Analysis of Planar Circuits with a Combined 3D FDTD-Time Domain Modal Expansion Method

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Abstract

A method combining the conventional 3D FDTD algorithm with the time domain modal expansion has been applied to the analysis of planar circuits enclosed within metallic packages. This method allows for the reduction of the 3D FDTD computational domain to a restricted region close to the planar circuit. This technique has been applied to two different structures: a microstrip and a CPW discontinuity. The results show a significant improvement of the computational efficiency without any appreciable degradation of the accuracy.

1. Introduction

Since its appearance in 1966 [1], the Finite Difference Time Domain (FDTD) method has been extensively applied to the analysis and characterization of discontinuities in planar structures. First, Koike et al. analyzed a microstrip gap [2], then, Zhang et al. [3] characterized a microstrip open circuit, later, Liang et al. adopted the FDTD method to characterize Coplanar Waveguide (CPW) discontinuities [4]. Later the method has been used to simulate many kinds of planar circuits and their interaction with the package and interconnects [5-9].

Recently, a new technique has been proposed to improve the efficiency of the original FDTD method to treat waveguide discontinuity problems [10-14]. This method is based on the combination of the 3D FDTD with the time domain eigenfunction expansion of the electromagnetic field. Mrozowski et al. proposed to adopt this technique also for the 2D analysis of Microwave Monolithic Integrated Circuits (MMIC) [15]. In the present contribution, the method [14] has been adapted to the simulation of a three dimensional planar structures such as CPW and microstrip discontinuities. The method has been compared with experiments and with the conventional 3D FDTD method. The results obtained show a significant improvement of the original computational efficiency, without any appreciable degradation of the accuracy.

2. The Method

A detailed description of the method is given in [14]. Here the method is briefly outlined. Consider a planar circuit enclosed in a metallic box, Fig. 1.

Along the direction perpendicular to the metallization plane (z direction of Fig. 1) the structure is seen as the cascade of regular and irregular regions. The former (zones A and C in Fig. 1) are the uniform waveguides corresponding to the empty parts of the metallic box above and below the planar circuit. The latter (zone B in Fig. 1) includes the feeding coaxial connectors and the planar circuit itself. The Electromagnetic (EM) field into the irregular region is evaluated by using the conventional 3D FDTD algorithm and a unidirectional graded mesh [16]. The uniform regions are modeled, in time domain, by means of transmission lines representing the waveguide modes. Each modal voltage (V_n in formula 1) satisfies the following wave equation:

$$\frac{\partial^2 V_n}{\partial z^2} - \frac{1}{c_0^2}\frac{\partial^2 V_n}{\partial t^2} - k_{cn}^2 V_n = 0 \quad (1)$$

where k_{cn} is the eigenvalue of the waveguide mode of order n. This equation is solved adopting a 1D centered difference scheme, thus leading to:

$$V_{n,k}^{t+1} = \frac{c_0^2 \Delta t^2}{\Delta z^2}\left(V_{n,k+1}^{t} - 2V_{n,k}^{t} + V_{n,k-1}^{t}\right) - c_0^2 \Delta t^2 k_{cn}^2 V_{n,k}^{t} + 2V_{n,k}^{t} - V_{n,k}^{t-1} \quad (2)$$

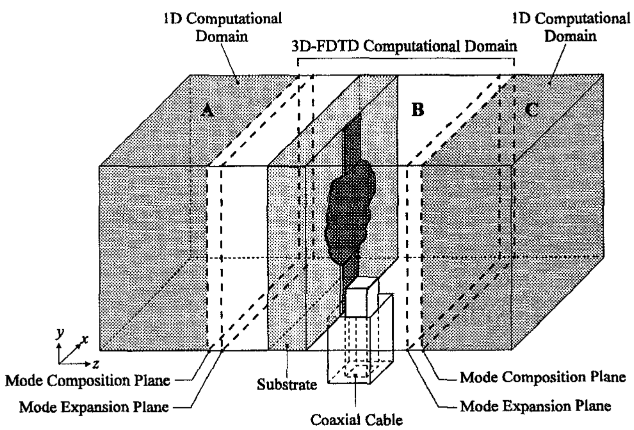

Fig. 1. Arbitrary planar circuit including feeding coaxial connector. The circuit is enclosed within a metallic box.

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In this manner the complexity of the problem is reduced from 3D to 1D, thus resulting in a computational saving. Since the algorithm is marching in time, at each step the transmission lines are interfaced with the 3D FDTD computational domain (Fig. 1).

First, the modal voltages are computed by taking the scalar product of the waveguide eigenvectors with the transverse electric field over the mode expansion plane (Fig. 1).

Second, the transverse electric field over the mode composition plane in (Fig. 1) is evaluated as a superposition of waveguide modes. These two steps provide all boundary conditions for the 3D domain. For the 1D domain the modal lines are to be shorted.

3. Description of the structures

The method has been applied to two different planar circuits using microstrip and CPW technologies. The structures analyzed consist of a microstrip via-hole and a double step in coplanar waveguide. Both include the package and the feeding coaxial lines. The feeding lines have been approximated as 50 Ω coaxial lines with square cross section (not shown in figures).

Fig. 2 shows the sketch of the microstrip via-hole. For simplicity, the section of the via-hole has been approximated with a square shape [7, 17].

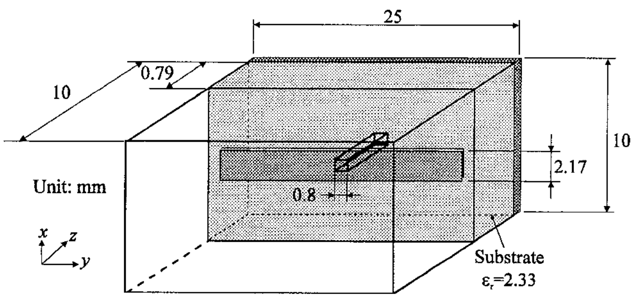

Fig. 2. Sketch of the microstrip via-hole.

The microstrip circuit has been enclosed into a package, the dimension being 10×25×10 mm. This package exhibits a first resonant frequency around 15 GHz [7]. The structure has been excited by a gaussian pulse with the 95% of the power within the band 0-14 GHz. The exciting field pattern, (fundamental mode) has been calculated numerically by performing an FDTD simulation of the uniform coaxial line [5]. In order to allow for an easy separation between the reflected and the incident pulse, a length of 32 mm has been adopted for the input cable. For the output cable, only 10 mm has been used. This length is sufficient for the higher order modes, excited at the microstrip-connector transition, to vanish. The entire structure has been simulated using a variable mesh [16, 18] of 25×81×32 cells.

Fig. 3 shows the sketch of the CPW double step. In this case the package has a dimension of 3.1×30×17.1 mm. the feeding coaxial lines are 50 and 10 mm long respectively and the entire structure has been discretized with 31×110×41 cells. The 95% of the power of the exciting pulse is within the band 0-8 GHz.

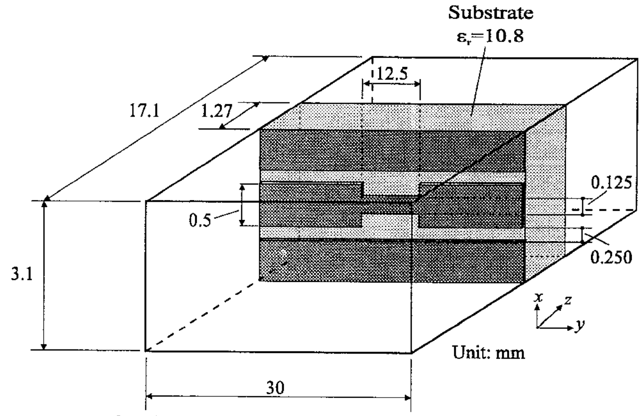

Fig. 3. Sketch of coplanar waveguide double step.

4. Results

The combined method requires the precomputation of the correct number of modes necessary for the description of the EM field at the interface planes. To evaluate this parameter we have taken into account all the propagating modes plus the evanescent modes whose magnitude is reduced by less than 10 times. The number of modes stated by this conservative criterion can be often reduced when information about the field scattered by the discontinuity is available [13]. In order to simulate the via hole, 10 modes are sufficient. Table 1 summarizes the dimensions, the computing time and the speed-up factor with respect to the conventional FDTD, obtained for this simulation.

In this case, the mesh has been reduced by about a factor 2, and, since the number of modes is quite low, the computational costs of the 1D-3D interface and of the 1D field evaluation is negligible. This is pointed out by Table 1.

MICROSTRIP VIA-HOLE				
Method	Dimensions N_x*N_y*N_z	Number of Modes	Time [sec]	Speed-up
FDTD	25*81*32	****	2540	****
FDTD + Modes	25*81*17	10	1243	2.06

Table 1. CPU time (HP 735 WS) and Speed-up factors for the microstrip via-hole.

Table 2 summarizes the results obtained simulating the second structure. In this case the reduction of the mesh is only about one fourth. Moreover, a higher number of modes and two interface regions were required.

Fig. 4 shows the insertion loss of the via hole over the whole operating frequency range of the package. The agreement between the combined approach and the full 3D

FDTD method is less than ± 0.5 dB of error, thus proving the validity of the method adopted.

COPLANAR WAVEGUIDE STEP				
Method	**Dimensions $N_x*N_y*N_z$**	**Number of Modes**	**Time [sec])**	**Speed-up**
FDTD	31*110*41	****	9768	****
FDTD + Modes	31*110*30	28	8262	1.18
FDTD + Modes	31*110*30	16	7491	1.30

Table 2. CPU time (HP 735 WS) and Speed-up factors for the CPW step.

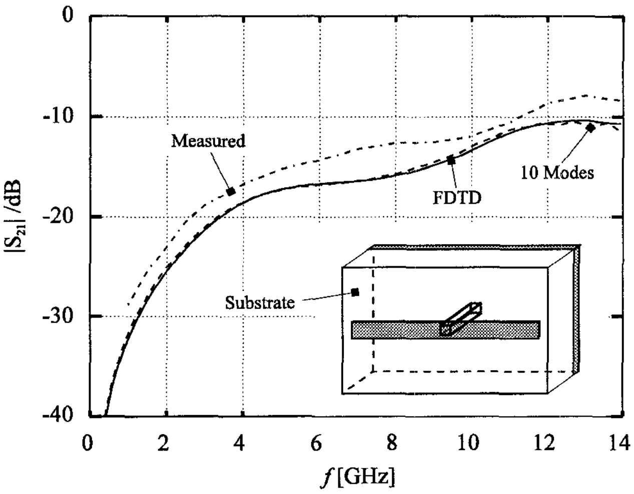

Fig. 4. Theoretical and experimental results for the $|S_{21}|$ of the microstrip via-hole.

The slight underestimation of the insertion loss with respect to the measurement has to be ascribed mainly to lossless structure assumption.

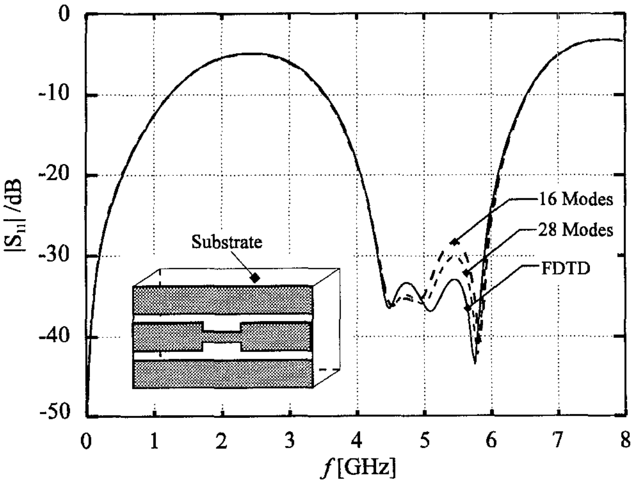

Fig. 5 $|S_{11}|$ of the CPW step. Comparison among conventional FDTD and FDTD+Modal expansion.

Fig. 5, shows the results obtained for the CPW double step. In this case, 16 and 28 modes have been adopted to evaluate the EM field at the interface planes.

All simulations coincide over most of the frequency spectrum, except within the notch. Note, however, that, increasing the number of modes leads to the convergence of the results to the 3D FDTD case.

4. Conclusions

A method combining 3D FDTD with the time domain modal expansion of the EM field has been successfully applied to the simulation of a microstrip via hole and a CPW double step. The analyses have taken simultaneously into account for the influence of the package and interconnections. The obtained results demonstrate an improvement of the computational efficiency with respect to the conventional 3D FDTD approach. Computational cost reduction by a factor 1.18 (CPW double step) and 2.06 (microstrip via hole) have been obtained.

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References

[1] K. S. Yee, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media," in IEEE Trans. AP, Vol. 14, pp. 302-307, May 1966.

[2] S. Koike, N. Yoshida, I. Fukai, "Transient Analysis of Microstrip Gap in Three-Dimensional Space," in IEEE trans. MTT, Vol. 33, No. 8, pp. 726-730, Aug. 1985.

[3] X. Zhang, J. Fang and K. Mei, "Calculation of the Dispersive Characteristics of Microstrips by Time-Domain Finite Differencers Method," in IEEE trans. MTT, Vol. 36, No. 12, pp. 1775-1787, Dec. 1988.

[4] G. Liang, Y. Liu and K. Mei "Full-Wave Analysis of Coplanar Waveguide and Slot-Line Using the Time-Domain Finite-Difference Method," in IEEE trans. MTT, Vol. 37, No. 12, pp. 1949-1957, Dec. 1989.

[5] M. Rittweger and I. Wolf, "Analysis of Complex Passive (M)MIC-Components Using the Finite Difference Time-Domain Approach," IEEE MTT-S Digest, pp. 1147-1150, 1990.

[6] M. Rittweger, M. Abdo and I. Wolf, "Full-Wave Analysis of Coplanar Discontinuities Considering

Three-Dimensional Bond Wires," IEEE MTT-S Digest, pp. 465-468, 1991.

[7] P. Mezzanotte, M. Mongiardo, L. Roselli and R. Sorrentino, W. Heinrich, "Analysis of Packaged Microwave Integrated Circuits by FDTD," IEEE trans. MTT, Vol. 42, No. 9, pp. 1796-1801, Sep. 1994.

[8] P. Mezzanotte, M. Mongiardo, L. Roselli and R. Sorrentino, "FDTD Analysis of High Performance MMIC Package," IEEE. MTT intl. S. Digest, Vol. 1, pp. 337-340, May 23-27 1994, S. Diego, CA.

[9] P. Mezzanotte, G. Pompei, L. Roselli, R. Sorrentino, "FD-TD Analysis of Coplanar Wave Guide to Slot Line Transitions Accounting for Air-Bridge, Shielding Effects and Coaxial Connectors," Eu.M.C. 94 Digest, Vol. 2, pp. 1929-1932, Sep. 5-8 1994, Cannes, F.

[10] M.Mrozowski, "Eigenfunction Expansion Techniques in the Numerical Analysis of Inhomogeneously Loaded Waveguides and Resonator," Zeszyty Naukowe Politechniki Gdanskiej, Nr 512, Elektronika 81, Gdansk, Poland, 1994.

[11] M.Mrozowski, "A Hybrid PEE-FDTD Algorithm for Accelerated Time Domain Analysis of Electromagnetic Waves in Shielded Structures," IEEE MGWL, Vol. 4, No. 10, pp. 323-325, Oct. 1994.

[12] H. Wolter, M. Dohlus and T. Weiland, "Broadband Calculation of Scattering Parameters in Time Domain," IEEE Trans. AP, Vol. 30, No. 5, pp. 3164-3167, Sep. 1994.

[13] F. Alimenti, P. Mezzanotte, L. Roselli, R. Sorrentino, "On the Analysis of Multiple Waveguide Discontinuities by Combined 1D-3D FDTD Method," Proc. 25th European Microwave Conference, pp. 449-452, Sep. 1995, Bologna, Italy.

[14] F. Alimenti, P. Mezzanotte, L. Roselli, R. Sorrentino, "Efficient Analysis of Waveguide Components by FDTD Combined with Time Domain Modal Expansion," IEEE MGWL, Vol. 5, No. 10, pp. 351-353, Oct. 1995.

[15] M.Mrozowski and M. Okoniewski, "Accelerated Vector Wave Equation Algorithm for the Time Domain Analysis of Guided Wave Problems in MMICs," Proc. of PIERS, page 177, July 1995.

[16] D. H. Choi and W. J. R. Hoefer, "A Graded Mesh FD-TD Algorithm for Eigenvalue Problems", Proc. 17th Eu.M.C. pp. 413-417, Rome 1987.

[17] R. Sorrentino, F. Alessandri, M. Mongiardo, A. Avitabile, L. Roselli, "Full-Wave Modeling of Via Hole Grounds in Microstrip by Three-Dimensional Mode Matching Technique," IEEE trans. MTT, Vol. 40, No. 12, pp. 2228-2234, Dec. 1992.

[18] P. Mezzanotte, L. Roselli, Huber, W. Heinrich, "On the accuracy of the Finite-Difference Method using Mesh Grading," IEEE MTT-S Digest, pp. 781-784, May 14-19 1995, Orlando, Fl.