MODELING OF DISCONTINUITIES IN MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUITS USING THE CURVILINEAR FINITE DIFFERENCE TIME DOMAIN APPROACH

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ABSTRACT

In this paper we describe a full-wave approach based upon the curvilinear Finite Difference Time Domain (FDTD) algorithm for accurate modeling of discontinuities in microstrip lines that do not conform to the Cartesian coordinate system. The use of the curvilinear FDTD approach circumvents the staircasing problem that arises in the TLM method, as well as in the conventional FDTD approach based upon the Yee-grid, and, consequently, allows one to accurately model arbitrary geometries without the use of a very fine mesh. The scattering parameters of several representative discontinuities are calculated, and numerical results are compared to those available from microwave simulators such as TouchStone.

INTRODUCTION

The design of digital as well as microwave and millimeter wave integrated circuits requires accurate modeling of discontinuities for these circuits to perform correctly. More accurate modeling in the computer simulation design stages allows the circuit under design to be constructed with less prototyping, and this allows the design cycle time to be reduced. The reduction in time for a given design cycle is an extremely important and advantageous quality.

The use of full-wave, electromagnetic solution techniques provides the means for obtaining more accurate models for the types of circuit geometries and discontinuities encountered in present day integrated circuit design. A full-wave, electromagnetic field approach, for example, will account for all coupling mechanisms which may be present in a given geometry.

FORMULATION

The Finite Difference Time Domain (FDTD) [1] method is a robust, full-wave electromagnetic solution technique. The method is extremely useful for describing very general types of geometries because of the fact that material properties are associated with each cell (Fig. 1). The cells are used to piece together a representation of the geometry under consideration. Each cell may have a different property associated with it, and this feature allows for the description of very general geometries. In its original form, the FDTD method is written in Cartesian coordinates and the mesh is comprised of a uniform cell size (Fig. 1). In this form, Maxwell's equations are discretized in space and time to second order accuracy. The one major deficiency of this approach is its inability to accurately describe certain types of geometries because of the rectilinear nature of the grid.

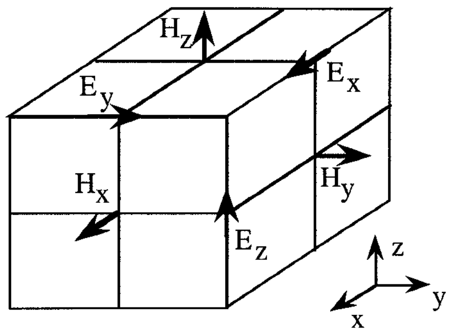

Figure 1. The Yee cell used in the uniform, Cartesian FDTD method. The individual electromagnetic field components are located at the positions shown on the cell.

For example, geometrical features which are curved or intersect at oblique angles cannot be modeled exactly and, instead, are handled by using a staircasing approximation. This undesirable feature can be overcome by writing Maxwell's equations in curvilinear coordinates [2-5], albeit at the expense of the discretized versions of these equations becoming slightly more complicated. Equation (1) shows the differential equation written in curvilinear coordinates which must be satisfied for the first polarization of the magnetic field.

$$\frac{\partial h^1}{\partial t} = \frac{1}{\mu\sqrt{g}}\left[\frac{\partial e_2}{\partial u^3} - \frac{\partial e_3}{\partial u^2}\right] \tag{1}$$

The two discretized equations for updating this magnetic field polarization on a generalized element (Fig. 2) are given by

$$h^1(i,j,k)^{n+\frac{1}{2}} = h^1(i,j,k)^{n-\frac{1}{2}} - \frac{\Delta t}{\mu\sqrt{g}}\Big[e_2(i,j,k-\tfrac{1}{2})^n - e_2(i,j,k+\tfrac{1}{2})^n - e_3(i,j-\tfrac{1}{2},k)^n + e_3(i,j+\tfrac{1}{2},k)^n\Big] \tag{2}$$

$$\begin{aligned} h_1(i,j,k) = g_{11}h^1(i,j,k) + \frac{g_{12}}{4}\Big[&h^2(i-\tfrac{1}{2},j-\tfrac{1}{2},k) + h^2(i-\tfrac{1}{2},j+\tfrac{1}{2},k) + h^2(i+\tfrac{1}{2},j-\tfrac{1}{2},k) \\ &+ h^2(i+\tfrac{1}{2},j+\tfrac{1}{2},k)\Big] + \frac{g_{13}}{4}\Big[h^3(i-\tfrac{1}{2},j,k-\tfrac{1}{2}) \\ &+ h^3(i-\tfrac{1}{2},j,k+\tfrac{1}{2}) + h^3(i+\tfrac{1}{2},j,k-\tfrac{1}{2}) + h^3(i+\tfrac{1}{2},j,k+\tfrac{1}{2})\Big] \end{aligned} \tag{3}$$

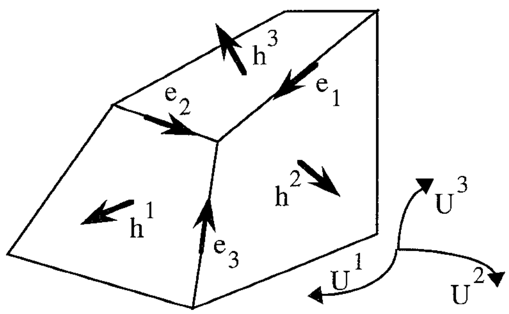

Figure 2. The generalized, nonorthogonal cell used in conjunction with the curvilinear FDTD method. The cell is hexahedral. Superscripts refer to contravariant components and subscripts refer to covariant components.

where the notation followed is the same as in [5]. The primary difficulty encountered when writing Maxwell's equations in a generalized coordinate system is the requirement that the fields represented on a hexahedral brick must be decomposed using two sets of base vectors. The generalized mesh element in this case is a hexahedron, and the face normal is in general not collinear with the direction of the edge that intersects through the face. The base vectors are known as the covariant (or unitary) and contravariant (or reciprocal unitary) base vectors. The covariant field components lie along the edges of the hexahedral element, while the contravariant field components are normal to the faces of the hexahedral elements. In one time step, the contravariant magnetic (electric) field polarization is updated in time because Maxwell's equations relate the time rate of change of the magnetic (electric) flux passing through the surface to the circulation of the electric (magnetic) field enclosing that surface. Before the dual fields can be updated in the next half-time step, these contravariant field components must be converted to the covariant form. Equation (3) listed above accomplishes this task. The *g's* shown in the equations above are the metric quantities associated with the grid. These quantities are calculated from the Cartesian coordinates of the nodes in the mesh. The most important aspect to the generalized Maxwell equation solver given in the form above is the quality that second-order accuracy in both time and space is preserved through the use of the metric quantities. This means that the curvilinear FDTD is as accurate in its discretized form as the original Cartesian, uniform FDTD. This important feature is not preserved in several of the FDTD algorithms on nonorthogonal grids, and, consequently these approaches are neither as accurate nor stable as the present method.

NUMERICAL RESULTS

The microstrip bend problems chosen for analysis are shown in Fig. 3 and Fig. 4. The double 90-degree bend problem was chosen to test the algorithm as well as provide a comparison to the double 45-degree bend problem. The meshes which were generated for the two geometries are shown in Fig. 5 and Fig. 6. The actual meshes used in the FDTD simulation are more dense than those shown in the figures. These meshes were generated using a CAD/CAE tool known as Patran [6].

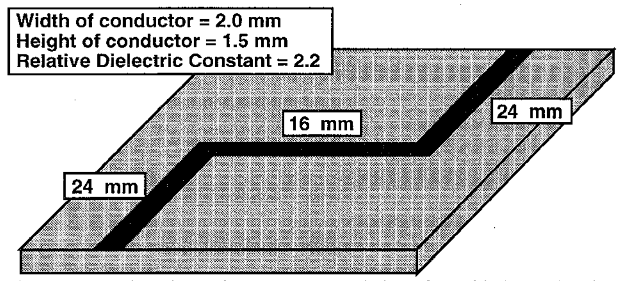

Figure 3. The microstrip geometry consisting of two 90-degree bends.

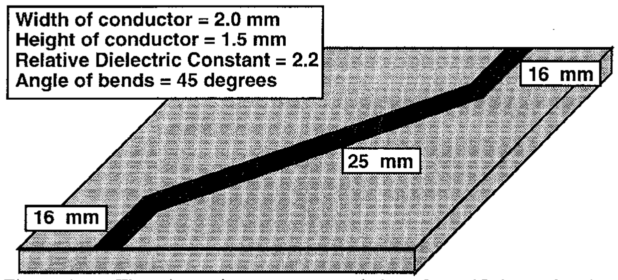

Figure 4. The microstrip geometry consisting of two 45-degree bends.

Patran is a commercially available mesh generator which has been used extensively for the generation of problem geometries and the corresponding meshes in the finite element solution technique. The major challenge to be addressed in using Patran is the development of a translator program which takes the mesh information available from Patran and

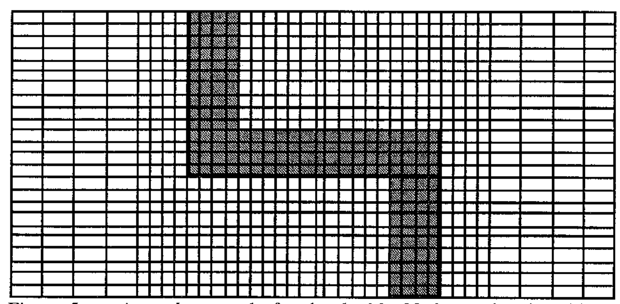

Figure 5. A mesh example for the double 90-degree bend problem. The main characteristic to note is the nonuniformity of the mesh in the regions away from the microstrip conductor.

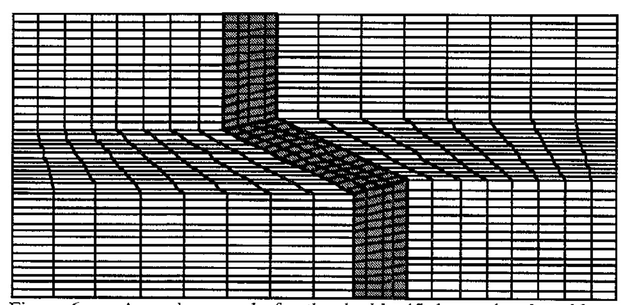

Figure 6. A mesh example for the double 45-degree bend problem. The main characteristic to note is the conformity of the mesh to the geometry. No staircasing, as would be required for a uniform, Cartesian FDTD analysis, is used.

reconfigures this information to create a structured, regular mesh.

The microstrip lines in each case were excited by assigning incident values to the electric field under the strip and allowing sufficient distance between the excitation plane and the input port for the characteristic microstrip modal pattern to be achieved. The time domain excitation had a Gaussian profile with a 3-dB frequency of 35 GHz. The boundaries for the computation were terminated using a combination of first and second-order Mur absorbing boundary conditions [7]. The second-order Mur condition was used on the top wall, and the first-order Mur was used on the four side walls. The bottom wall is, of course, a perfect electric conductor.

The output quantities of interest are the voltage at the input and output ports and the associated scattering parameters. The voltage is easily found by integrating the electric field between the strip and the ground plane. Fig. 7 shows the voltage at the input and output ports for the double 90-degree bend problem. The observed reflections from the first bend and then the second bend are readily seen in the time domain voltage waveforms. Fig. 8 shows the time domain voltage waveform at the input and output ports for the double 45-degree bend problem. The observed reflections are much smaller for this case when compared with the double 90-degree problem. The scattering parameters are found by taking the Fourier transform of the incident, reflected, and transmitted time domain waveforms. The scattering parameters for the geometries are shown in Figs. 9, 10, 11, and 12. For comparison, the results are compared with TouchStone [8]. The comparison with TouchStone results is extremely good at low frequencies. The TouchStone model for the microstrip bends is applicable only to about 14 GHz, therefore the curvilinear FDTD is useful in predicting the response at higher frequencies. Other effects such as radiation are also accounted for in the FDTD algorithm, while not being included in the TouchStone models. Finally, the curvilinear FDTD algorithm is very well suited for a host of other geometries which have been handled in the past by using the staircasing approach.

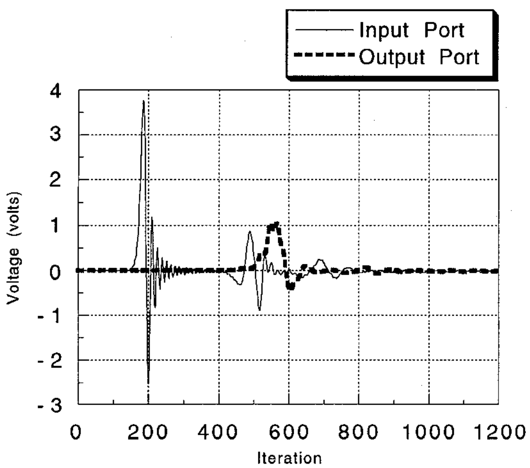

Figure 7. The time domain FDTD voltage waveforms for the double 90-degree bend problem at the input and output ports.

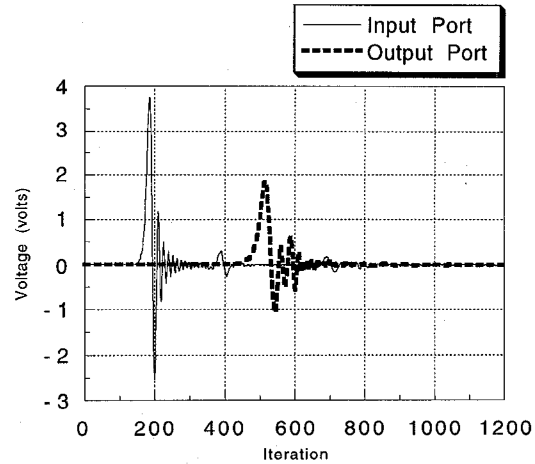

Figure 8. The time domain FDTD voltage waveforms for the double 45-degree bend problem at the input and output ports.

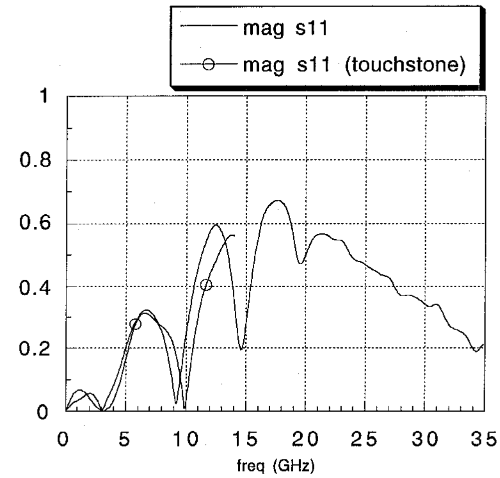

Figure 9. The magnitude of the scattering parameter S_{11} for the double 90-degree bend problem. The numerical results from the nonuniform FDTD simulation are compared to results from the RF/microwave simulator TouchStone.

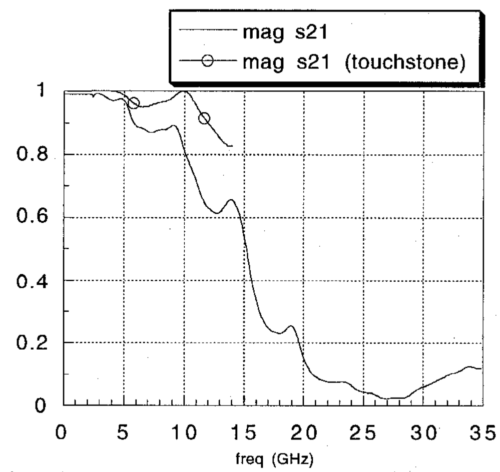

Figure 10. The magnitude of the scattering parameter S_{21} for the double 90-degree bend problem. The numerical results from the nonuniform FDTD simulation are compared to results from the RF/microwave simulator TouchStone.

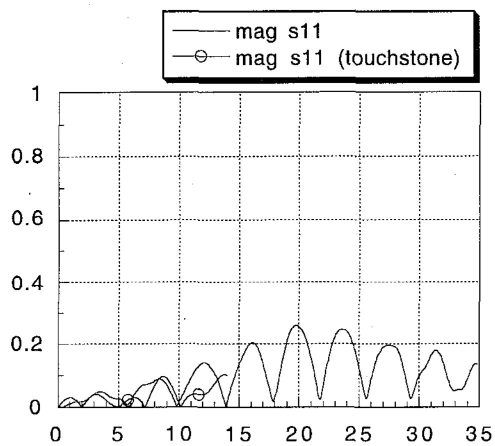

Figure 11. The magnitude of the scattering parameter S_{11} for the double 45-degree bend problem. The numerical results from the curvilinear FDTD simulation are compared to results from the RF/microwave simulator TouchStone.

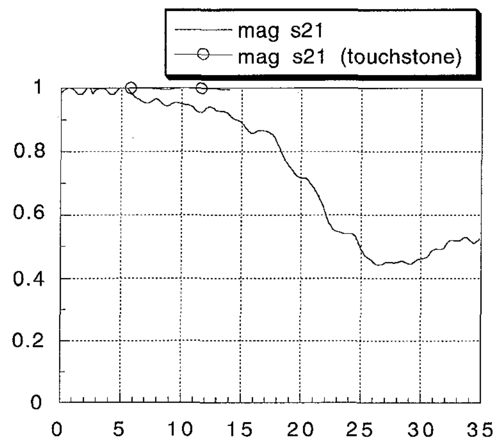

Figure 12. The magnitude of the scattering parameter S_{21} for the double 45-degree bend problem. The numerical results from the curvilinear FDTD simulation are compared to results from the RF/microwave simulator TouchStone.

CONCLUSIONS

In this paper, the curvilinear Finite Difference Time Domain method has been described and applied to the electromagnetic modeling of discontinuities in integrated circuit design. The curvilinear FDTD approach is necessary for the more accurate description of geometrical features which are curved or involve oblique angles. The curvilinear FDTD method is more accurate than other proposed FDTD approaches on nonorthogonal grids, and this superior accuracy is accomplished by transforming Maxwell's equations from curvilinear space into a regular, rectilinear domain. In this way, the curvilinear FDTD is then similar to the usual Cartesian form of the FDTD method. The need for staircasing approximations to the geometry at hand is eliminated in this approach, and therefore the actual geometry is more accurately described. Subsequently, this will lead to a more accurate electromagnetic solution for the problem.

REFERENCES

[1] A. Taflove and K.R. Umashankar, "The finite-difference time-domain method for numerical modeling of electromagnetic wave interactions," *Electromagnetics,* vol. 10, pp. 105-126, 1990.

[2] R. Holland, "Finite difference solutions of Maxwell's equations in generalized nonorthogonal coordinates," *IEEE Trans. Nuc. Sci.,* vol. NS-30, no. 6, pp. 4689-4591, Dec. 1983.

[3] M. Fusco, "FDTD algorithm in curvilinear coordinates," *IEEE Trans. Antennas Propagat.,* vol. AP-38, no. 1, pp. 76-89, Jan. 1990.

[4] M. Fusco, M.V. Smith, and L.W. Gordon, "A three-dimensional FDTD algorithm in curvilinear coordinates," *IEEE Trans. Antennas Propagat.,* vol. AP-39, no. 10, pp. 1463-1471, Oct. 1991.

[5] J.F. Lee, R. Palandech, and R. Mittra, "Modeling three-dimensional waveguide discontinuities using FDTD algorithm in curvilinear coordinate system," *IEEE Trans. Microwave Theory Tech.,* vol. 40, no. 2, pp. 346-352, Feb. 1992.

[6] Patran, PDA Engineering, 2975 Redhill Avenue, Costa Mesa, CA, 92626.

[7] G. Mur, "Absorbing boundary conditions for the finite-difference approximation of the time-domain electromagnetic field equations," *IEEE Trans. Electromagn. Compat.,* vol. EMC-23, no. 11, pp. 377-382, Nov. 1981.

[8] TouchStone, EEsof, Inc., 5795 Lindero Canyon Rd., Westlake Village, CA, 91362.