Some Considerations for Using the Finite Difference Time Domain Technique to Analyze Microwave Integrated Circuits

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Abstract— **In this letter, we described the incorporation of the autoregressive method (AR model) and Litva's dispersive boundary condition (DBC) into the finite-difference time-domain method (FD-TD). It is found that the performance of the FD-TD technique is greatly enhanced when used to simulate microwave passive circuits. The results of this study show that for the analysis of typical high-Q circuits, CPU-time savings of up to 90% can be realized by combining AR model and FD-TD. After testing a number of different 50-ohm microstrip lines, we conclude that DBC shows good performance and gives excellent results when implemented with FD-TD, if the parameters are chosen properly. The use of this boundary condition can result in a considerable improvement in the accuracy of FD-TD simulations. These results help to demonstrate the usefulness of incorporating both the DBC and AR model with the FD-TD algorithm when analyzing practical microwave circuits.**

I. Introduction

In the last few years, there has been an increasing number of workers in the field of EM modeling, who have provided strong evidence that points to the usefulness of the FD-TD method for solving complex electromagnetic problems. The technique has the considerable advantage that is can be applied without much difficulty to problems where the structures are complex—i.e., to problems that are difficult to solve using conventional methods. Of greatest importance, it provides simulated results which correspond very closely to measurements. On the other hand, it is known that FD-TD is not without some serious drawbacks, largely because of the current state of computer technology. In fact, advances in the FD-TD technique have closely paralleled advances in computer memory and speed.

Although the FD-TD method has been used to analyze integrated packages for microwave and digital circuits since 1988 [1], there are two major difficulties that must always be overcome when applying FD-TD to microstrip circuits. The first, and perhaps the most difficult of these problems, relates to FD-TD's slow rate of convergence for high-Q problems. In fact, for very high-Q structures, especially where the ratio of the maximum and minimum dimensions of the structures happens to be large, FD-TD does not usually provide a practical solution because of the inordinate amount of computer time that is required. The second difficulty is related to the strongly dispersive waves that propagate on microstrip lines which are fabricated on substrates with high dielectric constants. If the boundary conditions used for terminating the computational domain are unable to adequately absorb these dispersive waves, errors will appear in the FD-TD simulations, which may not be acceptable to the design engineer if he is working to stringent specifications.

The use of digital signal processing techniques is an effective way to speed up FD-TD analysis of these electromagnetic problems. In [2] and [3], workers used MUSIC and ARMA to help FD-TD predict the resonant frequencies of resonators. Another good application of signal processing is described in [4] and [5]. The Prony technique is used to predict results, which simulate future iterations of FD-TD, based on short segments of data using the FD-TD algorithm. In applying AR modeling, we take advantage of the intrinsic nature of the FD-TD algorithm, where the basic computations are carried out in a leapfrog fashion.

The objective of this letter is to demonstrate that by incorporating AR modeling [6] and the DBC [7] boundary condition with the FD-TD algorithm, we are able to develop an EM simulator whose practical applications surpass those of Yee's original FD-TD algorithm. The demonstration will be carried out by analyzing a typical microstrip filter. It will be shown that the new hybrid technique can be used to accurately analyze passive integrated circuits and that reasonable computational times can be realized using conventional computer facilities.

II. Methodology

In this paper we adopt Yee's original algorithm [8] for solving Maxwell's equations in three dimensions. A Gaussian pulse is used as a source. It is applied at the center of the front edge of the excitation plane (see Fig. 1). After a certain number of time steps, the properties of boundary at the front edge are switched from being a magnetic wall to a DBC boundary. The DBC boundary is also used at the end plane. The characteristics of the DBC used in this letter are described by

$$\left(\frac{\partial}{\partial z}+\frac{1}{\nu_1}\frac{\partial}{\partial t}+\alpha_1\right)\left(\frac{\partial}{\partial z}+\frac{1}{\nu_2}\frac{\partial}{\partial t}\right)E=0 \qquad (1)$$

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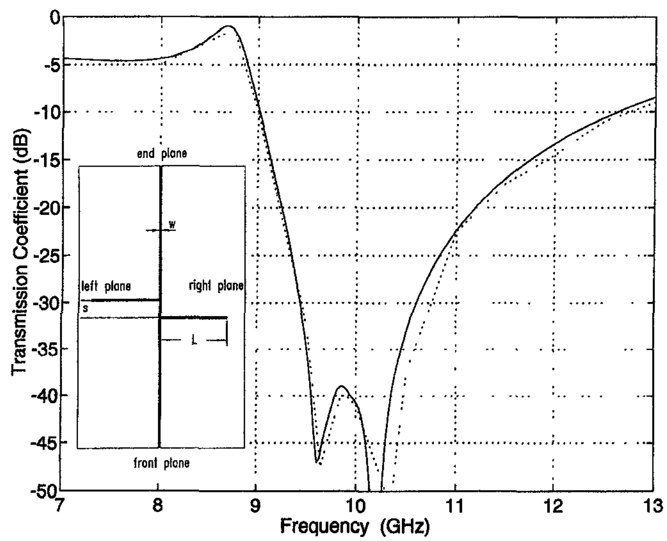

Fig. 1. The top view of a double-stub microstrip filter. ($w = 0.1219$ mm, $L = 2.921$ mm, $s = 0.7569$ mm, $\epsilon_r = 9.9$, $h = 0.127$ mm, $dx = h/4$, $dy = dz = w/4$, $\epsilon_{reff1} = 6.66$, $\epsilon_{reff2} = 8.15$, and the frequency response (S21) of a double-stub microstrip filter. The dotted line is the result in [9], and the solid line is the result of FD-TD + AR model.

where $v_1 = \frac{c}{\sqrt{\epsilon_{reff1}}}$, $v_2 = \frac{c}{\sqrt{\epsilon_{reff2}}}$, $\alpha_1 \equiv 0$, and E is the tangential electric field on either the front or the end planes. c is the velocity of light in space. ϵ_{reff1} and ϵ_{reff2} are the effective dielectric constants for two separate frequencies, designated as 1 and 2, which have been used in designing the DBC. Mur's first order absorbing boundary is applied to the remaining planes in the computational domain.

To set up the AR model, we use a short data set that is generated using the FD-TD algorithm. After training the data, the AR parameters $(a_i, i = 1, 2, 3 \cdots p)$ are extracted, as well as the order p of the process. We can then use these coefficients in the AR model to predict future FD-TD data, i.e., to extend the FD-TD data set until it converges sufficiently so that it can be used to extract EM-based parameters. The process is started by calculating the nth term, which is represented by

$$u(n) = -a_1 u(n-1) - a_2 u(n-2) - \cdots - a_p u(n-p) + \nu(n) \quad (2)$$

where $\nu(n)$ is an error term.

III. Results and Discussions

Table I gives the results obtained for the tests of Litva's DBC. To be specific, it gives the reflection coefficient (RC) for the DBC, when 50-ohm microstrip lines are analyzed for different RT/duroid materials. It is noted that these materials correspond to widely varying dielectric constants (ϵ_r) and substrate thicknesses (h). The table shows all values of RC to be less than −50 dB. These results strongly suggest that the DBC can be used for solving practical problems.

The double-stub microstrip filter [9] in Fig. 1, which is composed of three microstrip lines, is simulated using the FD-TD method. In this example, the waves are strongly dispersive when they propagate along the microstrip line. A comparison between the waves reflected by a Mur's first-order absorbing boundary and the DBC is made. The corresponding values for the RC's are −34.90 dB and −69.68 dB at 10.207 GHz, respectively. It is obvious that if the design requirement is for an RC lower than −34.90 dB, Mur's first-order ABC cannot be used. Before applying the AR model to the FD-TD data, the data must be resampled. Because of the stability condition that the FD-TD algorithm must comply with, from an information-theoretic point of view its data is coersampled. The FD-TD data are resampled at the rate of 1 out of 20 using a decimation technique. In Fig. 2 the data samples between 155 to 445 (which correspond to samples 3100 to 8900 of the original FD-TD data) are used to train a 110th-order AR model. The AR model is then used as a predictor to extend the FD-TD data set, giving samples 446 to 1050. In addition to showing the original decimated FD-TD, Fig. 2 gives a comparison between FD-TD derived data and AR predicted data. The comparison is given in the portion of the trace extending from sample 446 to sample 1050. As can be seen, there is excellent agreement.

The transmission coefficient for the filter is given in Fig. 1. This result is in close agreement with the frequency domain

TABLE I
Reflection Coefficient (RC) of the Litva's DBC. 50-Ohm Microstrip Lines Are Fabricated on RT/Duroid Substrate. ϵ_{reff1} and ϵ_{reff2} Are Given By TOUCHSTON.

RT/duroid	5870	5880	6006	6010	6010	6010
ϵ_r	2.33	2.20	6.15	10.5	10.5	10.8
h (mm)	0.787	1.575	0.635	0.635	1.905	0.635
dx (mm)	h/4	h/5	h/4	h/11	h/5	h/11
w (mm)	2.36	5.09	0.94	0.59	2.27	0.57
dy,dz (mm)	w/12	w/16	w/6	w/10	w/6	w/10
ϵ_{reff1} (1 Ghz)	1.97	1.88	4.42	6.98	7.04	7.15
ϵ_{reff2} (10 Ghz)	2.01	1.96	4.59	7.36	8.59	7.55
RC (dB) (5 Ghz)	−88.57	−92.82	−82.66	−57.66	−63.04	−51.46
RC (dB) (15 Ghz)	−85.78	−78.52	−74.06	−60.80	−65.80	−66.04

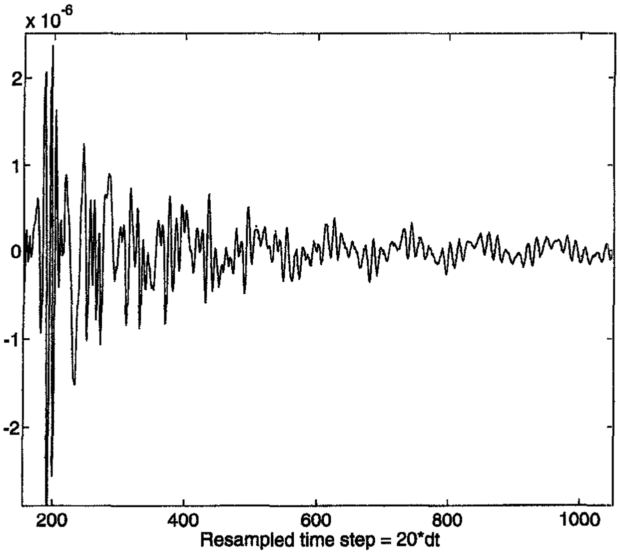

Fig. 2. Comparison between the time domain responses given by the AR model (dashed line) and the direct FD-TD method (solid line) from 3100 to 8900 iterations ($dt = 0.051$ ps).

result derived by [9]. In this example, about 90 000 time samples are required if FD-TD is used alone to derive the results shown in Fig. 1. If Yee's original FD-TD algorithm is used to solve the problem, the computational time is prohibitively long; i.e., it is not a practical technique for problems of this type. With the incorporation of AR modeling, only 10% of the data set was derived using Yee's FD-TD algorithm, which means that a 90% saving in the CPU time is realized by taking advantage of the power of an advanced signal processing technique.

IV. Conclusions

Strong dispersion on microstrip lines and relatively long computation times are two major difficulties encountered whenever one uses the FD-TD method to characterize microwave integrated circuits. Litva's dispersive boundary condition is found to be a very good candidate for absorbing strongly dispersive waves that propagate along microstrip lines. This is the first time that it has been used with the FD-TD method for solving practical microwave circuit problems. The results obtained in this study demonstrate that the DBC is now a practical technique for formulating the computational domain for dispersive problems. It has been shown that the autoregressive method can greatly reduce the CPU time requirements for the FD-TD method, and, as giving very accurate results.

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