A Signal Averaging Technique for a Wide Bandwidth Absorbing Boundary Condition in the TLM Method

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Abstract

This paper reports a new and simple technique for obtaining an accurate wide bandwidth absorbing boundary condition (ABC). The technique is based on signal averaging of the scattering parameters calculated from current and voltage waves propagating in planar structures. Although the ABC has been modelled by a match-termination for normal incident waves, the errors due to imperfect ABCs can be significantly reduced from the computed scattering parameter data using a signal averaging technique. The computed reflection coefficients in highly dispersive microstrip lines have been improved from -30 dB to better than -58 dB for the entire frequency range 1-150 GHz.

I: Introduction

Differential-equation based numerical methods such as TLM have been proven to be appropriate approaches for the analysis of open microwave structures and complex geometries [1]. In order to model open problems, extra absorbing boundary conditions (ABCs) are needed to correctly terminate the computational domain. In the TLM method, the absorbing boundary can be modelled by a single impulse reflection coefficient. This match-termination for normal incidence provides a good ABC for waves scattering in low-dispersive transmission line structures such as a microstrip line on low permittivity substrate [2]. However, there is a major challenge to overcome when applying the TLM method to dispersive transmission lines fabricated on high permittivity dielectric substrates. For example, when analyzing a highly dispersive microstrip line, the transmission coefficient, S_{21}, exhibits slight gain or loss (~ ±0.25 dB) and considerable ripples in the effective dielectric constant (ε_{eff}). These errors can be reduced by choosing a smaller mesh size and by placing the exterior walls far away from the microstrip conductors. However, for microwave structures where the ratio of the maximum to minimum dimensions is very large, such as a dielectric resonator antenna coupled to a microstrip line through an aperture, the implementation of these two conditions requires a huge memory and therefore an enormous amount of computing time even if the substrate thickness is discretized by only a few cells [3], [4].

Different ABCs have been developed for the application with FD-TD algorithms. The most often referred to in the literature are those derived by Higdon and Mur [5], [6]. Recognizing the similarities of the TLM and FD-TD methods, Eswarappa et al. adapted Higdon's ABCs for the TLM method [7]. Their results demonstrated that the second and third order ABCs perform better than first order ABCs. In general, higher order ABCs are more accurate at the expense of an increased risk of instability. In addition, these local ABCs, which use the field at neighboring space and time nodes, have at least one adjustable parameter, the effective permittivity of the waveguide. The choice of the effective permittivity forces the ABCs to absorb incident waves with a limited range of propagation velocities. The local ABCs therefore still produce some small reflections due to the strongly dispersive characteristics of some microwave circuits which leads to their narrow bandwidth characteristics. The objective of this paper is to present a novel technique to improve

0-7803-3246-6/96/$4.00

the performance of match-termination for normal incidence ABC. By identifying the signal error flow due to imperfect ABCs in a planar microwave structure, and by combining the scattering parameters computed using voltage and current waves, it is found that errors due to the imperfect ABCs can be significantly reduced

II: Method of analysis

For the analysis, we assume a Gaussian pulse is propagating along an open dispersive microstrip line as shown in Figure 1. This paper demonstrates the case of a 64 μm wide microstrip line etched on 90 μm thickness GaAs substrate. The substrate thickness is discretized into seven cells. The relative permittivity of the substrate is 12.9 and the effective permittivity varies between 8.2 and 9.6 for the practical frequency of interest, 1 to 150 GHz. The lateral and top absorbing boundary sides of the open structure are modelled by a single impulse where the reflection coefficients are equal to 0 and -0.5644 for the free space and dielectric interfaces, respectively.

In the computation, the voltage is determined as a line integral of the electric field between the conductor and the ground plane.

$$V(t) = \int_{\text{grd plane}}^{\text{conductor}} \vec{E}_y \bullet \vec{\delta l} \qquad (1)$$

Similarly, the current waves can be used to determine the scattering parameters of microwave circuits. The current is calculated as a loop integral of the magnetic field around the strip:

$$I(t) = \oint_{\text{Strip}} \vec{H} \bullet \vec{\delta l} \qquad (2)$$

Figure 2 shows two dispersed incident Gaussian pulses, calculated using the discretized form of equations (1) and (2), and the undesired reflections from the imperfect ABCs at the +z and ±x planes. Both incident current and voltage pulse levels have been normalized to unity to illustrate the relation between ABC errors in the two transient responses. Although in the literature only high order ABCs have been considered for outgoing waves in the direction of propagation, this simulation illustrates the

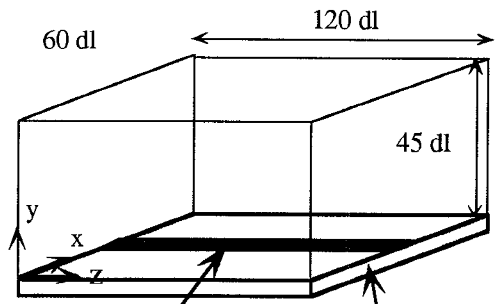

Figure 1 Analyzed microstrip line structure (dl=12.85 μm)

effects of reflections due to boundaries transverse to the direction of propagation. With an arbitrary choice of the structure size and pulse width, the x plane reflections are also noticeable in the transient response. These reflections can be identified by changing the position of the x plane absorbing boundaries. They are very small compared to the incident pulse.

The different errors due to imperfect absorbing boundary conditions are summarized in the error signal flow graph presented in Figure 3. Considering this signal error flow, the voltage and the current in the frequency domain at the same reference plane can be represented as:

$$V_T(\omega)=V_{inc}(\omega)+\left(\varepsilon_{vx}^{+}(\omega)+\varepsilon_{vy}^{+}(\omega)+\varepsilon_{vz}^{+}(\omega)\right)+ \left(\varepsilon_{vx}^{-}(\omega)+\varepsilon_{vy}^{-}(\omega)+\varepsilon_{vz}^{-}(\omega)\right) \qquad (2)$$

$$I_T(\omega)=I_{inc}(\omega)+\left(\varepsilon_{ix}^{+}(\omega)+\varepsilon_{iy}^{+}(\omega)+\varepsilon_{iz}^{+}(\omega)\right)- \left(\varepsilon_{ix}^{-}(\omega)+\varepsilon_{iy}^{-}(\omega)+\varepsilon_{iz}^{-}(\omega)\right) \qquad (3)$$

The total voltage field, $V_T(\omega)$, includes the incident voltage signal $V_{inc}(\omega)$, the three voltage errors travelling in the +z direction $\varepsilon_{vx}^{+}(\omega)$, $\varepsilon_{vy}^{+}(\omega)$ and $\varepsilon_{vz}^{+}(\omega)$ and the remaining errors, $\varepsilon_{vx}^{-}(\omega)$, $\varepsilon_{vy}^{-}(\omega)$ and $\varepsilon_{vz}^{-}(\omega)$ propagating in the -z direction as shown in Figure 3. Using the discrete Fourier transform, DFT, the reflections

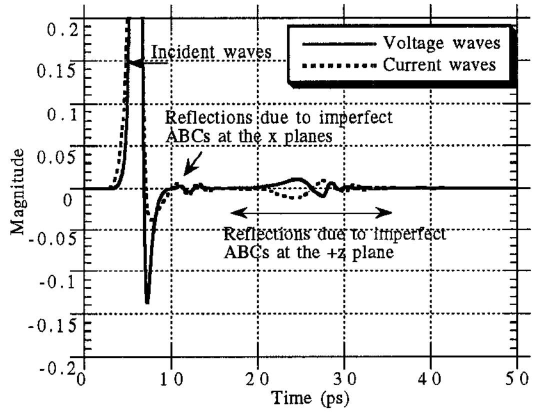

Figure 2 Transient response of current and voltage waves at an observation location along a dispersive open microstrip line (the incident waves have been normalized to one)

due to boundaries transverse to the direction of propagation ($\varepsilon^{+}_{vx}(\omega)$, $\varepsilon^{-}_{vx}(\omega)$) are smaller than -55 dB. The errors due to the top plane are negligible, but they may be important for antenna applications. However, for a wave travelling in a planar structure in the +z direction, $\varepsilon^{-}_{vz}(\omega)$ is the most significant error in the TLM simulation. The return loss due to these ABCs in the +z plane is approximately -30 dB as shown in Figure 4.

Since equivalent voltage and current terms are related by the impedance, we can demonstrate that the most significant errors propagating in the -z direction can be cancelled by averaging the complex scattering parameters of the current and voltage waves. Hence, the reflection coefficient using this signal averaging technique (SAT) can be calculated by:

$$S_{11}(\omega)=\frac{1}{2}\left(\frac{\varepsilon^{-}_{vz}(\omega)}{V_{inc}(\omega)}+\frac{-\varepsilon^{-}_{iz}(\omega)}{I_{inc}(\omega)}\right) \tag{5}$$

The return loss given by equation (5) is plotted in Figure 4 and is better than -58 dB from 1 to 150 GHz. The SAT technique does not exhibit any frequency dependent characteristics and it is easy to implement, and when applied in

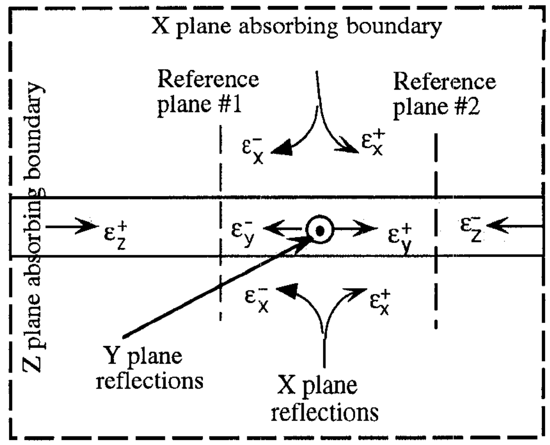

Figure 3 (Top view) Error signal flow due to imperfect ABCs in the TLM analysis of an open microstrip line.

conjunction with the traditional match-termination ABC, provides a 30 dB improvement over the match-termination for normal incident waves computed from voltage or current waves. In [7] the reflection coefficient for the second and third order ABCs have been determined for a dispersive microstrip line etched on a Duroid substrate (ε_r=10.2). The substrate thickness was discretized into 20 cells. Compared to these published results (Figure 4), the match-termination for normal incidence combined with the SAT provides improved performance. It also has very broad band characteristics compared to the available higher order ABCs

Similarly, the SAT can be used to compute the transmission coefficient of planar microwave circuits:

$$S_{21}(\omega)=\frac{1}{2}\left(\frac{V_{trans}(\omega)}{V_{inc}(\omega)}+\frac{I_{trans}(\omega)}{I_{inc}(\omega)}\right) \tag{6}$$

where $V_{trans}(\omega)$ and $I_{trans}(\omega)$ are respectively the DFT of the total voltage and current fields computed at the reference plane 2 as shown in Figure 3. This formulation has the advantage that the errors propagating in the -z direction cancel but not the field. The transmission coefficient of the GaAs microstrip line computed by equation (6) does not exhibit any significant gain or loss as is the case when $S_{21}(\omega)$ is calculated from voltage or current waves. Although the match-termination for normal incident ABC introduces only small reflections in the transient responses, the values for ε_{eff} computed from current and voltage fields exhibit important ripples as shown in Figure 5. Hence, the effective permittivity is very sensitive to numerical errors. However, if the signal averaging technique is used to calculate the ε_{eff}, these ripples can be removed as demonstrated in Figure 5.

III: Conclusions

The match-termination for normal incidence ABC produces considerable reflections in the analysis of strongly dispersive microstrip lines. Using the signal averaging technique, we have demonstrated that most of the undesired reflections travelling in the opposite direction of the incident field can be removed from the frequency domain scattering parameter results. The return loss has been improved to better than -58 dB over a wide bandwidth. This technique does not require any extra dynamic memory nor a complex algorithm as compared to higher order ABCs and it does not exhibit any narrow bandwidth characteristics.

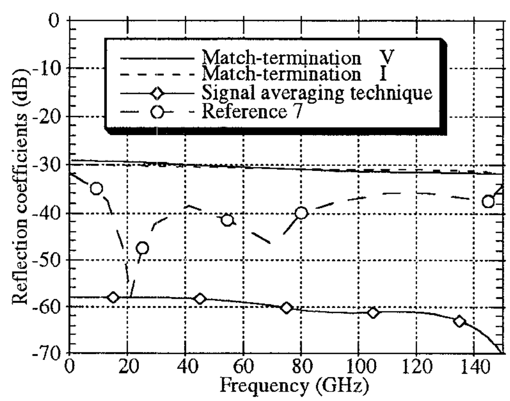

Figure 4 Computed reflection coefficients for different ABCs showing the improvement obtained by SAT compared to match-termination for normal incidence and third order Higdon's ABCs [7].

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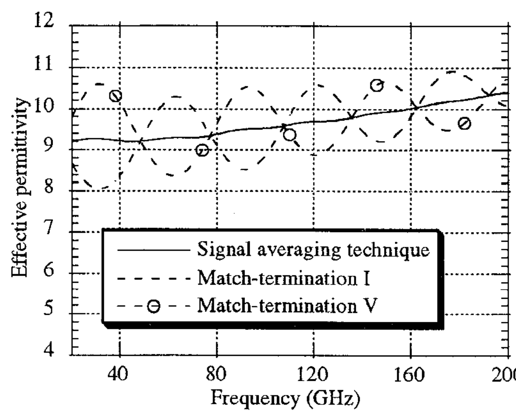

Figure 5 The effective permittivity of a GaAs microstrip line