Time-Domain Characterization of Packaging Effects via Segmentation Technique

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***Abstract*—The analysis of a monolithic microwave integrated circuit (MMIC) placed in a surface-mount plastic package is presented. Critical issues such as poor grounding conditions and crosstalk are addressed and discussed. The significance of a full-wave characterization of the component is shown. Results are validated with data available in the literature showing good agreement. A segmentation approach is also proposed to efficiently analyze the problem. The package effects are extracted and can be combined with MMIC parameters at the design stage to predict the performance of the packaged circuit.**

***Index Terms*— Circuit topology, packaging, transmission-line matrix.**

I. Introduction

THE INCREASE in clock rate and integration density in modern integrated circuit (IC) technology leads the designer to deal with problems for which traditional lumped circuit-design methodology fails to accurately account for the complex interactions between different parts of the circuit. Problems such as dispersion, crosstalk, and package effects require a full electromagnetic approach in order to predict their impact on the final configuration.

A typical problem is the characterization of a monolithic microwave integrated circuit (MMIC) once it is mounted in a package. The presence of leads, bond wires, and grounding p-i-n's affects the MMIC behavior. These effects must be included in the early design stages. In order to avoid costly design cycles, an electromagnetic approach becomes attractive to accurately predict the performances of a packaged circuit. Promising results have been obtained with the use of full-wave methods [1]–[6].

Among the numerical techniques available, the transmission-line matrix (TLM) method [7] is particularly suitable to analyze such complex geometries because of its flexibility and accuracy. In addition, it allows a transient analysis of the component, which is of particular importance in the presence of digital signals and nonlinear elements.

In this paper, we present the analysis of a surface-mount plastic package containing a simplified MMIC (a thru connection and a microstrip spiral inductor). In this way, the package effects are clearly shown. Problems such as poor grounding terminations and crosstalk with neighboring lines are also considered as they can occur at relatively low frequencies.

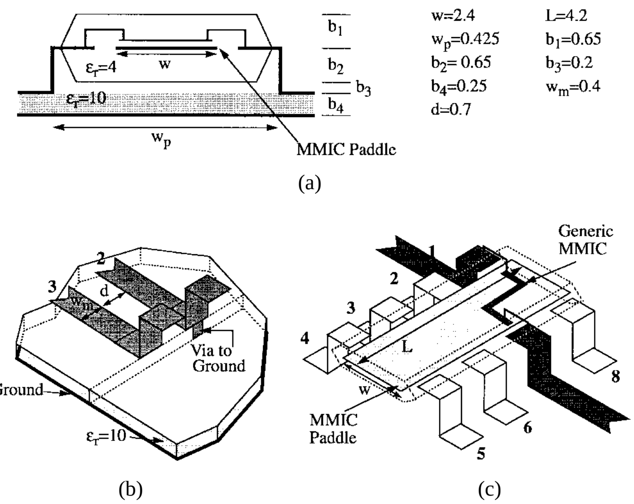

Fig. 1. Plastic package dimensions and geometrical details. All dimensions are in millimeter. (a) Package section. (b) Detail of the grounding to the motherboard. (c) MMIC mounted on the plastic package.

Finally, we propose an approach to isolate the package effects. The whole structure is segmented and the package is characterized by its scattering parameters. In this way, the package needs only to be modeled once for a given configuration. The behavior of the packaged MMIC's can then be computed by cascading the MMIC parameters with those of the package.

II. TLM Analysis of the SOIC-8 Package

The described critical issues appear in the analysis of the SOIC-8 surface-mount package. The structure comprises eight leads which allow the IC to be soldered onto the motherboard. Some of the leads are extended to the paddle (a term for the ground plan of the package) to provide grounding to the MMIC [e.g., lead 2 in Fig. 1(b) and (c)], while other leads are connected by bond wires to the MMIC providing input and output to the circuit [e.g., leads 1 and 7 in Fig. 1 (c)]. The geometry of the whole structure is shown in Fig. 1.

The behavior of the sole MMIC device is altered by the discontinuities present in the package, such as the microstrip steps, the bonding wires, and mutual coupling among the leads. At low frequencies, these discontinuities can be modeled

Manuscript received February 4, 1997; revised May 14, 1997. This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada, by the Science Council of British Columbia, by MPR Teltech Inc. of Burnaby, B.C., Canada, and by the University of Victoria, Victoria, B.C., Canada. The work of M. Righi was supported by an NSERC Post-Doctoral Fellowship.

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Publisher Item Identifier S 0018-9480(97)07395-X.

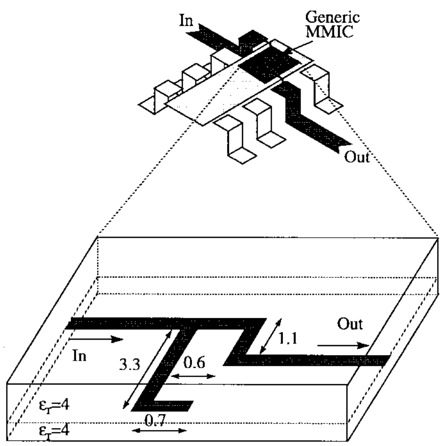


Fig. 2. Detail of the unpackaged MMIC (through-connection with stub). Embedded microstrip width: 0.3 mm. All dimensions are in millimeters.

with an equivalent lumped-element circuit composed of only reactive elements with straightforward topology. On the other hand, at high frequencies the parasitic phenomena become more complex and difficult to model. In addition, the packaged ground may suffer from poor characteristics. A poor MMIC ground will reinforce the parasitic loads, as the return currents must flow along the paddle edges to the grounding p-i-n's. Modes of wave propagation between the MMIC and the motherboard grounds may also be sustained. The full-wave analysis of such a structure accounts for all these parasitic phenomena simultaneously, including the radiation losses.

As test cases, we have considered three package configurations. The first configuration is a simple microstrip circuit consisting of a through connection with an open-circuited stub [8], [9]. This will allow the evaluation of the overall significance of the package effects. As a second example, a microstrip spiral inductor has been analyzed under poor grounding characteristics. Finally, the same package configuration is used to determine the parasitic coupling of an electromagnetic signal entering the package to a microstrip placed on the motherboard beneath the plastic package.

A. Through-Connection

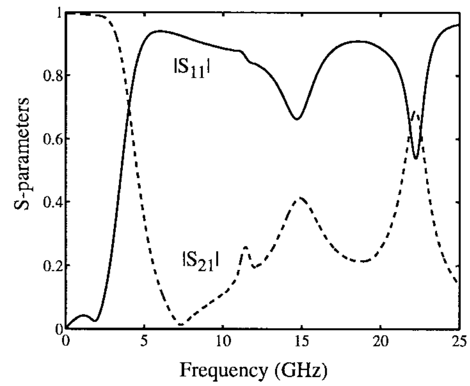
Consider the through-connection circuit shown in Fig. 2. From basic transmission-line theory it can be seen that this circuit provides a no-pass point at about 9 GHz when no parasitic effects are considered. In order to analyze the packaging effects, we considered the MMIC circuit depicted in Fig. 2 mounted on the SOIC-8 plastic package described in Fig. 1.

The simulation of the packaged MMIC was performed by discretizing the whole structure with a uniform mesh of size 178 $\times$ 106 $\times$ 43 cells. The three-dimensional (3-D) symmetrical condensed node (SCN) [10] was used. Single reflection-coefficient boundary conditions have been used to terminate the computational domain. The spatial discretization step was $\Delta l = 0.05$ mm. In this way, the whole structure is considered, from the input and output microstrip lines on the motherboard to the plastic package itself.

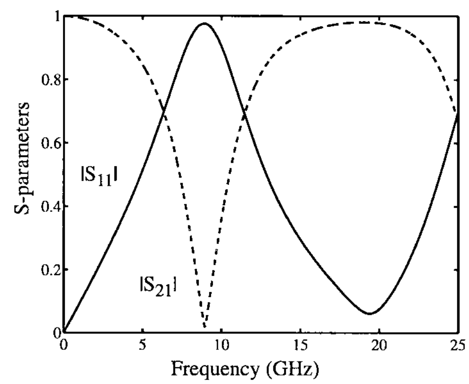
In this configuration, leads 1 and 7 provide input and output to the MMIC. All other leads are grounded though vias to the motherboard, although only leads 2, 4, 5, and 8 are extended to touch the paddle to provide grounding to the MMIC.

The TLM results for the scattering parameters in the frequency domain are shown in Fig. 3(a). In order to isolate the sole microstrip-circuit characteristics, the MMIC has been simulated unpackaged, and its S-parameters are shown in Fig. 3(b).

Note that the MMIC scattering parameters are drastically changed by the presence of the package. Not only is a shift of the no-pass point introduced, but also a more pronounced filtering action by the package is detected in the low-frequency



(a)



(b)

Fig. 3. TLM Analysis. (a) Scattering parameters of the SOIC-8 package. (b) Scattering parameters of the unpackaged MMIC circuit.

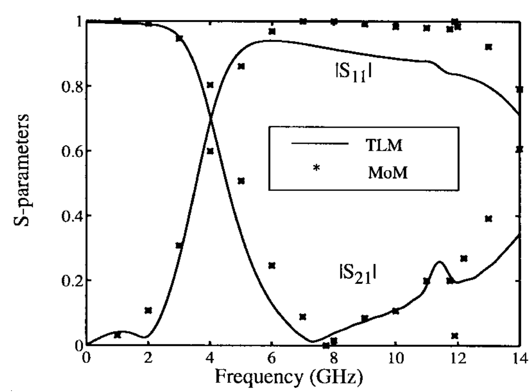


Fig. 4. Scattering parameters of the SOIC-8 package. The TLM results (as shown in Fig. 3) are compared with the MoM [8] in the frequency range of 0–14 GHz.

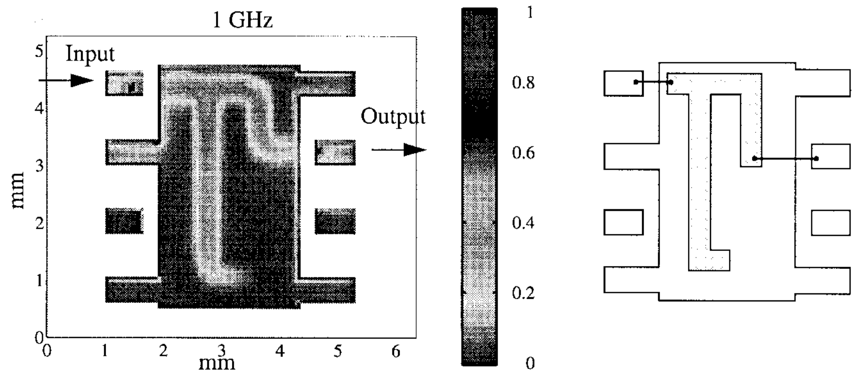


Fig. 5. Steady-state current distribution on the ground paddle at 1 GHz.

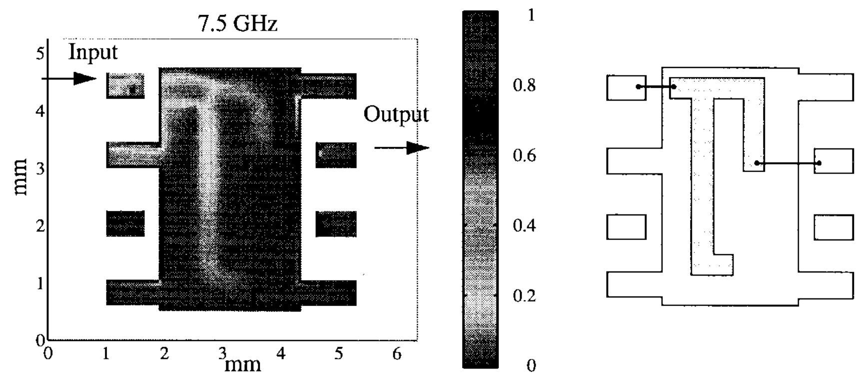


Fig. 6. Steady-state current distribution on the ground paddle at 7.5 GHz.

range. These results are validated by comparing them with a method of moments (MoM) approach [8], as shown in Fig. 4.

The comparison is favorable, since the MoM analysis was performed by assuming that all the dielectric layers extend across the entire computational volume.

From the transient analysis it is possible to extract information on the steady-state currents on the ground paddle. The information provided by the visualization of the return current path at the frequency of operation is very useful in determining the relative importance of the grounding leads.

In Figs. 5 and 6, the steady-state currents at low frequency (1 GHz) and at the no-pass point (7.5 GHz) are shown. From these plots it appears that the currents essentially flow under the microstrip up to the paddle edge, where they continue until they reach the grounding leads. The additional inductances introduced by these longer paths are partially responsible for the degrading of the circuit performance.

B. Poor Grounding

In order to highlight the effects of the grounding leads, a microstrip spiral inductor has been analyzed under poor grounding characteristics [see Fig. 7(a)].

In this case, the configuration was as follows. Leads 1 and 5 provide input and output to the spiral, while all other leads are grounded on the motherboard by means of vias, but only leads 4 and 8 are extended to provide ground on the package. Poor ground was simulated by assuming a faulty solder connection on one of the vias so that either via 4 or via 8 is ineffective.

Results are shown in Fig. 8. The results for the two cases of ineffective vias are overlapping and only one of the two is shown. This similarity can be explained considering the high degree of symmetry of the structure. Note that a poor ground reduces the bandwidth of operation of the inductor by 500 MHz because of the additional inductance provided by the longer path of the return currents.

C. Crosstalk

The same microstrip inductor has been used to evaluate the presence of crosstalk between the input line and a crossing microstrip on the motherboard [see Fig. 7(b)]. A transient analysis of the problem has been performed and the time-domain waveforms coupled to the victim crossing line have been extracted. This type of analysis is essential in the case of verification of signal integrity. The scattering parameters relative to the victim line are shown in Fig. 9.

Note that an unexpected amount of power is coupled on the near end. In the frequency range of 7–9 GHz, as much as 13% of the voltage is transferred to the victim line. This coupled power can lead to false switching on the gate driven by the victim line. The use of a full-wave method is particularly important in such a case, as a superficial characterization of the problem would tend to dismiss coupling on this remote line.

III. Segmentation

Although the information obtained from a full-wave analysis is very valuable, it is also computationally expensive.

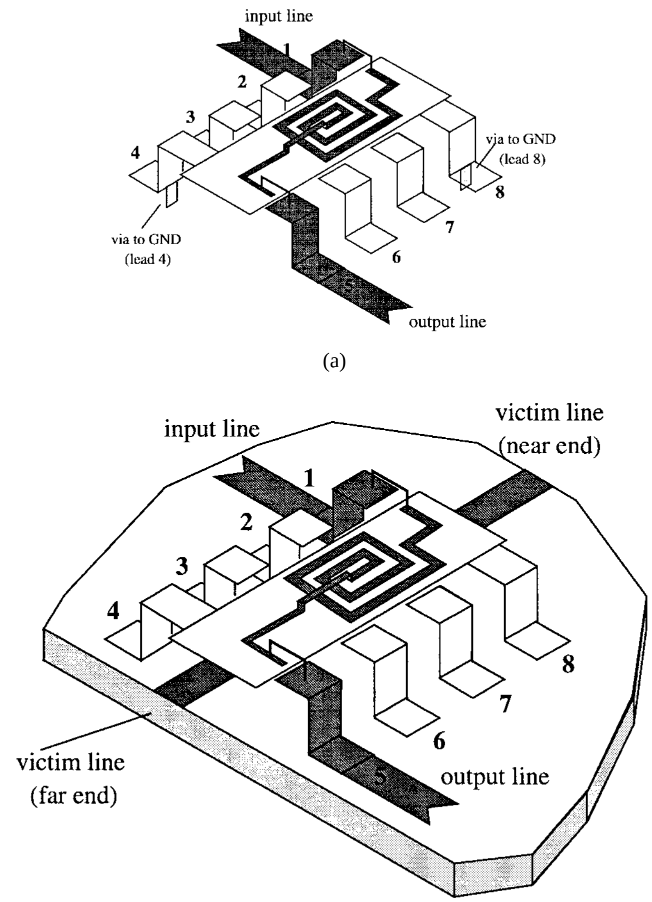


Fig. 7. (a) Geometry of the microstrip spiral inductor under poor grounding conditions (either via on lead 4 or 8 are made ineffective). (b) Geometry of the package with a microstrip line beneath it to evaluate crosstalk.

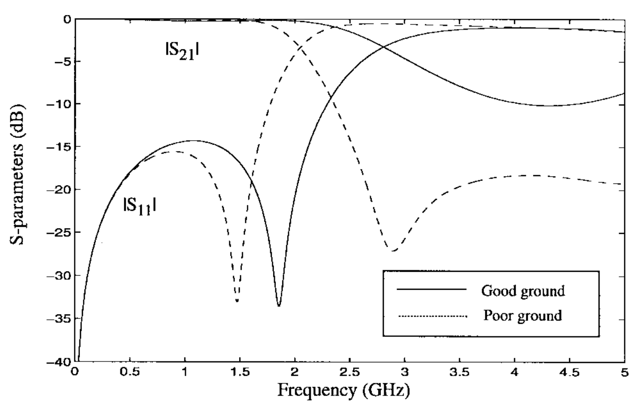


Fig. 8. Scattering parameters for the microstrip spiral inductor on the MMIC under good and poor grounding conditions.

Computational memory of the order of 70 Mbytes and central processing unit (CPU) time of the order of 15 h on an HP-735 workstation for the simulations shown in the previous section are common. Therefore, it becomes attractive to segment the problem in such a way that the package must be simulated only once to extract its characteristics, while the MMIC is later included. In this way, the MMIC alone can be more quickly designed with full-wave computer-aided design (CAD)

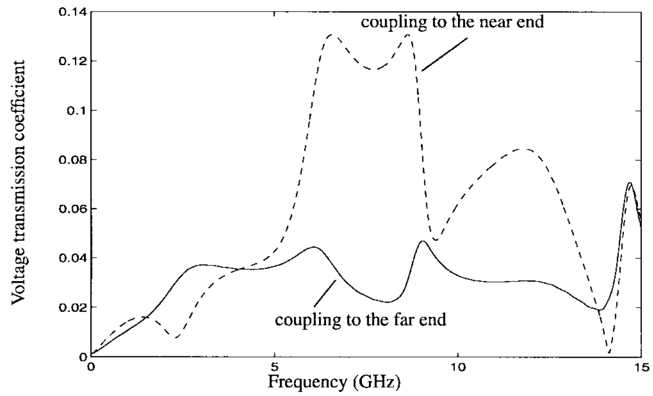


Fig. 9. Voltage transmission coefficient from the input line to the victim line for the configuration in Fig. 7(b).

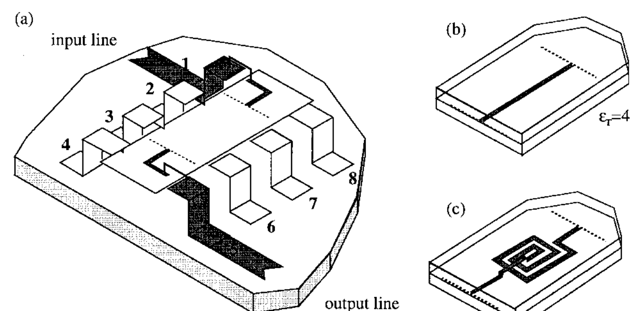


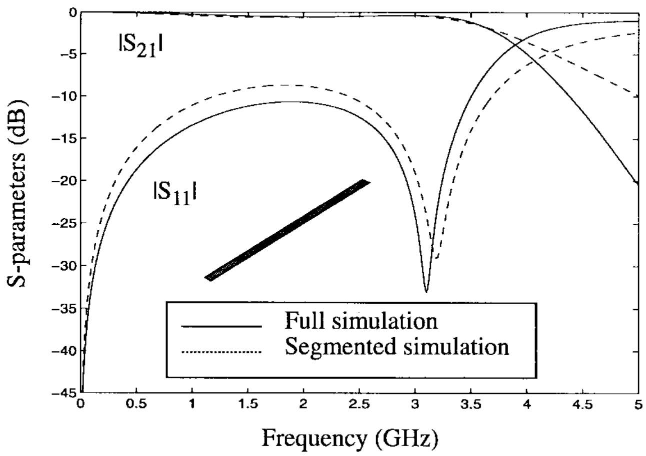
Fig. 10. Segmented structure. (a) Input and output sections. (b) Embedded thru connection. (c) Embedded spiral inductor. The dashed lines represent the reference planes.

or other design tools, and inserted in the package to verify its behavior at a simulation level, thus avoiding costly and time consuming cut-and-try cycles. In addition, the package behavior can be included in the MMIC design cycle from the design stage so that it can be optimized under real packaged conditions. A library of packages can be prepared and the MMIC characteristics (in different packages) can be predicted.

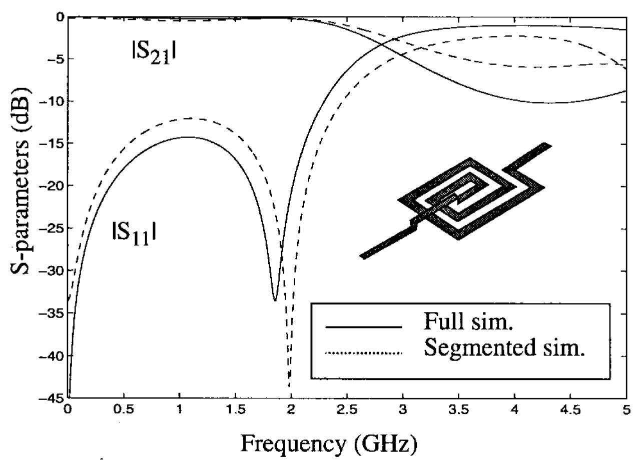
A possible approach to reduce the computational expenditures has been proposed by Jackson [8], through the use of a circuit model. In the proposed approach, a segmentation based on sub-circuits coupled by S-parameters has been adopted. We have segmented the structure in three sections. A first section consists of the microstrip on the motherboard, the transition to the package, the bonding wire, and the initial section of the MMIC. A second section is composed of the MMIC itself (in this case, a thru connection and a microstrip spiral inductor). A third section (similar to the first) provides transition to the output line on the motherboard. The process is illustrated in Fig. 10, where the dashed lines represent the reference planes at which the segmentation was operated.

Despite its simplicity, the thru connection is a representative example against which we can validate our procedure with a full simulation of the whole structure. A similar validation has been performed for the circuit consisting of the spiral inductor.

The three sections have been simulated independently. The resulting scattering parameters have then been cascaded in the



(a)



(b)

Fig. 11. Scattering parameters of the segmented structure compared with those of a full simulation. (a) Thru connection. (b) Spiral inductor.

frequency domain. In this case, it was assumed that only the dominant microstrip mode is present at the reference planes and a single-mode interaction was considered between the different sections. At low frequencies, this assumption was validated by plotting the return currents on the paddle and verifying that the current indeed flows under the microstrip. The segmentation plane can thus be considered an electrical port. At higher frequencies, the return currents are less confined under the microstrip. Therefore, this segmentation approach becomes less accurate. In this case, the full-wave analysis of the whole structure remains the most robust approach.

To determine the scattering parameters of the sole transitions it has been necessary to terminate the initial segment of the MMIC line on absorbing-boundary conditions (ABC's). Care was taken not to extend the ABC's too close to the paddle edges so that the return currents are not disturbed. In this way the correct current flow at the port is preserved. For the scattering parameters of the transition, the assumption $S_{22} = S_{11}$ has been made in order to reduce the computational effort.

The scattering parameters of the MMIC section can be obtained either with the TLM, with a significantly reduced computational effort (memory of about ∼12 Mbyte and CPU time of the order of 1 h), with a different CAD tool, or from analytical results where available.

The scattering parameters of the segmented structure and of the full structure for the two cases are shown in Fig. 11.

From these results it appears that the proposed approach is reliable in the frequency range dc to ∼4 GHz. Above this frequency, the assumption of single-mode interaction between the different sections fails to accurately describe the overall behavior of the circuit, thus requiring a more sophisticated multiport approach.

IV. Conclusion

The full-wave analysis of a surface-mount plastic package containing a test MMIC has been presented. The need for a full-wave tool to characterize the package effect is highlighted, and valuable insight into the behavior of the packaged MMIC is gained. Poor grounding conditions have been shown to significantly change the performance of the circuit, and crosstalk with crossing lines cannot be neglected.

A segmentation approach has also been proposed. The package effects have been extracted and combined with MMIC parameters to predict the performance of the packaged circuit at a fraction of the computational costs. In addition, the MMIC circuit can be optimized by including the package effects from the design stages.

Acknowledgment

The authors wish to thank Dr. J. Herring for useful discussions.

References

[1] M. Righi, J. L. Herring, and W. J. R. Hoefer, "Efficient hybrid TLM/mode-matching analysis of packaged components," this issue, pp. 1715-1724.

[2] R. Mittra, S. Chebolu, and W. D. Becker, "Efficient modeling of power planes in computer packages using the finite difference time domain method," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1791–1795, Sept. 1994.

[3] T. S. Horng, "A rigorous study of microstrip crossover and their possible improvements," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1802–1806, Sept. 1994.

[4] R. W. Jackson, "An electromagnetic model for determining resonance frequencies of low-cost MMIC packages," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1816–1819, Sept. 1994.

[5] Z. B. Popovic and B. D. Popovic, "Time-efficient modeling of the effect of metal packages on electrical circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1820–1826, Sept. 1994.

[6] Y. Chen, R. Mittra, P. Harms, and W. Beyene, "A technique for deriving the equivalent circuit of an SOP package using the FDTD in conjunction with Touchstone," in *Proc. IEEE 5th Topical Meeting Elect. Performance Electron. Packaging.*, Napa, CA, Oct. 1996, pp. 135–137.

[7] W. J. R. Hoefer, "The transmission-line matrix method—Theory and applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 882–893, Oct. 1985.

[8] R. W. Jackson, "A circuit topology for microwave modeling of plastic surface mount packages," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1140–1146, July 1996.

[9] ——, "Microwave circuit modeling of an elevated paddle surface mount package," in *Proc. IEEE 5th Topical Meeting Elect. Performance Electron. Packaging.*, Napa, CA, Oct. 1996, pp. 199–201.

[10] P. B. Johns, "A symmetrical condensed node for the TLM method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 370–377, Apr. 1987.

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