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Decomposition of Coplanar and Multilayer Interconnect Structures with Split Power Distribution Planes for Hybrid Circuit–Field Analysis

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Abstract

A novel technique for decomposing complex interconnect systems into signal propagation and power distribution parts is presented. The decomposition is performed around the discontinuities in the signal or return current paths. The decomposed structure is ideally suited for hybrid analysis where one part of the problem is modeled using circuit methods and the second part is analyzed using field solvers. The method significantly extends the available decomposition techniques in its generality and its applicability to a wide range of structures, including coplanar structures as well as structures containing conductive planes with voids such as splits, slits, or gaps. The decomposed structure offers the possibility of more efficient analysis compared to the analysis of the non-decomposed structure.

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Neven Orhanovic received his B.S. degree in Electrical Engineering from the University of Zagreb, Croatia and his M.S. and Ph. D. degrees in Electrical and Computer Engineering from Oregon State University, Corvallis. From 1992 until 1999, he was with Interconnectix and Mentor Graphics Corp. developing numerical methods and simulation software in the area of interconnect analysis and interconnect synthesis. He is currently with Applied Simulation Technology working mainly on full-wave analysis methods.

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Introduction

The interconnect structures found in today's printed circuit boards (PCBs) support several fundamental types of wave propagation. These fundamental modes of propagation can be separated into two categories: 1) modes that require two or more conductors to support the propagating waves; 2) modes of propagation that can be supported by single conductor containing a cavity or a void. The conductors that support the propagation can further have different shapes with widely varying dimensions and aspect ratios. Some of the conductors or voids in the conductors are thin and narrow and support mainly one dimensional (1D) propagation along the tangential (or longitudinal) direction. These 1D conductors or voids can usually be modeled accurately and efficiently using multiconductor transmission line models and conventional lumped element discontinuity models (Figure 1). Other conductors or voids are wide or thick and they can support more complex propagation in two or three dimensions (2D/3D). In most digital systems, the conductors used for signal propagation are mainly 1D while the conductors used for power distribution are 2D/3D. The 2D/3D conductors require more complex analysis techniques, which involve direct or indirect solutions of partial differential equations or integral equations in two or three space dimensions.

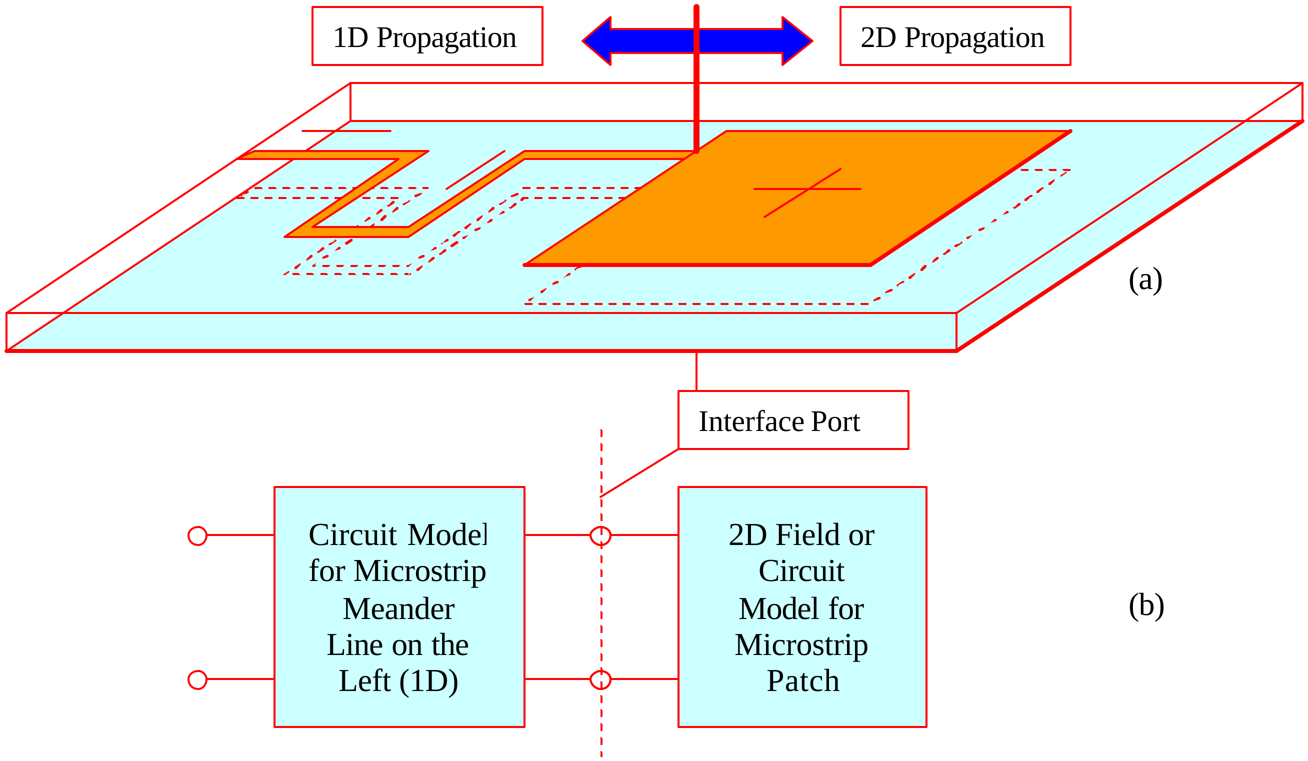

Figure 1: Simple structure supporting mainly 1D propagation on the left and mainly 2D propagation on the right. For this example, the decomposition into 1D and 2D partitions is trivial (b).

Although the same techniques used for the analysis of 2D/3D systems of conductors can be applied to 1D conductors, the procedure is inefficient in general. The main reason for the inefficiency of 2D/3D analysis methods when applied to 1D problems is in the presence of both very large and very small features in the structure. The ratio of the sizes of the smallest and larges features in the structure is directly related to the efficiency of 2D/3D analysis methods. A particular class of analysis approaches usually works best for a particular type of structures. It is therefore highly advantageous to decompose the structure into parts that support one type of propagation each, and to analyze the constituent parts using separate analysis methods.

The 1D and 2D/3D types of conductors and voids can typically be mixed freely in the interconnect system. As a result, the overall system will support a number of different 1D and 2D/3D modes of propagation simultaneously. The exact modes of propagation will depend on the details of the structure as well as on the details of the excitations. Furthermore, the supported modes of propagation can be tightly coupled. A mode propagating in a region of the structure can excite a different mode in the same region. Consequently, the decomposition of the interconnect system into parts, such that each part supports one fundamental mode of propagation, is not a trivial problem.

Figure 2 shows a simple homogeneous stripline example where two fundamental propagation modes exist simultaneously: the TEM stripline mode and the TEM parallel plate mode. This simple structure can be decomposed into stripline and parallel plate parts only if an appropriate mode coupling mechanism is introduced.

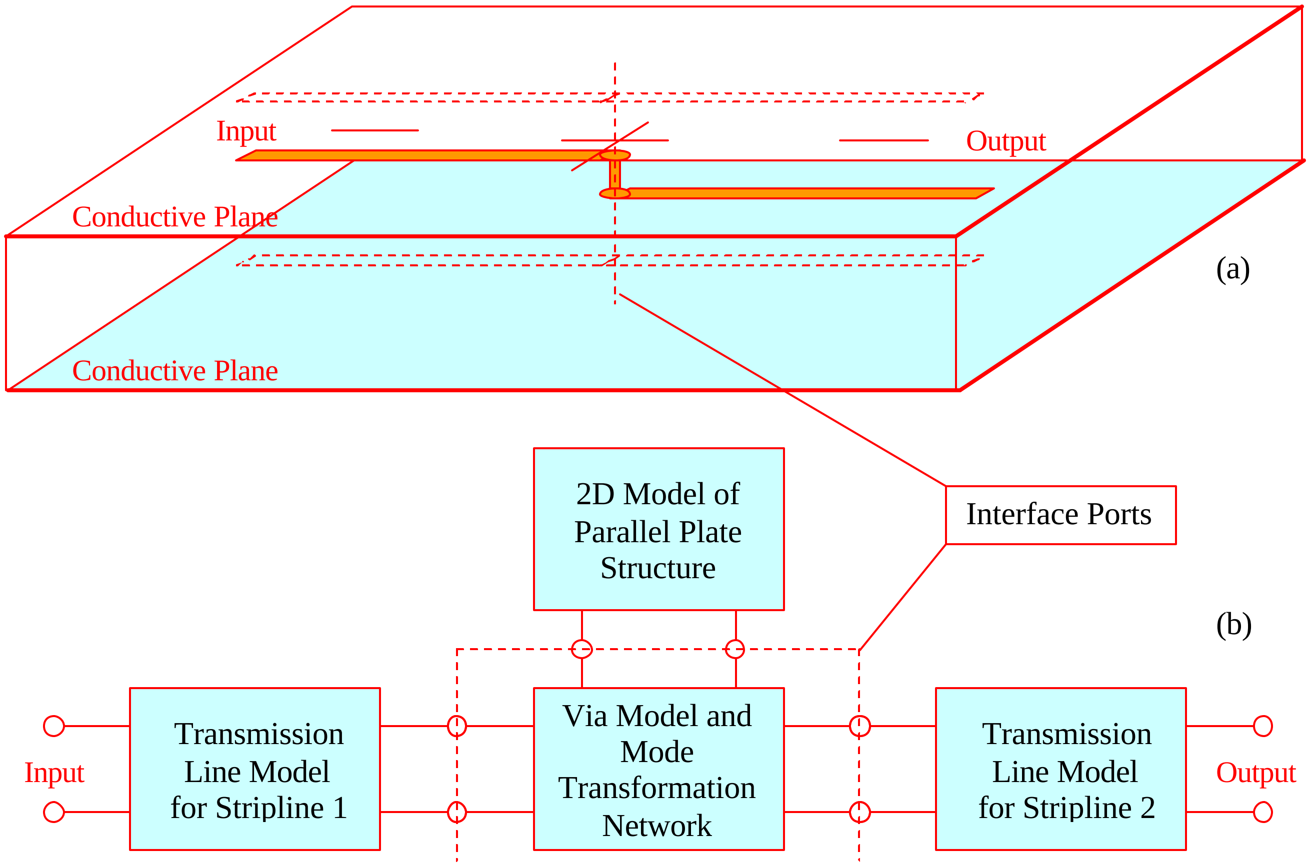

Figure 2: Simple homogeneous stripline structure for which the 1D and 2D propagation regions overlap. The decomposition of the structure into 1D and 2D propagation partitions requires an appropriate mode transformation network.

A number of structure decomposition techniques have been proposed in the literature (e.g., [1–8]). Some of the methods perform simple geometrical separations of the structure into non-overlapping parts [1–3]. As each part of a general structure can support more than one form of fundamental propagation, these methods do not always take full advantage of analysis technique specialization for each constituent part. Others, decompose the circuit around via discontinuities [4–6]. The technique proposed in [6] decomposes a stripline structure filled with a homogenous dielectric medium into a parallel plate structure and a transmission line. The decomposition is performed around a via discontinuity. The method handles the two separated structures efficiently, but it is applicable to a class of very special structures. In [7] the method of [6] is generalized for an arbitrary system of coupled planar conductors around arbitrary vertical discontinuities using a dependent voltage and current source mode coupling circuit. This method is still not general enough to deal with all of the structures present in complex PCBs and IC packages. The generalization to [6] proposed in [8] promises applicability to a wider range of cases, including magnetically coupled structures. However, this generalization comes with the penalty of additional implementation complexity and larger storage and computational requirements.

The purpose of this paper is to propose a method for separating the 1D propagation network from the 2D/3D propagation partition at the discontinuities in the horizontal return plane. The paper extends the decomposition proposed in [7] and makes it applicable to planar discontinuities such as various voids in the signal return planes. The 1D part of the decomposed structure is solved using circuit simulation methods while the 2D/3D part can be solved using any of a number of analysis approaches. The generalization for the analysis of 2D partitions described in [8] can also be used in conjunction with [7] and our proposed decomposition method. The method is exemplified on microstrip examples containing voids in the return plane as well as on a coplanar structure.

Decomposition Approach for Microstrips

The proposed decomposition is first explained for a microstrip structure. Figure 3 shows a microstrip line passing over a split in the return plane.

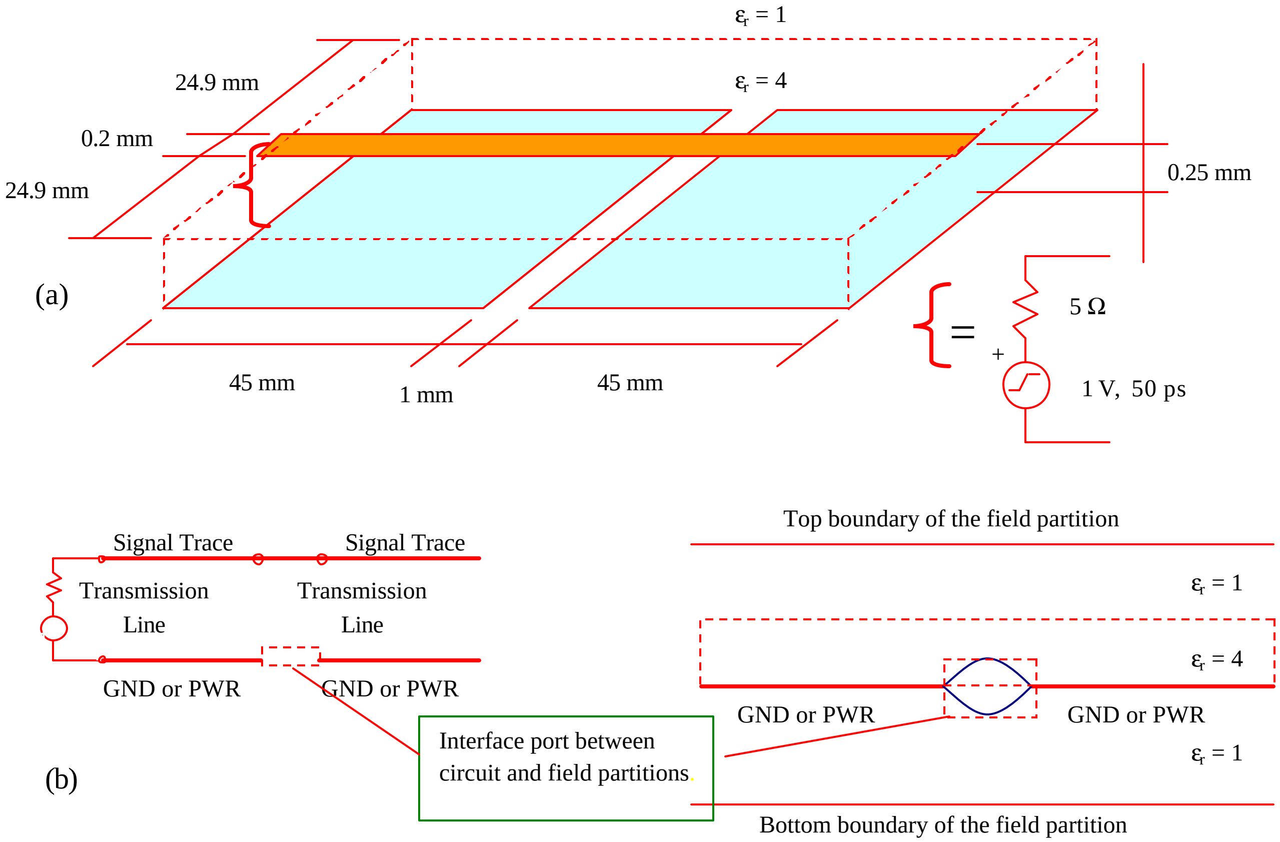

Figure 3: Example structure used to illustrate the decomposition around a slit in the return plane.

The split can represent a slit or gap in a single plane or two separated power planes with different DC voltage levels. The structure is decomposed into two microstrip lines on either side of the split and the split model. The difficulties in the accurate modeling of the structure of Fig. 3(a) arise due to the presence of the split. Conversion of propagation modes occurs around the split where the dominant quasi-TEM mode of the microstrip couples with the dominant slotline mode of the split. The split or gap can also have an irregular shape or it can couple to other oddly shaped gaps in the same plane or in nearby planes.

A general and efficient approach to modeling such structures is to decompose the structure into the 2D propagation partition and the signal propagation partition. The 2D propagation partition, consisting of the original structure without the signal trace, can be analyzed using field analysis methods. The signal propagation partition can be analyzed using transmission line models. The two partitions are connected in the area of the discontinuity underneath the signal trace. If the analysis of the planes is performed in the time domain using FDTD, the connection between the two parts can be made using FDTD–SPICE interfacing methods ([9–14]). The placement of the FDTD to SPICE interface port is shown in Fig. 3(b). A similar connection approach can be used if other field analysis methods are used [15]. Since the traces are not included in the part of the structure that is analyzed using field solution methods, the amount of detail and the discretization requirements for this part of the model are reduced significantly compared to those of the original structure.

Figure 4 compares the results obtained by using FDTD–SPICE on the decomposed structure to those obtained using FDTD on the non-decomposed structure that includes the signal trace. The voltages at the trace input and output are shown along with the voltages at the two ends of the split. Good agreement is observed. The simulation of the decomposed structure was more than ten times faster than for the corresponding non-decomposed structure. For complex multilayer boards with coupled thin traces, the computational advantages of the decomposition are usually larger.

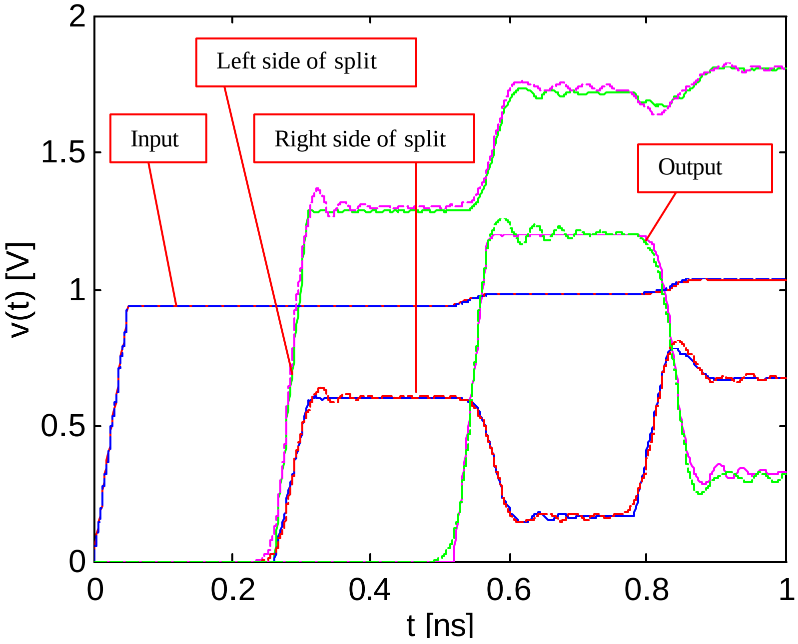

Figure 4. Voltage response of microstrip trace over open split in the return plane: proposed method (solid lines) and FDTD analysis of original structure without decomposition (dashed lines).

The split in the above example completely separates the plane into two parts. The modeling procedure is the same for slits or holes in the plane. Figure 5 shows the microstrip structure of Fig. 3 with a slot in the return plane. The length the voltage responses for varying lengths of the slot are shown in Fig. 6. The results obtained using the proposed decomposition technique are again plotted with solid lines and the results obtained by analyzing the full non-decomposed structure in FDTD are shown by dashed lines.

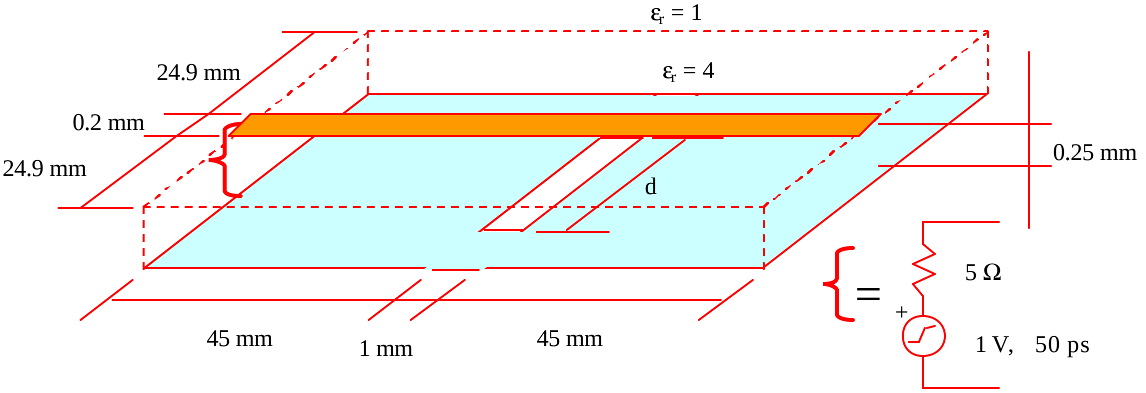

Figure 5. Microstrip trace over a slot of variable length d. The width of the slot is held constant.

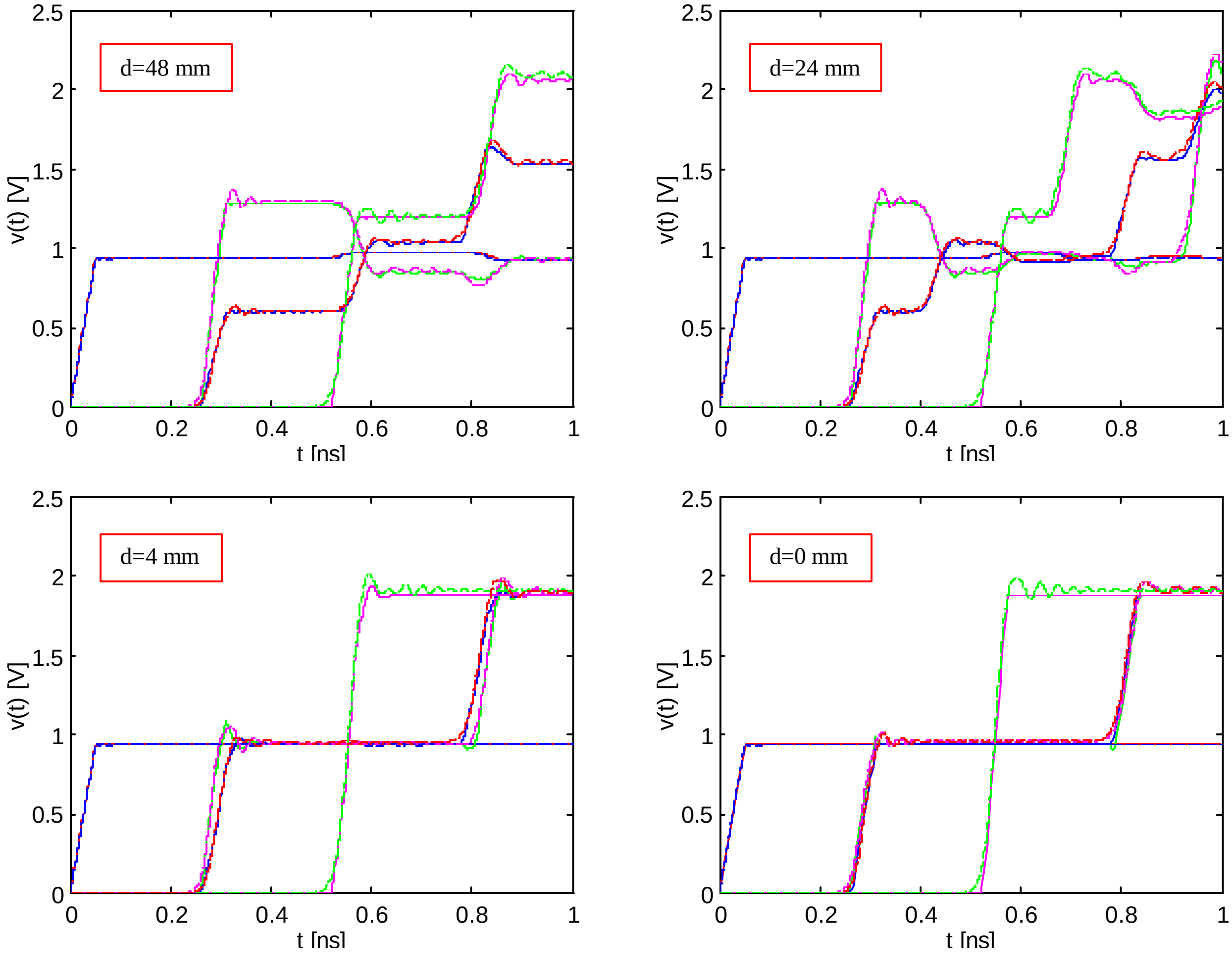

Figure 6. Voltage responses of the structure shown in Fig. 5 for four different slot lengths.

Good agreement between the decomposed result and the result computed by analyzing the non-decomposed structure in FDTD is observed. As the length of the slot decreases, its effect on propagated signal diminishes. When the delay along the length of the slot becomes smaller than the rise time of the signal, the effect of the slot becomes negligible.

For microstrip traces passing over isolated conductor islands or multiple slots, the decomposition procedure described above needs to be applied at each crossing.

Decomposition Approach for Coplanar Structures

The decomposition for coplanar structures is a direct application of [7] to horizontal discontinuities. The approach is described on the coplanar structure of Fig. 7. Figure 7(a) shows the top view of the structure. The signal conductor is 200 µm wide while each of the neighboring return conductors is 9.2 mm wide. The separation between the signal conductor and each of the neighboring return conductors is 300 µm. The length of the structure is 90 mm. The conductor material is copper. The conductors are positioned on top of a low loss dielectric substrate that is 1 mm thick and has a dielectric constant of 4. The decomposition is performed at the discontinuity in the center of the structure (Fig. 7(b)). The 2D propagation partition consists of the original stricture without the signal trace. It contains two ports that interface with the 1D partition. The 1D propagation partition is represented by a circuit model. The circuit model contains two transmission lines that model the 1D propagation on the two sides of the discontinuity. The two transformation networks shown in the circuit model are needed to take into account the mode conversions at the discontinuity [7]. The interface ports consist of a circuit model as well as a field solver model. Their implementation using FDTD–SPICE analysis techniques is described in [13–14].

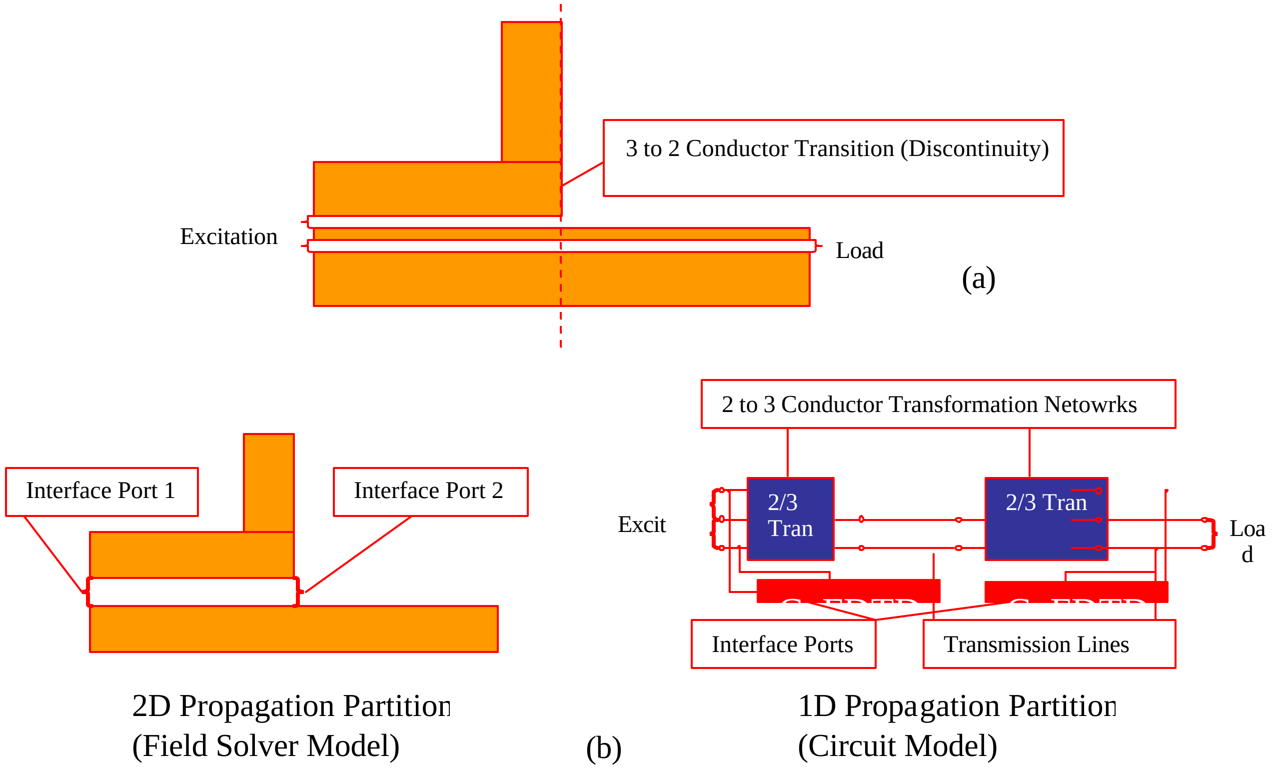

Figure 7. Decomposition at planar discontinuities: (a) structure; (b) decomposition into 1D and 2D parts.

A comparison of the results obtained using the decomposition method of Fig. 7 and the results obtained using direct FDTD discretization of the original structure is shown in Fig. 8. Different inputs were used to excite the structure between the bottom and center conductors and between the top and center conductors in order to excite two different modes on the three conductor system. The excitation circuit is shown in Fig. 9 together with the reference directions of the voltages in the plots. A high impedance load terminates the structure of Fig. 7 on the right end.

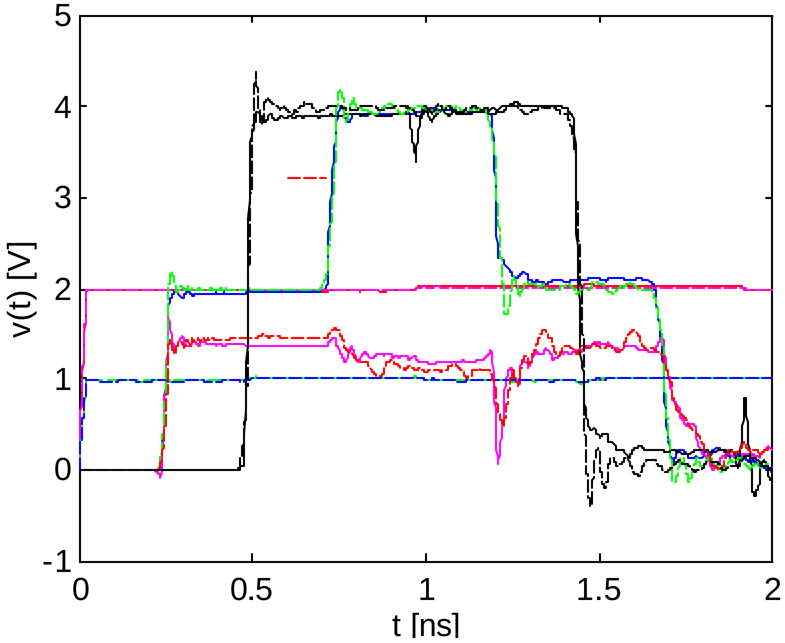

Figure 8. Voltage response of the coplanar structure of Fig. 7: FDTD–SPICE analysis of decomposed structure (solid lines), FDTD simulation of non-decomposed structure (dashed lines).

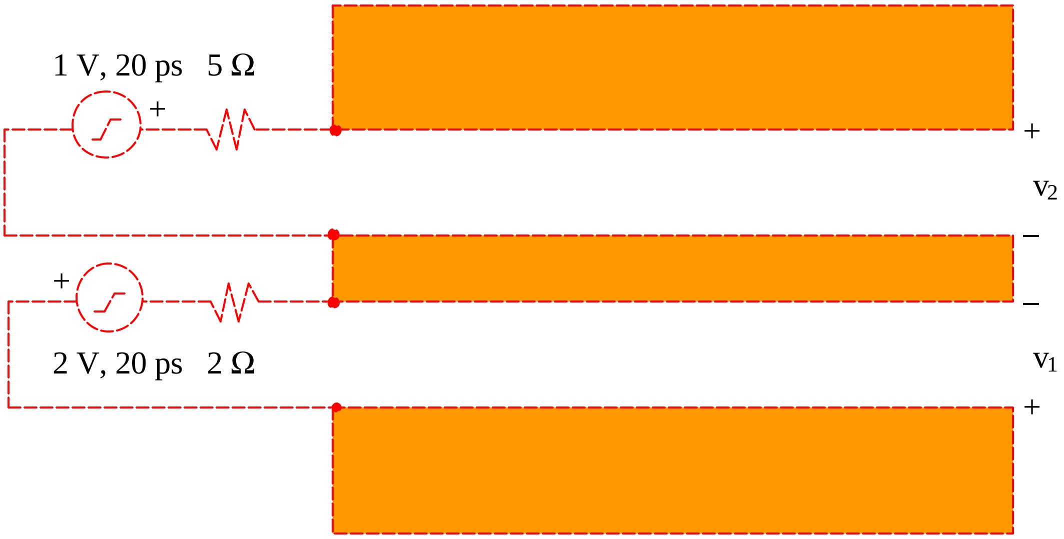

Figure 9. Excitation circuit for the structure of Fig. 7. Both lowest order modes of the three conductor system are excited.

Concluding Remarks

An extension to the decomposition technique described in [7] was described on several examples. The decomposition can be applied to microstrips passing over voids in the return planes and for coplanar geometries. When used with appropriate analysis methods, the decomposition results in a general, efficient, and practical simulation procedure that can be applied to a large set of structures found on today's printed circuit boards and in other interconnect systems.

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