$0.6\text{x}10^{-5}$ V

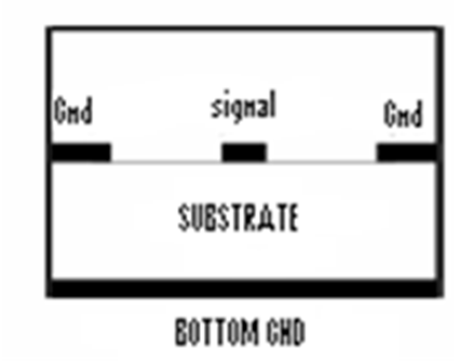

Figure 1. Grounded Coplanar Waveguide

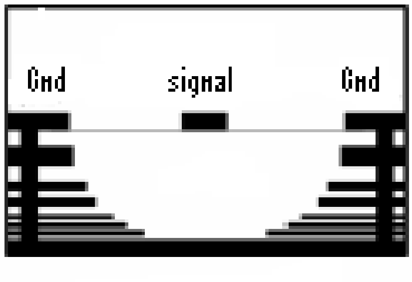

Figure 2. Stacked Grounded Coplanar Waveguide

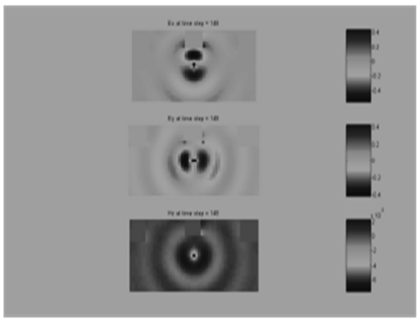

Figure 3. ADI FDTD simulation for CPW

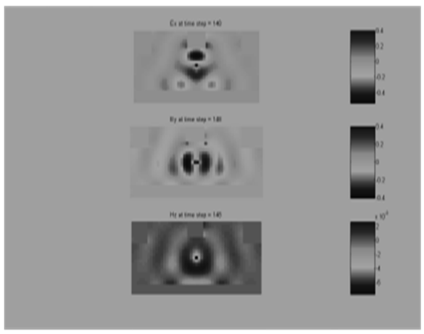

Figure 4 . ADI FDTD simulation for SG CPW

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