TIME-DOMAIN VECTOR-POTENTIAL ANALYSIS OF COMPLEX RF MULTILAYER STRUCTURES VIA SEGMENTATION TECHNIQUE

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ABSTRACT

The newly developed time-domain vector - potential (TDVP) approach, based on the finite-difference solution of the wave equation for the magnetic vector potential $\vec{\mathcal{A}}$, is applied to the analysis of multilayer structures typical for RF/microwave printed-circuit boards (PCB), widely used in the personal communication systems (PCS) technology. The transient analysis of complex multiport discontinuities, where cross-talk and resonant phenomena occur, is used to obtain their scattering parameters. The subsequent modeling of the whole unit is carried out by making use of the S-parameter library, prepared by the TDVP algorithm, and, a suitable microwave-circuit simulator, e.g. EESof Touchstone & Libra. The TDVP algorithm is also used to predict the resonant frequencies of patch cavities which are encountered in multilevel multiconductor structures.

I. Introduction

The study of the electromagnetic wave propagation in complex multilayer structures is of substantial practical interest nowadays, closely related to the development of the third generation of wireless systems, namely, the personal communication systems (PCS). PCS involve modules operating at about 1.9 GHz frequency range. Therefore, their design often requires a full-wave analysis in order to avoid unwanted cross-talk and resonance. The time-domain analysis is especially promising tool in these studies, featuring numerical efficiency, versatility and broadband frequency results.

The time-domain vector-potential (TDVP) approach was recently proposed for transient electromagnetic field analysis in [2]-[3] as an alternative to the most popular nowadays Yee-cell finite-difference time-domain (FDTD) technique [1]. The TDVP algorithm is based on the finite-difference treatment of the second-order scalar wave equation for each of the components of the magnetic vector potential $\vec{\mathcal{A}}$. It reduces the CPU time requirements with approximately 50%. It also offers an important advantage to reduce the memory requirements with at least one-third for structures free of dielectric-to-dielectric interfaces.

In this paper the TDVP algorithm has been used to compute the S-parameters of complex-geometry discontinuities encountered in multilayer printed RF circuit boards in order to investigate unwanted coupling and cross-talk phenomena in a relatively broad frequency band. Further on, the S-parameters of these discontinuities have been used to model the behavior of a whole module via the commercial microwave simulator EESof Libra & Touchstone. The whole procedure is time-saving and can be used for a reliable prediction of the behavior of complex RF/microwave circuit units.

Two examples are presented in this paper:

1. Investigation of the dispersion characteristics of the coupling effects in two-level cross lines (Fig. 1).
2. Modeling of a split-ground RF circuit where un-

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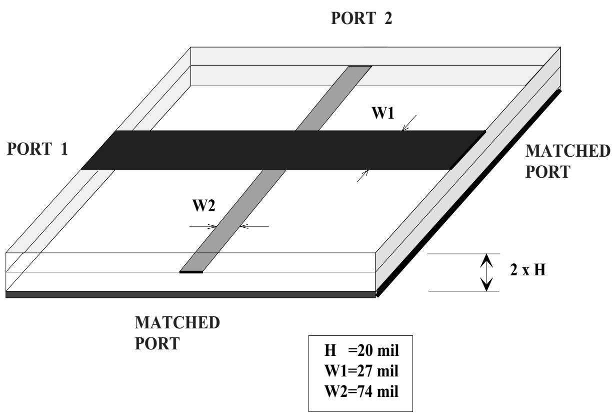

Fig. 1. The two-level cross lines. The dielectric constant of the substrate is $\varepsilon_r = 4.5$.

wanted cross-talk and resonance occur (Fig. 2).

II. Transient Analysis of Electromagnetic Fields via the Vector Potential Function

The electromagnetic field can be described with only three scalar quantities instead of the six field vectors' components, if the analytical model does not include equivalent magnetic currents. These three scalar quantities are the spatial components of the magnetic vector potential $\vec{\mathcal{A}}$ which is related to the electric scalar potential ϕ by a certain gauge condition. Maxwell's equations for a lossless medium lead to the following relations between the field vectors and the four-component potential function ($\vec{\mathcal{A}}$,ϕ):

$$\vec{H} = \frac{1}{\mu}\nabla \times \vec{\mathcal{A}} \qquad (1)$$

$$\vec{E} = -\frac{\partial \vec{\mathcal{A}}}{\partial t} - \nabla\phi \ . \qquad (2)$$

It also follows that the potential function ($\vec{\mathcal{A}}$,ϕ) must satisfy the second-order equation:

$$\nabla \times \nabla \times \vec{\mathcal{A}} + \mu\varepsilon\frac{\partial^2 \vec{\mathcal{A}}}{\partial t^2} + \mu\varepsilon\frac{\partial}{\partial t}\nabla\phi = \mu\vec{J} \ . \qquad (3)$$

After introducing the Lorentz' gauge condition for the vector and the scalar potentials:

$$\mu\varepsilon\frac{\partial\phi}{\partial t} = -\nabla\cdot\vec{\mathcal{A}} \ , \qquad (4)$$

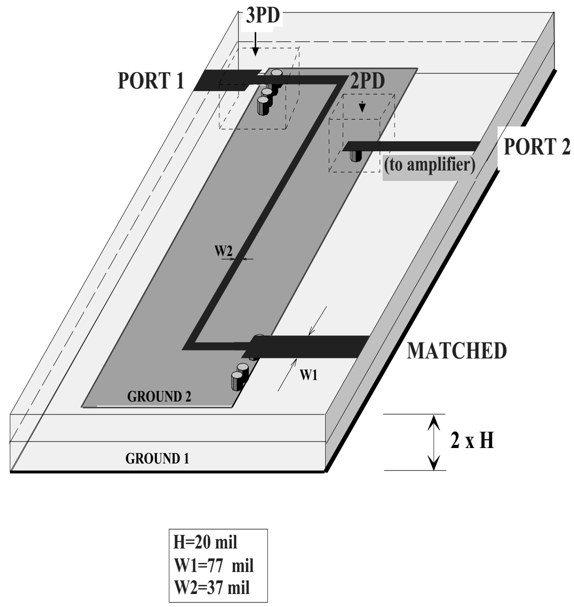

Fig. 2. The microstrip-amplifier module. The dielectric constant of the substrate is $\varepsilon_r = 4.5$. The 2-Port Discontinuity (2PD) and the 3-Port Discontinuity (3PD) are outlined with dash-boxes.

the following equation for $\vec{\mathcal{A}}$ is obtained:

$$\nabla^2\vec{\mathcal{A}} - \mu\varepsilon\frac{\partial^2\vec{\mathcal{A}}}{\partial t^2} - \frac{\nabla(\mu\varepsilon)}{\mu\varepsilon}\nabla\cdot\vec{\mathcal{A}} = -\mu\vec{J} \ , \qquad (5)$$

where $\vec{J}$ represents the electric current density. The following important conclusions become obvious:

- The field is fully described only by the three spatial components of $\vec{\mathcal{A}}$.
- In a homogeneous region, with a contrast coefficient $\nabla(\mu\varepsilon)/(\mu\varepsilon) = 0$ at every point, the three components of $\vec{\mathcal{A}}$ are decoupled and each of them satisfies the scalar wave equation

$$\nabla^2\mathcal{A}_\xi - \mu\varepsilon\frac{\partial^2\mathcal{A}_\xi}{\partial t^2} = -\mu J_\xi \ , \qquad (6)$$

where ξ denotes the respective spatial component. This implies the possibility to divide the algorithm into three consecutive parts for the computation of the independent propagation of each component, which would result in reduced memory requirements. Moreover, if the excitation currents and the boundary conditions imply the existence of a single $\vec{\mathcal{A}}$ component, the

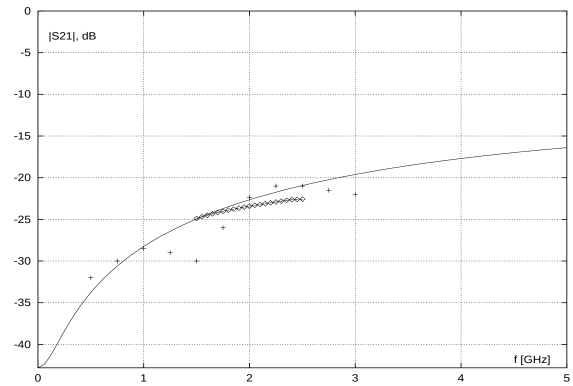

Fig. 3. Magnitude of transmission coefficient S_{21} of the two-level cross lines. With line - TDVP results, with box-line - SONNET results, with crosses - measurements.

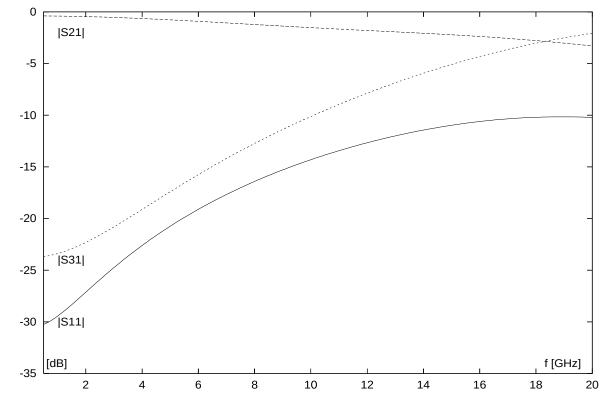

Fig. 4. Port 1 of the 3-Port Discontinuity - magnitudes of reflection and transmission coefficients.

field will be described entirely by this component, the other two components not being generated throughout the time-stepping algorithm. This is the prerequisite for substantial memory and CPU-time savings in comparison with the conventional FDTD method in the case of homogeneous regions where wire or planar conductors are present.

III. Simulations and Results

A. Computation of the S-parameters via the TDVP technique.

1. *The two-level cross line*.
   The calculation of the S-parameters of the structure shown in Fig.1 was carried out to investigate the cross-talk between the transmission lines located at two different levels as a function of frequency. The structure was simulated by the TDVP code and by the commercial software SONNET. Both results have been compared with measurements. The transient analysis produced broad-band frequency results (up to 20 GHz). The results of the simulations and measurements for the magnitude of the $|S_{21}|$ parameter are shown in Fig. 3. Fig. 3 also includes the calculations made by SONNET.

2. *The transition between one-level 50-Ohm lines with split ground (3-Port Discontinuity) and the transition between grounded patch and the 73-Ohm line (2-Port Discontinuity).*

   These discontinuities were studied in conjunction with the module in Fig. 2, where unwanted interference between the signal line (Port 1 to Matched Port) and the microwave amplifier (Port 2) was detected. The S-parameters were calculated and was found that in the working frequency range at approximately 1.9 GHz there is substantial coupling between Port 1 and Port 2 of the RF circuit due to the excitation of resonant modes in the parallel-plate structure formed between the Ground 1 and Ground 2 plates.

   Fig. 4 shows the $|S_{11}|$,$|S_{21}|$ and $|S_{31}|$ parameters of the 3-Port Discontinuity. An insertion loss greater than -23 dB is observed between the signal line and the parallel-plate guide formed between Ground 1 and Ground 2 (port 3 of the 3PD).

   The $|S_{11}|$ and $|S_{21}|$ parameters of the 2-Port Discontinuity (2PD) are shown in Fig. 5. Here the parallel-plate guide formed between the two ground plates is assumed as **port 1** and the 73-Ohm line (to amplifier) - as **port 2** of the 2PD.

   Besides, as it could be expected, the cavity formed between the two ground plates, displayed resonant properties. The resonant frequencies of the cavity are well observed in the Fig. 6 showing the reflection and the insertion losses in respect with PORT 1 and PORT 2 of the module in Fig. 2.

B. Modeling the Microstrip - Amplifier Module.

The modeling of the RF circuit was carried out using the S-parameters computed by the TDVP analysis and the library of the EESof Libra itself. The results of simulations and measurements for the Port 1 reflection and transmission coefficients are plotted in Fig. 7. The resonant character of the cavity influ-

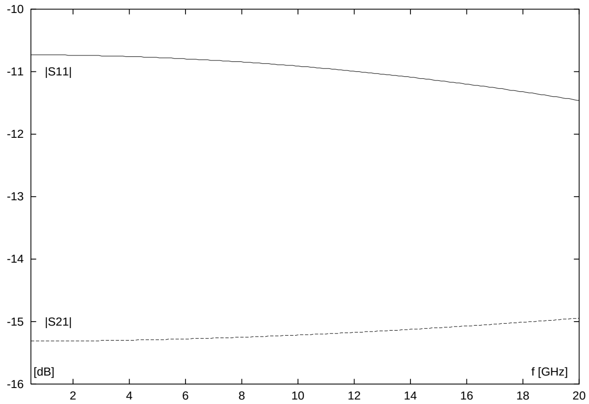

Fig. 5. Port 1 of the 2-Port Discontinuity - magnitudes of reflection and transmission coefficients.

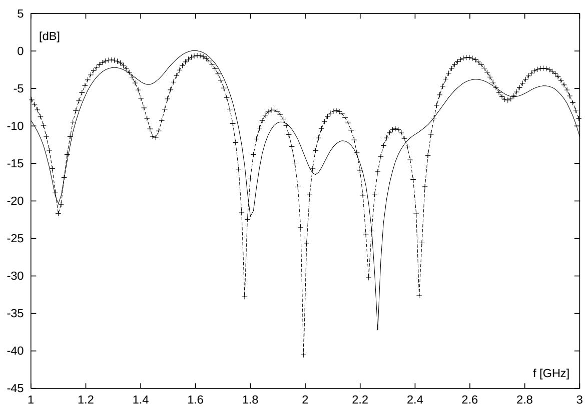

Fig. 6. Reflection and insertion losses of cavity: $|S11|$ - with line, $|S21|$ - with line-points.

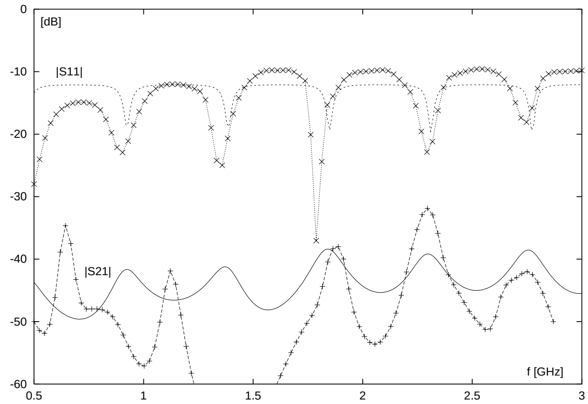

Fig. 7. Magnitudes of the reflection and transmission coefficients of the Microstrip-Amplifier Module. With line - TDVP/Touchstone output, with lines-points - measurements.

ence is well seen in both figures. Unwanted coupling occurs (the $|S_{21}|$-parameter becomes larger than -40 dB) exactly in the working frequency range between 1.5 and 2.0 GHz. When the amplifier is biased, the coupling between the signal line and the amplifier output increases up to -20 dB.

IV. Conclusion

The application of the newly developed time-domain vector-potential (TDVP) technique to the analysis of complex multilevel transmission line discontinuities is considered in this paper. The reduced CPU-time and memory requirements of the algorithm allow the simulation of structures with complicated geometry and the computation of their S-parameters which are used in the postprocessing modeling of complex RF/microwave printed circuit boards. The results are in good agreement with measurements. The proposed hybrid modeling via the TDVP technique and the EESof Touchstone & Libra simulator can be an efficient and versatile tool for predicting the behavior of packaged RF/microwave integrated circuits.

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