FDTD Multimode Characterization of Waveguide Devices Using Absorbing Boundary Conditions for Propagating and Evanescent Modes

Luis A. Vielva, *Student Member, IEEE*, José A. Pereda, *Student Member, IEEE*
Andrés Prieto, *Member, IEEE*, and Angel Vegas

***Abstract*—The characterization of microwave devices by means of the FDTD method is highly dependent on the availability of suitable absorbing boundary conditions. This letter presents absorbing boundary conditions that are particularly appropriate for the analysis of waveguide devices because both propagating and evanescent modes are absorbed. Additionally, the modal decomposition of the total field provided by FDTD is shown to constitute an alternative procedure to frequency domain methods in the wideband multimode characterization of microwave devices.**

I. Introduction

The FINITE-DIFFERENCE Time-Domain (FDTD) method is now established as a powerful tool for analyzing microwave devices. A key requirement for the efficacy of the method is the ability to implement absorbing boundary conditions (ABC's) that are well suited to the target structure. When analyzing wave-guiding structures by means of the FDTD method, it has been traditional to use ABC's designed to absorb waves that propagate along the device. However, in many practical devices there are discontinuities that provoke the generation of evanescent modes that are not absorbed by these ABC's. To overcome this drawback, the ABC's have been placed far from the discontinuities so that the evanescent waves are almost completely attenuated when they reach the terminal plane. However, the efficiency of the FDTD method in characterizing waveguide devices can be greatly improved if boundary conditions that are able to absorb both the propagating and evanescent waves are used.

To our knowledge, FDTD wideband characterization of waveguide devices using local ABC's has been carried out only for the fundamental propagating mode. However, it is possible to obtain the scattering parameters for the different modes by recording the total field and decomposing it into a sum of modes [1]. In this letter, dielectric discontinuities in rectangular waveguide are analyzed by FDTD using ABC's that absorb both propagating and evanescent modes. The results obtained for the scattering parameters of the different modes are compared with those provided by the mode matching (MM) technique.

Manuscript received January 6, 1994. This work was supported by the Spanish CICYT under project TIC93-0671-C06-02..

The authors are with the Departamento de Electrónica, Universidad de Cantabria, Cantabria, Spain.

IEEE Log Number 9402610.

II. ABC's and Multimode Characterization of Waveguide Devices

The characterization of waveguide devices by the FDTD method requires the introduction into the structure of an excitation that corresponds to the transverse pattern of the incident mode. When this incident wave meets a discontinuity, higher order modes, which are usually of an evanescent nature, appear. If a wave corresponding to an evanescent mode reaches a plane on which an ABC designed to absorb propagating waves is enforced, it is completely reflected towards the interior of the computational domain. The approach that is normally used to overcome this drawback is to place the ABC sufficiently far from the discontinuity that the evanescent modes will have negligible amplitude when they reach the planes surrounding the computational domain. This approach is very demanding in terms of memory and CPU time. It is possible to reduce substantially these computer requirements by implementing a boundary condition capable of absorbing both propagating and evanescent modes. The first order differential operators

$$L_p = \left(\frac{\partial}{\partial x} + \frac{1}{v_a}\frac{\partial}{\partial t}\right); \qquad L_e = \left(\frac{\partial}{\partial x} + \alpha_a\right) \tag{1}$$

constitute the ABC for the propagating and evanescent waves, respectively, when applied to the tangential components of the electromagnetic field on the terminal plane [2].

The boundary condition $L_pU = 0$ is a perfect ABC for a wave, U, that propagates along the x axis with a phase velocity v_a and $L_eU = 0$ completely absorbs an evanescent wave that decays along the x axis with an attenuation constant α_a. An ABC capable of absorbing both propagating and evanescent waves can be built up as the product of first-order absorbing operators of both kinds. It is possible to choose optimal values of α_a and v_a [3] that lead to a minimum global reflection coefficient associated with the ABC if we know beforehand the frequency behavior of $\alpha(f)$ and $v(f)$ for the modes that are to be absorbed. When noncanonical structures are used as terminal waveguides, these functions can be obtained efficiently by applying the 2D FDTD method to the transverse section of the waveguides.

The FDTD method directly provides sequences representing the time domain total field. In a wideband FDTD simulation, it is possible to obtain the frequency domain total field by means

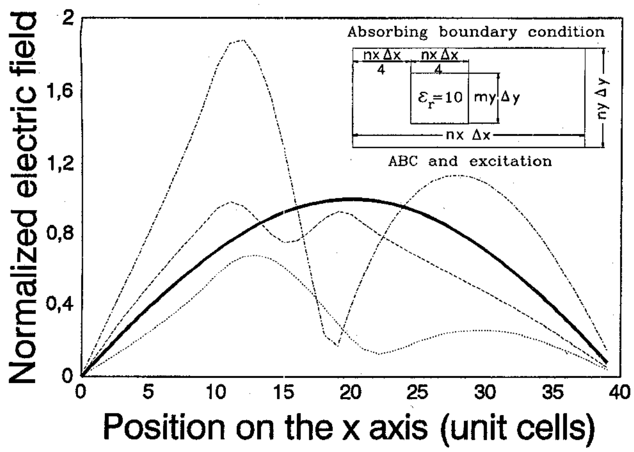

Fig. 1. Inset: top view of the structure analyzed. x = 0.5715 mm, y= 0.5 mm, nx= 40, my = 10. Main figure: electric field in the transversal section of the waveguide, at the plane of the second discontinuitie, normalized with respect to the maximum incident electric field (solid line). Dotted line: 9.3 GHz; dashed line: 10.1 GHz; dash-dot line: 10.8 GHz.

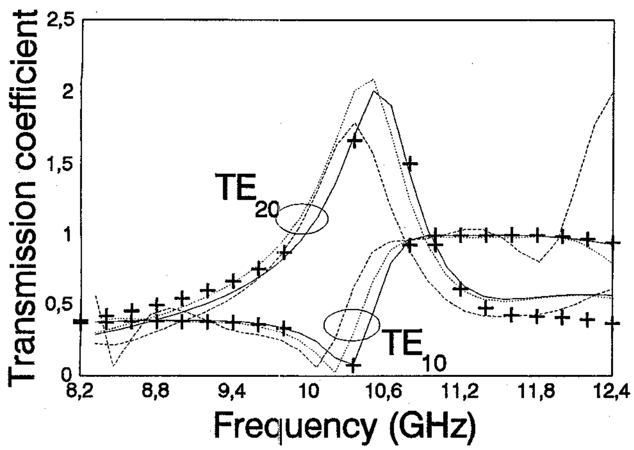

Fig. 2. Transmission coefficient calculated for the two lower-order modes of the structure in Fig. 1. using ABC's designed to absorb just propagating waves, placed at different distances from the discontinuity plane. Solid line: 22.5 mm; dotted line: 7.5 mm; dashed line: 5 mm; crosses: mode-matching technique.

of an spectral analysis procedure of these sequences. Once this total field at a given frequency $\vec{E}_T(\vec{r}_i, \omega_k)$ is known at the selected mesh points $\vec{r}_i$ at which the scattering parameters are to be calculated, it can be decomposed into a sum of modes as:

$$\vec{E}_T(\vec{r}_i, \omega_k) = \sum_{n=1}^{N} C_n \vec{E}_n(\vec{r}_i, \omega_k) e^{j\theta_n} \quad (2)$$

where C_n and θ_n are real quantities representing the magnitude and phase of each one of the N modes, $\vec{E}_n$, used to describe the total field. To obtain the best possible representation in terms of the chosen modes we have used a generalized least squares procedure solved by a singular value decomposition (SVD) algorithm [4]. This technique of decomposing the total field allows us to obtain the coefficients of the generalized scattering matrix (GSM) corresponding to the transmissions and reflections for each mode with respect to the mode used as the excitation.

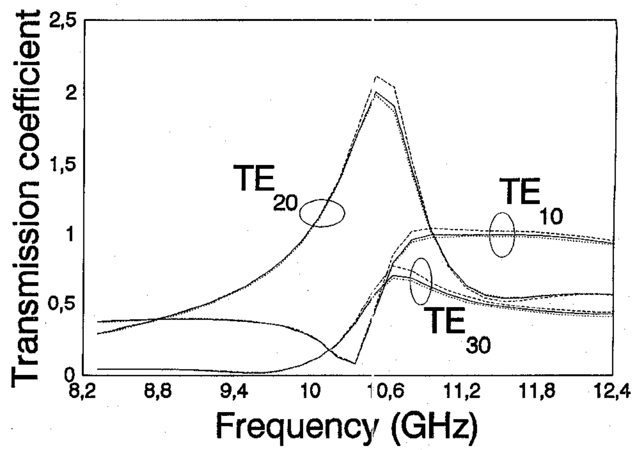

Fig. 3. Transmission coefficient for the three lower-order modes of the structure in Fig. 1. Solid line: ABC for propagating waves placed at 22.5 mm from the discontinuity; dotted line: ABC of second order for propagating and first order for evanescent mode placed at 5mm from the discontinuity; dashed line: ABC of second order for both kind of modes placed at 2.5 mm from the discontinuity.

III. Numerical Results

A WR90 waveguide loaded with a complete-height dielectric slab with $\varepsilon_r = 10$, width = 5.715 mm, and length = 5 mm, placed 5.715 mm from one side wall, as is shown in the inset of Fig. 1, has been simulated. A gaussian pulse that covers the X band and has a transverse pattern corresponding to the TE_{10} mode is introduced through one of the ports. The scattering parameters have been calculated at the plane of the second discontinuity. Fig. 1 also shows the total electric field on this plane, normalized with respect to the maximum incident field, for various frequencies. This total field is decomposed into the different modes by using the SVD algorithm to obtain the transmission coefficients of each mode with respect to the incident mode. Fig. 2 shows the scattering parameters for the dominant mode and the first evanescent mode obtained with the MM technique and with FDTD when an ABC designed to absorb only propagating waves is placed at 22.5 mm, far enough from the discontinuity so that the evanescent modes have no influence. This figure also illustrates how the results obtained with this kind of ABC become worse as the ABC is placed nearer to the discontinuity. When the ABC is designed so as to absorb both propagating and evanescent modes, the terminal plane can be placed much closer to the discontinuity, as can be seen in Fig. 3. At a given frequency, higher-order evanescent modes have greater attenuation constants so that they decay faster. The minimum attenuation constants in the considered frequency range are $\alpha = 90$ for the TE_{20} mode and $\alpha = 320$ for the TE_{30} mode, so that even placing the ABC quite close to the discontinuity good results can be achieved by absorbing just the TE_{10} and TE_{20} modes. The first ABC compared is second order for the propagating mode and first order for the evanescent modes. The second ABC compared is second order for both propagating and evanescent modes. Both ABC's have been tuned to absorb as much as possible the TE_{20} mode. Using these ABC's the terminal plane can be placed at 5 mm and 2.5 mm, respectively, from the discontinuity, almost an order of magnitude closer than when the ABC for just propagating modes was used.

IV. Conclusion

The use of ABC's designed to absorb both propagating and evanescent modes makes it possible to reduce the requirements of memory and CPU time associated with the FDTD analysis of waveguide devices. The procedure for wideband multimode characterization presented here shows a way of combining the FDTD method with techniques related to the GSM. This approach, which makes it possible to calculate the GSM in the entire frequency range of interest with only one simulation for each of the incident modes, is more efficient in some cases than frequency domain methods, which require a simulation for each one of the frequency points.

References

[1] S. T. Chu and K. Chaudhuri, "Combining modal analysis and the finite-difference time-domain method in the study of dielectric waveguide problems," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no 11, pp. 1755–1760, Nov. 1990.

[2] V. Betz and R. Mittra, "A boundary condition to absorb both propagating and evanescent waves in a finite-difference time-domain simulation," *IEEE Microwave and Guided Wave Lett.*, vol. 3, no. 6, pp. 182–184, June 1993.

[3] L. A. Vielva, J. A. Pereda, A. Vegas, and A. Prieto, "FDTD-Prony analysis of 3D waveguide discontinuities using improved broadband absorbing boundary conditions," in *Proc. 8th Int. Conf. Antennas and Propagation*, Apr. 1993, Edinburgh, pp. 603–606.

[4] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical recipes in C.* Cambrigde University Press, 1988.