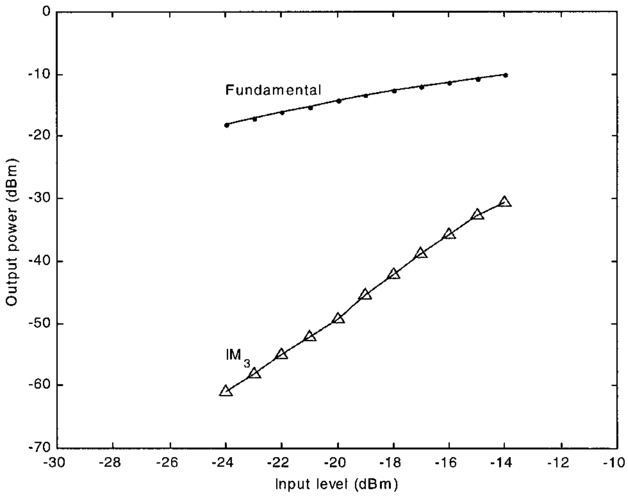

Figure 8 Fundamental and third-order responses at 5 GHz

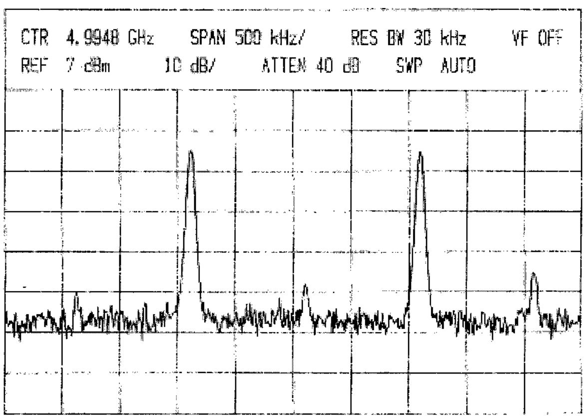

Figure 9 Measured output spectrum at 5 GHz

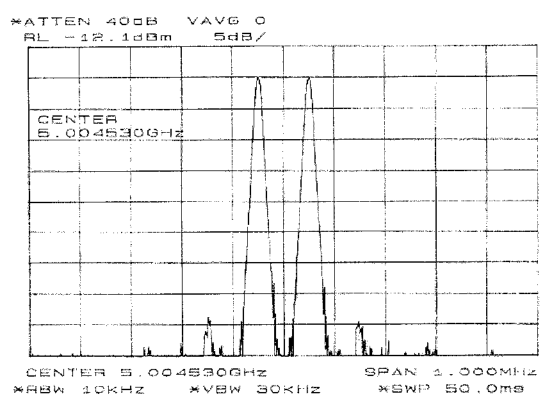

Figure 10 Two-tone intermodulation test at 5 GHz

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EFFICIENT DETERMINATION OF RESONANCE FREQUENCIES IN RESONANT STRUCTURES USING THE FDTD METHOD

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ABSTRACT: *In this paper, we present a finite-difference time-domain technique for determining the resonance frequencies of microwave components by deriving the standing-wave patterns rather than simulating the scattering parameter spectra of the component. We show that, compared to the S-parameter spectra simulation technique, the technique proposed herein can save the time needed to compute the resonant frequencies by an order of magnitude.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 28: 244–247, 2001.

Key words: *microwave resonator; finite-difference time-domain method; resonance frequency; scattering parameters*

1. INTRODUCTION

Accurate prediction of the characteristics of microwave circuits is typically carried out by performing full-wave electromagnetic simulations [1]. In a previous work, we have successfully applied the finite-difference time-domain (FDTD) method to model several widely used passive microwave components such as ring resonators and capacitors [2, 3]. It is well known that the high-frequency performance of these components is defined by their resonance properties; hence, accurate simulation of resonance frequencies is important for their successful design.

The resonance frequencies of a structure are usually determined by first simulating its scattering parameters, and then transforming these parameters from the time to the frequency domain. However, since the transient response of resonant structures following pulse excitation exhibits long-lasting ringing behavior, when excited by a pulse, it becomes necessary to derive the transient time record over a sufficiently long time window in order to allow the transient signal to decay well enough to yield accurate results for the reso-

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nant frequencies [2]. In this communication, we present a new method for computing the resonant frequencies by deriving the standing-wave patterns, which require considerably less computation time than the simulation of S-parameter spectra.

2. SIMULATION RESULTS

To illustrate the approach, we use an edge-coupled microstrip ring resonator with a rutile substrate as a case example. The thickness of the rutile layer is 1.5 mm, the conductive ring and the feedlines are 0.25 mm wide, the outside diameter of the ring is 10 mm, and the coupling gaps equal 0.125 mm. The conformal FDTD technique described in [4] was used for these simulations. The resonator was excited by an electric-field source, which was a Gaussian pulse with a bandwidth of 10 GHz modulated by a sinusoidal wave of 5 GHz. The excitation pulse was applied between the microstrip feedline and the perfectly conducting ground plane. All of the boundary surfaces of the computational domain were truncated by using perfectly matched layers (PMLs) [5], except for the ground plane at the bottom. Fields in the structure are simulated in the time domain via the FDTD algorithm, and the results are subsequently transformed into the frequency domain using the fast Fourier transformation (FFT) procedure. The frequency-domain data are then used to derive spatial field distributions and field contour plots at different frequencies.

Standing-wave patterns, characterized by high peaks and deep nulls in the field distribution, are formed in the structure at and near the resonant. Figure 1(a) and (c) shows the distributions of the electric-field component normal to the substrate surface of the ring resonator, while Figure 1(b) and (d) exhibits the corresponding contour plots in the plane below the metal ring inside the dielectric. Figure 1(a) and (b) corresponds to the first resonance frequency, whereas Figure 1(c) and (d) plots the field at the frequency below the first resonance. As seen from the figures, a shift of only 0.1 GHz from the resonance frequency of 1.24 GHz destroys the symmetric shape of the distribution, and decreases the magnitude of the field by a factor of 4. The results shown in Figure 1 were computed by using 60,000 time steps, with the time step equal to 0.25 ps. This number of time steps was sufficient for the fields to decay to the point of being negligible.

Figure 2 shows the contour plots of the same electric-field component, but at the second resonance frequency. These three plots, presented in Figure 2(a)–(c), correspond to using 60,000, 10,000, and 5000 time steps, respectively. The plots demonstrate that the simulations performed with 10,000 time steps produce the same standing-wave pattern as that ob-

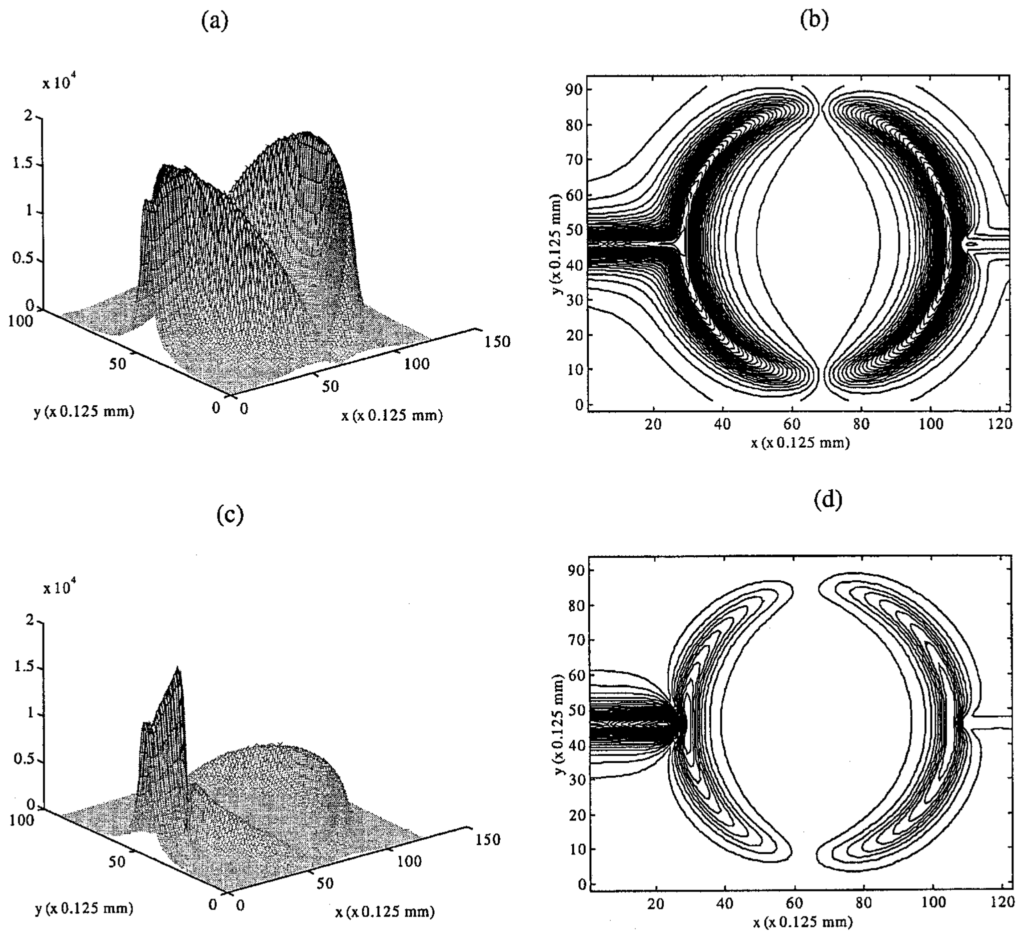

Figure 1 (a), (c) Distributions of the electric-field component normal to the substrate surface. (b), (d) Its contour plots in the plane below the metal ring. (a), (b) At the first resonance frequency $f = 1.24$ GHz. (c), (d) At frequency $f = 1.14$ GHz. Number of time steps used is 60,000. Time step is equal to 0.25 ps

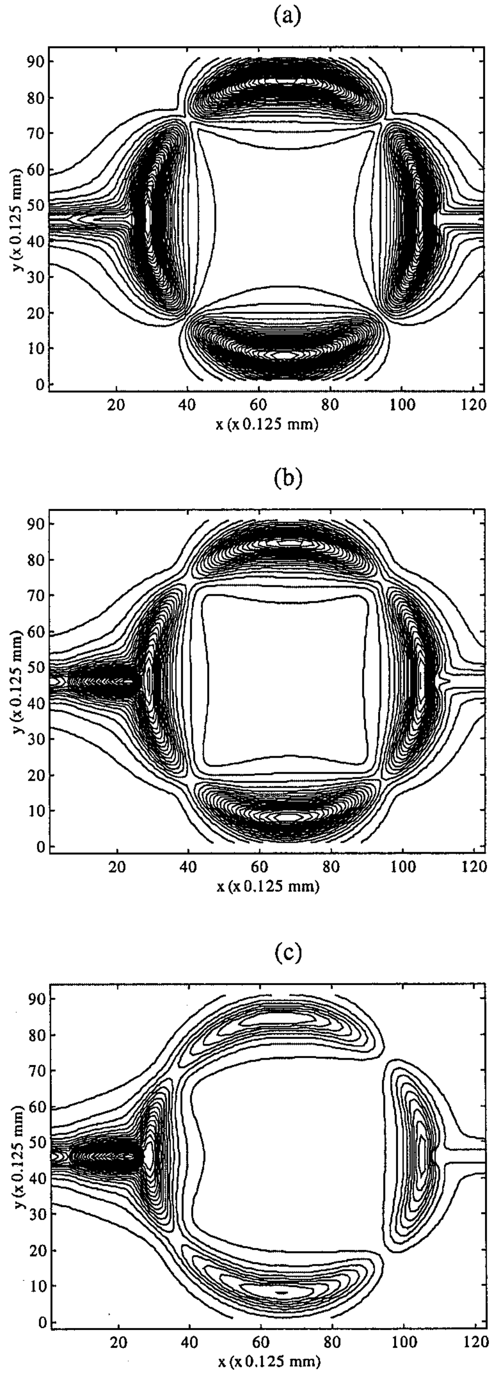

Figure 2 Contour plots of the electric-field component normal to the substrate surface in the plane below the metal ring computed using (a) 60,000, (b) 10,000, and (c) 5000 time steps. Time step is equal to 0.25 ps

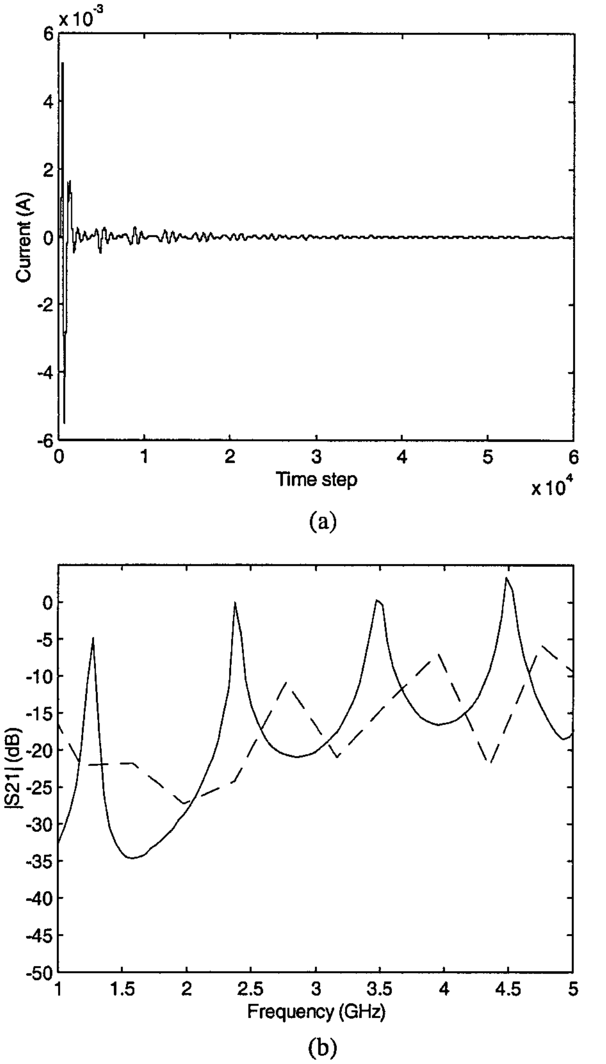

Figure 3 (a) Transient current response in the input feedline, and (b) $|S_{21}|$ spectra of the ring resonator simulated using 60,000 (solid curve) and 10,000 (dashed curve) time steps. Time step is equal to 0.25 ps

tained when 60,000 time steps are used, although 5000 time steps are not sufficient to generate a clear pattern for this case.

Figure 3(a) shows the transient current sampled at the input feedline, and Figure 3(b) plots the $|S_{21}|$ spectra of the ring resonator simulated by using 60,000 (solid curve) and 10,000 (dashed curve) time steps, respectively. It is evident from Figures 2 and 3 that accurate simulations of the S-parameter spectra require a sufficient number of time steps to achieve a complete decay of the fields in the structure, while the number of time steps needed to generate a well-formed standing-wave pattern could be less by as much as a factor of 6 or more. Similar simulations performed on a planar capacitor with alumina substrate have shown that 25,000 time steps are necessary to accurately compute the S-parameter spectra, while only 3000 time steps are required to form standing-wave patterns that yield resonant frequencies with the same accuracy as the S-parameter approach.

In conclusion, we have demonstrated the clear advantage of using the computation of standing-wave patterns over the S-parameter for determining the resonance frequencies of microwave components accurately via FDTD simulations. We have found that a time saving of a factor of 6 or higher can be achieved by using the proposed method instead of the S-parameter approach.

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HYBRID STF–FDTD APPROACH FOR EM SCATTERING ANALYSIS WITH AN EXTREMELY SLOW-DECAYING PULSE INCIDENCE

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ABSTRACT: *In this paper, we present a hybrid scattering transfer function (STF) and finite-difference time-domain (FDTD) approach for the calculation of electromagnetic transient responses with the incidence of an extremely slow-decaying pulse, e.g., a double-exponential pulse. We first introduce a scattering transfer function (STF) into the scattering system based on the principle of the linear system theory by using a fast-decaying pulse as the incident wave with the bandwidth of interest. Next, we derive the scattering response for an extremely slow-decaying pulse incidence with the help of the Fourier and inverse Fourier transforms. We have demonstrated the feasibility and superiority of the presented approach by analyzing some practical transient scattering cases.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 28: 247–251, 2001.

Key words: *scattering transfer function (STF); hybrid STF–FDTD approach; transient electromagnetic scattering*

I. INTRODUCTION

Electromagnetic wave coupling to communication cable systems has become an important topic in recent EMC studies [1, 2], and it often occurs in a place where there is a lightning strike or nuclear electromagnetic pulse. Electromagnetic wave coupling could seriously affect the quality and reliability of the communication systems or even damage the electronic devices. An electromagnetic pulse (EMP) could take an extremely long time to settle down, which can be mathematically described with a double-exponential pulse function [3]. Although the traditional approaches to deal with this kind of problem were presented based on the transmission-line theory or the time-domain EFIE [1, 2], they usually are less accurate or require a very long computational time to obtain a time-domain response for an extremely slow-decaying incident pulse.

In this paper, we solve an EMC coupling problem with the double-exponential pulse incidence by using a hybrid scattering transfer function (STF) and finite-difference time-domain (FDTD) method [4]. It will be extremely costly to use a direct application of the conventional FDTD to the above EMC problem since, in this case, the time increment Δt is too small in comparison to the duration of the incident EMP. For example, a typical nuclear electromagnetic pulse (NEMP) lasts more than 1 μs, while its corresponding Δt is usually selected to be at the level of 1 ps. Thus, a very large number of total time steps has to be used to obtain the accurate transient response of the NEMP problem in the FDTD calculations.

In order to detour the above difficulty in FDTD applications, we introduce the scattering transfer function (STF) concept to the analysis of the EM scattering problem. The fundamental procedure of the scheme is to make the transient scattering system equivalent to a linear signal system, as shown in Figure 1. To determine the scattering transfer function of the equivalent linear signal system, we use a fast-decaying pulse as the system incidence instead of the original slow-decaying pulse in the FDTD calculation. Thus, the frequency-domain response to the slow-decaying incident pulse is simply given by the multiplication of the derived STF and the frequency signal of the slow-decaying incidence. We can then obtain the corresponding time-domain response for the original slow-decaying pulse by using an inverse Fourier transform.

An essential prerequisite for the hybrid STF–FDTD approach is that the effective spectra of the fast-decaying pulse must cover those of the slow-decaying one. Otherwise, the spectra of the STF may not cover the whole spectra of interest.

II. METHOD OF ANALYSIS

Assume that an object in free space is illuminated by a transient wave $E^{\mathrm{inc}}(t)$, and the scattered field at the observation point P is denoted by $E^{\mathrm{sca}}(t)$. From the viewpoint of the linear system, we treat the incident wave as an input and the scattered wave as an output [5], as shown in Figure 1. Thus, we can obtain the scattered field in the spectral domain using the following relation:

$$E^{\mathrm{sca}}(f) = E^{\mathrm{inc}}(f)H(f) \tag{1}$$

where $E^{\mathrm{sca}}(f)$ and $E^{\mathrm{inc}}(f)$ are the Fourier-transformed versions of $E^{\mathrm{sca}}(t)$ and $E^{\mathrm{inc}}(t)$, respectively. Usually, the STF

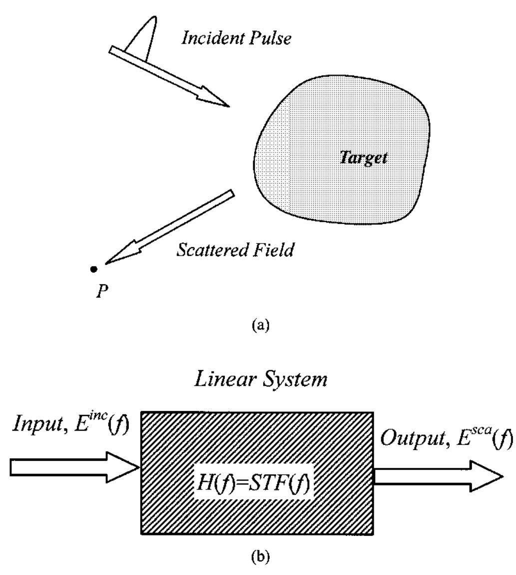

Figure 1 (a) Electromagnetic scattering system. (b) Its equivalent form