Time-Domain Finite Difference Approach for the Calculation of Microstrip Open-Circuit End Effect

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Abstract

The frequency-dependant characteristics of the microstrip open-end has been analysed using several full-wave approaches [1-5]. The time-domain finite difference (TD-FD) method presented in this paper is another independant approach, which is ralatively new in its application to obtain the frequency domain results [6]. The purpose of this paper is to establish the validity of the TD-FD method in modeling circuit components for MMIC-CAD applications.

Introduction

The frequency-dependant scattering matrix or equivalent circuit of a microstrip open-end has been calculated by the mode matching technique [1], spectral-domain method [2-3] and the moment method [4-5]. Recently, the time-domain finite difference (TD-FD) method has been shown to be yet another interesting alternative to calculate the microstrip system [6]. The TD-FD method has definite advantage over the frequency-domain methods when a broad band of information is sought, in that the result for the whole frequency range can be obtained with a single time-domain calculation, followed by the Fourier transform. Also, since the time-domain approach uses no approximation other than the numerical discretization, it can be regarded as an accurate full-wave method once the absorbing boundary condition is properly treated.

Numerical Approach

The time-domain finite difference method was first introduced in the 1960's [7] to solve electromagnetic scattering problems. In applying 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 in a leap-frog time marching manner once the initial and boundary conditions are specified. More details of the method can be found in [6,7].

Fig.1 shows the finite difference computation domain for this problem (because of the symmetry of the problem, only half of the structure is considered). On the front surface, excitation field is specified. In this case, it is a Gaussian pulse in time uniformly applied under the strip. The center plane has even-symmetric or magnetic-wall boundary condition. The bottom plane is a perfect conductor.

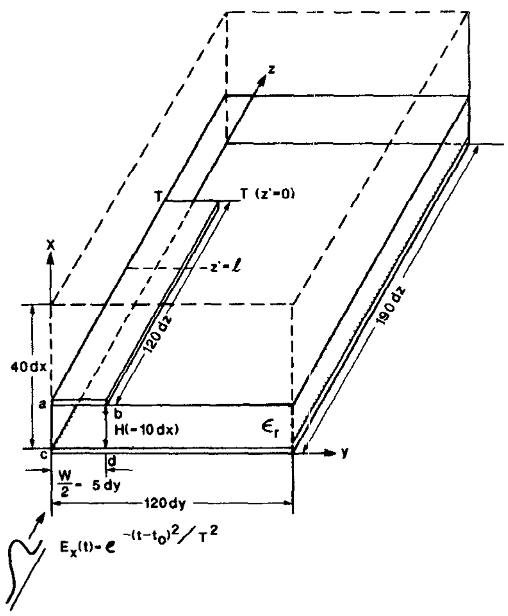

Figure 1. Microstrip Open-End Terminations (W=H=0.6mm, ε_r = 9.6, dh=H/10, dt=0.515 dh/c, t_0 = 350 dt, T = 40 dt)

On the other three surfaces or boundary planes of the computation domain, which are used to terminate the numerical calculation to accomodate the limited computer memories, a free space or "transparant" plane has to be simulated. This kind of boundary condition is the so called "artifitial absorbing boundary condition".

The treatment of the absorbing boundary is one of the most important (also the most difficult) problems in the calculation of microstrip related structures. It was found that the frequency domain data obtained from the Fourier transform of the time-domain fields are very sensitive to time domain errors, especially those due to the imperfect treatment of the absorbing boundary conditions [6]. The presently available local absorbing boundary conditions are mostly not good enough for the purpose of this work, due to the reason stated above. To improve the quality of the absorbing boundary condition, a new approach based on the " local cancelation of leading order error " has been developed in the practice. The details of this boundary algorithm can be found in [8], [9].

The treatment of the front surface is another important issue. During the time when the Gaussian pulse is excited, under the strip on plane "abcd" of Fig.1, the vertical electric field is enforced of the value of the pulse. Elsewhere on front surface the electric fields are specified to be zero. This is equivalent to a electric-wall boundary condition. After the pulse has been send out and part of it been reflected back from the open-end, the front surface should now behave "transparent" like what it is in the real case. That means, from the moment the reflected wave reach the front surface an absorbing type of boundary condition must be "switched on". But, through checking the calculated field values, it is found that the early enforced electric-wall boundary condition induced a DC current or tangential magnetic field on the front surface and near-by (Fig.2). This local DC field, though has no influence on the traveling pulse, does cause trouble in the boundary treatment. That is, if we switch on the radiation condition just on the front wall the numerical errors will accumulate very fast and and the solutions soon "blow up". To solve this problem, what actually has been done is that after the pulse leave the source region and before it is reflected back from the open-end, switch on the radiation boundary condition on a surface which is parallel to the front surface but a few space steps away from it, thus avoided the trouble caused by the DC current.

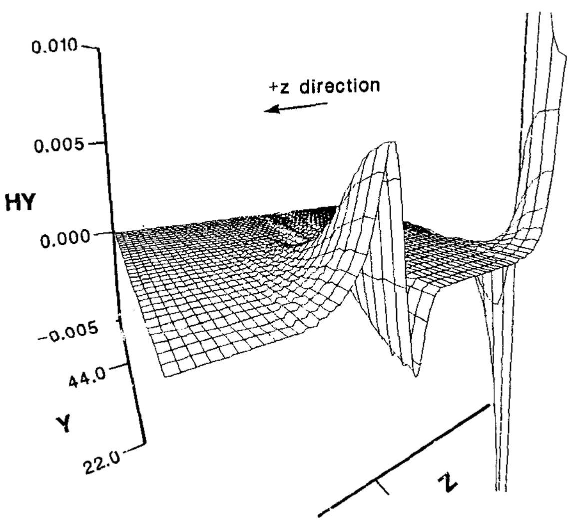

Figure 2. DC Magnetic Field on the Front Surface Due to the Electric Wall Boundary Treatment

Numerical Results

With the new boundary treatment and large enough computation domain, a microstrip open-end on an Alumina substrate ($\varepsilon_r = 9.6$) as shown in Fig. 1. is studied. Fig. 3 shows the time domain field (Ex component) inside a microstrip open-end. The plane where

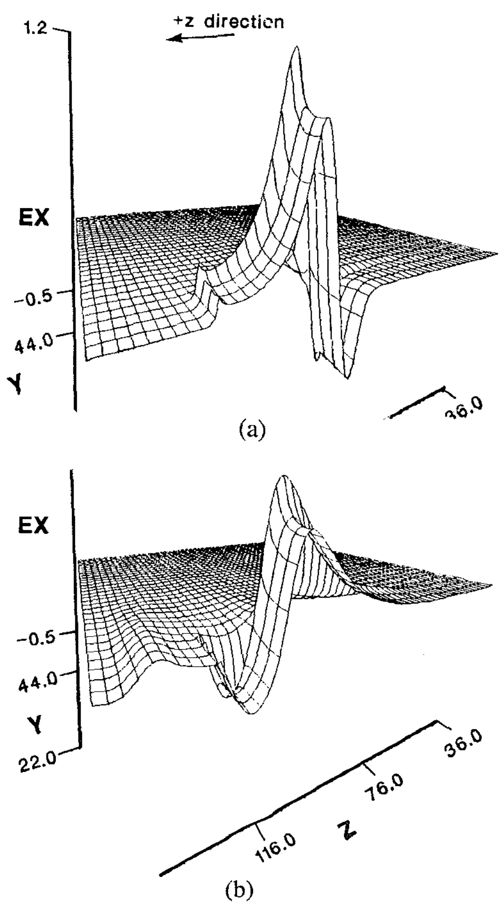

Figure 3. Gaussian Pulse Propagation and Reflection in the Microstrip Open-End Structure : Ex component just underneath the strip

(a) Incident Pulse Just Reach the Open-End

(b) Pulse Being Reflected Back and the Surface Wave Been Generated the plot is drawn is just underneath the metal strip. Part(a) is the field distribution at the moment when the Gaussian pulse just reaches the open-end and be reflected. The reflected wave is seen to have the same sign as the incident wave and is added to the incident wave. Part(b) shows the reflected wave and a small amount of traveling surface wave.

The microstrip open-end structure is a one-port network(Fig.1). It's scattering matrix has only one element, that is, S_{11} or the reflection coefficient. S_{11} is defined as

$$S_{11}(\omega) = \frac{V_{ref}(\omega)}{V_{inc}(\omega)} \tag{1}$$

where $V_{ref}(\omega)$ is the transformed reflection voltage at the input plane (i.e. the reference plane T-T in Fig.1) of the one-port, and V_{inc} is the transformed incident voltage at the same position. In this calculation, the incident field is obtained from that of a infinite long microstrip , and the reflected field from the open end is obtained through the substraction of the incident field from the total open-end field.

It's a common practice in microwave network calculation that to calculate S_{11} , the V_{ref} and V_{inc} used are not the waves right at the reference plane but rather waves transformed back to it from the positions a certain distance away on the transmission line. To be more specific (refer to Fig.1.),

$$S_{11}(\omega) = \frac{V_{ref}(\omega,z'=l)\cdot e^{\gamma(\omega)l}}{V_{inc}(\omega,z'=l)\cdot e^{-\gamma(\omega)l}} = \frac{V_{ref}(\omega,z'=l)}{V_{inc}(\omega,z'=l)}\cdot e^{2\gamma(\omega)l} \tag{2}$$

This is because that right at the plane of the discontinuity many high order, evanecent modes are excited. These modes are not supposed to be included in our calculation of S_{11} . To use waves a certain distance away from the discontinuity region allows the evanecent waves to die out and what left over are the traveling waves we desired to use. The $e^{\gamma(\omega)l}$ term can be calculated from the ratio of the fields at two different positions along the microstrip with a separation of l.

Fig. 4 shows the calculated results of the magnitude and phase of $S_{11}(\omega)$ for the open-end under consideration. The uniqueness of the solution to the use of either the field at one point under the metal strip or the voltage between the strip and the ground, when substitute into (2), has been checked to be well satisfied. This is expected to be true once the mode distribution is well established on the line.

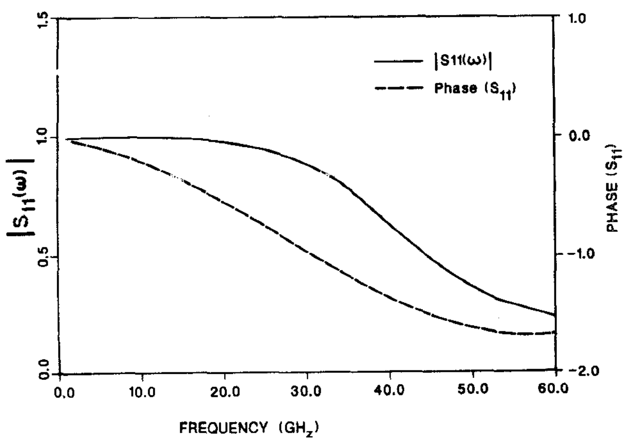

Figure 4. Frequency Dependant S-Parameter

The equivalent circuit as shown in Fig. 5 with frequency dependant circuit parameters is used to model the microstrip open-end. Here

$$Y(\omega)=G(\omega)+j\omega C(\omega) \tag{3}$$

and $Y(\omega)$ is related to $S_{11}(\omega)$ through

$$Y(\omega) = \frac{1-S_{11}(\omega)}{1+S_{11}(\omega)}\cdot\frac{1}{Z_0(\omega)} \tag{4}$$

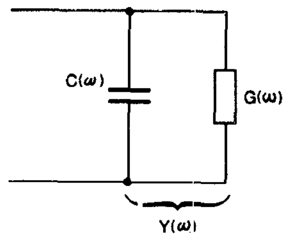

Figure 5. Equivalent Circuit of the Microstrip Open-End.

The calculated C(ω) and G(ω) are plotted in Fig. 6 together with the result of Katehi & Alexopoulos[4] for the same structure.

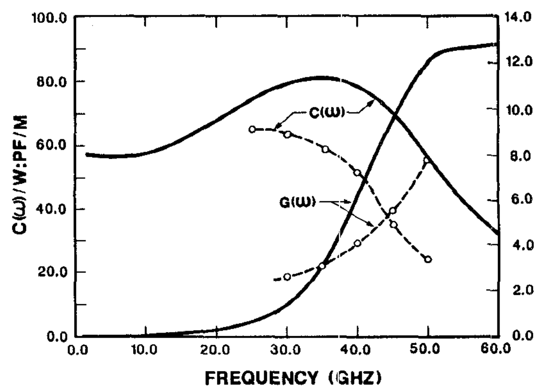

Figure 6. Frequency Dependance Equivatent Circuit Parameter C(ω)/W and G(ω) (solid lines: time domain result, dashed lines: Katehi & Alexopoulos[4]).

Another parameter which is often used to account for the the capacitive characteristic of the open-end is the effective increase in length Δl . The definition of it can be found in either [1] or [4]. The calculated $\Delta l(\omega)$, together with the comparison with several other published results, is given in Fig. 7. The normalized-frequency scale used here corresponds to the frequency range from zero to 100 GHz for the structure under consern. The DC result of the time-domain calculation is very close to the quasi-static result of [10], and the

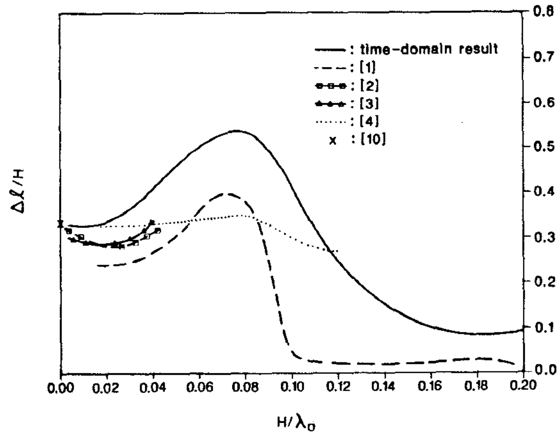

Figure 7. Effective Length Increase $\Delta l(\omega)$.

shape of the curve is very similar to that of James & Herderson [1], which has too low a DC value though. The peak which appeared near the cutoff frequency of the first TE-type higher order mode of the microstrip is also predicted in [11]. All the other published results did not show this phenomenon clearly, due either to the frequency range they are capable of calculate or to the model they used for calculation.

It has been shown that the Time-Domain Finite Difference approach is capable of calculating the microstrip end-effect over a large frequency range. This method, with minor modifications, can also be used to model other microstrip discontinuities [9]. Further investigations on different computer memory-saving schemes will make this method more suitable for CAD purpose.

Acknowledgement

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REFERENCES

[1] J. R. James and A. Henderson, "High-Frequency Behavior of Microstrip Open-Circuit Terminations ," IEE J. Microwave Opt. Acoust., vol. 3, pp. 205-211, Sept. 1979.

[2] R. H. Jansen , "Hybrid Mode Analysis of End Effects of Planar Microwave and Millimetrewave Transmission Lines ," IEE Proc. Vol. 128, Pt. H, No. 2, pp. 77-86, April. 1981.

[3] J. S. Hornsby, "Full-Wave Analysis of Microstrip Resonator and Open-Circuit End Effect ," IEE Proc. vol. 129, Pt. H, No. 6, pp. 338-341, Dec. 1982.

[4] P. B. Katehi and N. G. Alexopoulos , "Frequency-Dependent Characteristics of Microstrip Discontinuities in Millimeter-Wave Integrated Circuit ," IEEE Trans. Microwave Theory Tech., Vol. MTT-33, No. 10, pp. 1029-1035, Oct. 1985.

[5] R. W. Jackson and D. M. Pozar , " Full-Wave Analysis of Microstrip Open-End and Gap Discontinuities of Microstrip Discontinuities in Millimeter-Wave Integrated Circuit ," IEEE Trans. Microwave Theory Tech., Vol. MTT-33, No. 10, pp. 1036-1042, Oct. 1985.

[6] X. Zhang, J. Fang, K. Mei, and Y. Liu, "Calculation of the Dispersive Characteristics of Microstrips by the Time-Domain Finite Difference Method," IEEE Trans. Microwave Theory Tech., Vol MTT-36, No. 2, Feb. 1988

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

[8] K. K. Mei, J. Fang , "A Super-Absorbing Boundary Algorithm for the Numerical Solution of Wave Equations ," Submitted for Publication in J. Compu. Physics

[9] X. Zhang, "Time-Domain Finite Difference Analysis of the Frequency-Dependent Characteristic of the Microstrip Discontinuities ," Master Report, Dept. of EECS, Univ. of California, Berkeley, Nov. 1987.

[10] P. Silvester and P. Benedek, "Equivalent Capacitances of Microstrip Open Circuits ," IEEE Trans. Microwave Theory Tech., vol. MTT-20, pp. 511-516, Aug. 1972.

[11] D. S. James and S. H. Tse, "Microstrip End Effects," Electron. Lett., vol. 8, pp. 46-47, Jan. 27, 1972.