# Short Papers

## A New Approach for the Experimental Circuit Modeling of Coupled Interconnection Structures Based on Causality

S. Sercu and L. Martens

***Abstract*—In this paper, a time-frequency-domain technique for the experimental circuit modeling of coupled interconnection structures and discontinuities is presented. The technique models and de-embeds all discontinuities and coupled substructures of the device under test (DUT) one by one, and is based on the principle of causality. Validation of each part of the model is done in the time domain, while all calculations are performed in the frequency domain. To validate the accuracy of the circuit models, measured reflection, transmission, and near- and far-end crosstalk are compared with simulated results.**

***Index Terms*— Causality, circuit modeling, coupled interconnection structures.**

### I. Introduction

Since high-speed digital circuits operate at higher frequencies, the contribution of passive devices (such as the interconnections and the discontinuities between the different active circuits and the different parts of high-density packages) to the circuit behavior is no longer insignificant. These structures may cause reflection, crosstalk, and signal delay and distortion, and therefore, can degrade the circuit and system performance. In order to predict and optimize the performance of high-speed systems, designers must take into account the effect of these passive interconnections. Hence, circuit models are not only needed for the active devices, but also for the packages and interconnections. Moreover, physical models are needed for which each element refers to a well-defined part of the physical structure. This allows the designer to locate the parts of the structure which degrade the high-frequency behavior, and to redesign these sections.

Circuit modeling of an interconnection structure from measurements is generally done by optimization [1]. Based upon his or her experience and physical insight in the structure, the designer chooses the topology of the model. Matching the simulated reflection to the measurement data yields the parameter values of the proposed model. If it is not possible to achieve an agreement within the desired accuracy, another model topology must be proposed and evaluated. However, for large structures with many discontinuities and poor starting values, this procedure can lead to convergence problems and nonphysical parameter values. Recently, new methods are developed to derive circuit models for single or coupled interconnection structures from measurements or simulations [2]–[8].

In [9], a method is presented for the circuit modeling of passive two-port structures. The method extracts hybrid-circuit models from reflection and transmission measurements and is based on the principle of causality. For each discontinuity of the structure, a circuit model—consisting of lumped elements and transmission lines—is proposed. The topology of the model is chosen on the basis of the time-domain reflection (TDR) picture or of physical insight. All parameters of the proposed model, with exception of the characteristic impedance of the transmission line, are initialized to negative values. When the inversion of the proposed model is connected to the input port of the measurements, noncausal TDR and time-domain transmission (TDT) pictures are obtained due to the negative delay of the transmission line in the model. In an optimization process, the parameter values are changed until the time-domain pictures regain their causality. Once the parameters are determined, the model is de-embedded from the measurements and the procedure restarts until all discontinuities are modeled. Since each discontinuity is handled one by one, the method is very suitable for the circuit modeling of structures with multiple discontinuities and for the automatic generation of circuit models. This also means that only a limited number of parameter values must be determined by optimization. This makes the method faster, and it suffers less from local minima than modeling techniques, which use optimization to determine all parameters at once. The obtained models are physical circuit models (i.e., each element is related to a certain physical part of the structure under test).

In this paper, the algorithm is extended to the circuit modeling of two coupled interconnection structures. The algorithm in its present state can only model devices which are a cascaded interconnection of elementary sections. The algorithm is not able to model loop or tree structures. However, it is possible to extend the algorithm to model these structures as well. In Section II, the modeling algorithm is described. In Section III, the algorithm is illustrated in two examples.

### II. Modeling of Coupled Structures

We now describe the algorithm to model coupled or four-port interconnection structures. We assume that the device under test (DUT)—two coupled structures with multiple discontinuities—can be modeled as a cascaded interconnection of elementary two- or four-port substructures. Each substructure models a well-defined part of the DUT. Starting point for the algorithm are the $S$-parameters of the four-port structure.

In a *first step*, we propose two uncoupled models for the first four-port substructure of the DUT [see Fig. 1(a)] and we apply the procedure described in [9]. Both models can consist of lumped elements and transmission lines, and must be terminated with a transmission line. Then we invert the proposed models and connect the inverted models to the two inputs of the four-port [see Fig. 1(b)] and we calculate the corresponding time-domain pictures [see Fig. 1(c)]. The time-domain pictures are calculated from the $S$-parameters with an inverted fast Fourier transform (FFT) using a smooth step-signal excitation with a 10%–90% rise time $t_r$. This rise time determines the bandwidth for which the circuit model is valid and the distinguishable delay between two successive discontinuities. Due to the negative delay of the transmission lines, these pictures are not causal. Not only are the reflection and transmission pictures calculated, but the backward and forward crosstalk are also evaluated. If this backward crosstalk is noncausal, then it is not possible to model the first part of the DUT with an uncoupled model. The proposed circuit model must be replaced with, or extended to, a coupled model (see Fig. 2). This model can either be lumped (such as coupling inductors or capacitances) or distributed (such as coupled transmission lines).

In a *second step*, all parameters of the proposed model—except for the delay of the terminating transmission lines in the model of

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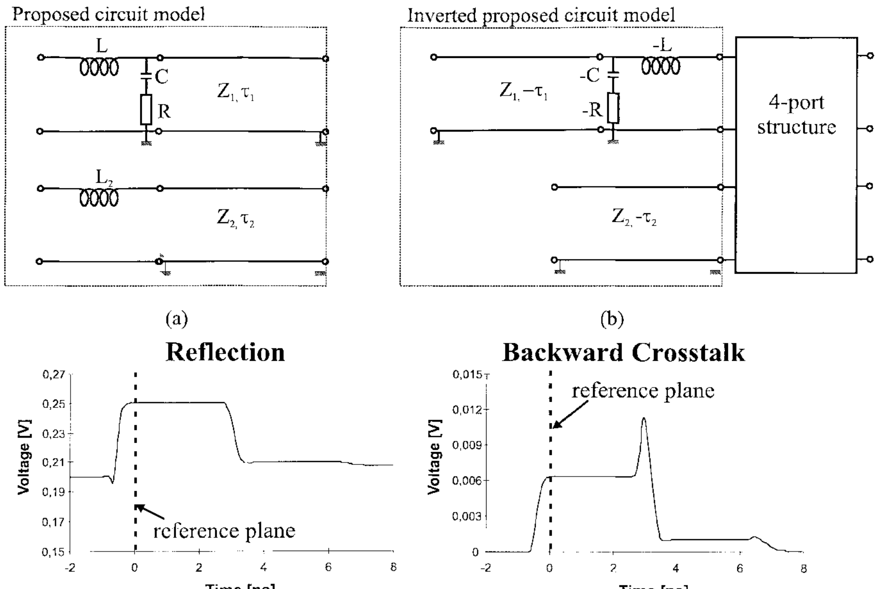



Fig. 1. (a) Proposed uncoupled circuit model. (b) Connection of the inverted proposed circuit model with the $S$-parameters of the four-port structure results in (c) noncausal reflection and backward crosstalk pictures.

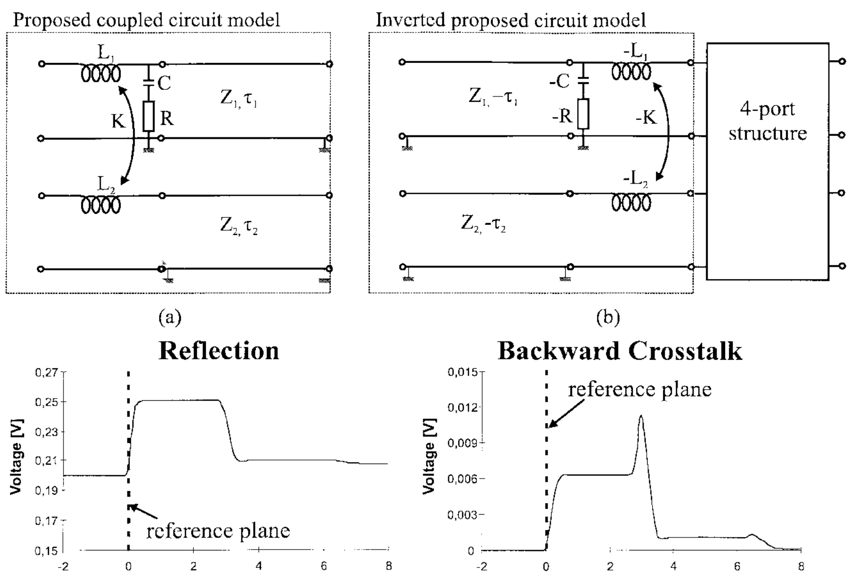
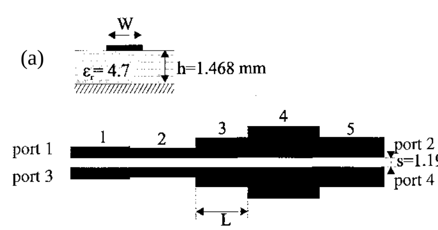



Fig. 2. (a) Proposed coupled circuit model. (b) Connection of the inverted proposed circuit model with the $S$-parameters of the four-port structure results after optimization in (c) causal reflection and backward crosstalk pictures.

the first discontinuity—are determined by optimization. The delay of the terminating transmission lines is assigned a fixed negative value equal to half the rise time of the injected time-domain step signal The parameter values for which not only reflection and transmission, but also backward and forward crosstalk regain their causality, are the values we are looking for. If the parameters cannot be optimized to obtain causal time-domain pictures, the topology of the model must be extended or replaced by a new one and the optimization is repeated.

In a *third step*, the circuit model of the first substructure is de-embedded from the measurements of the four-port structure and the next substructure is modeled using the same algorithm. Finally, this procedure is applied to all substructures delivering the complete model for the four-port interconnection.

(a)




(b)

| | W (mm) | L (mm) |
|---|---|---|
| 1 | 2.778 | 14.287 |
| 2 | 2.381 | 15.875 |
| 3 | 4.762 | 12.700 |
| 4 | 7.540 | 17.462 |
| 5 | 4.762 | 15.875 |

Fig. 3. (a) Two nonuniform symmetrical coupled microstrip lines. (b) Dimensions of the configuration.

It is almost always possible to find an appropriate topology for a discontinuity, but sometimes many optimizations and evaluations of several different models are required. The fastest way to find it is by

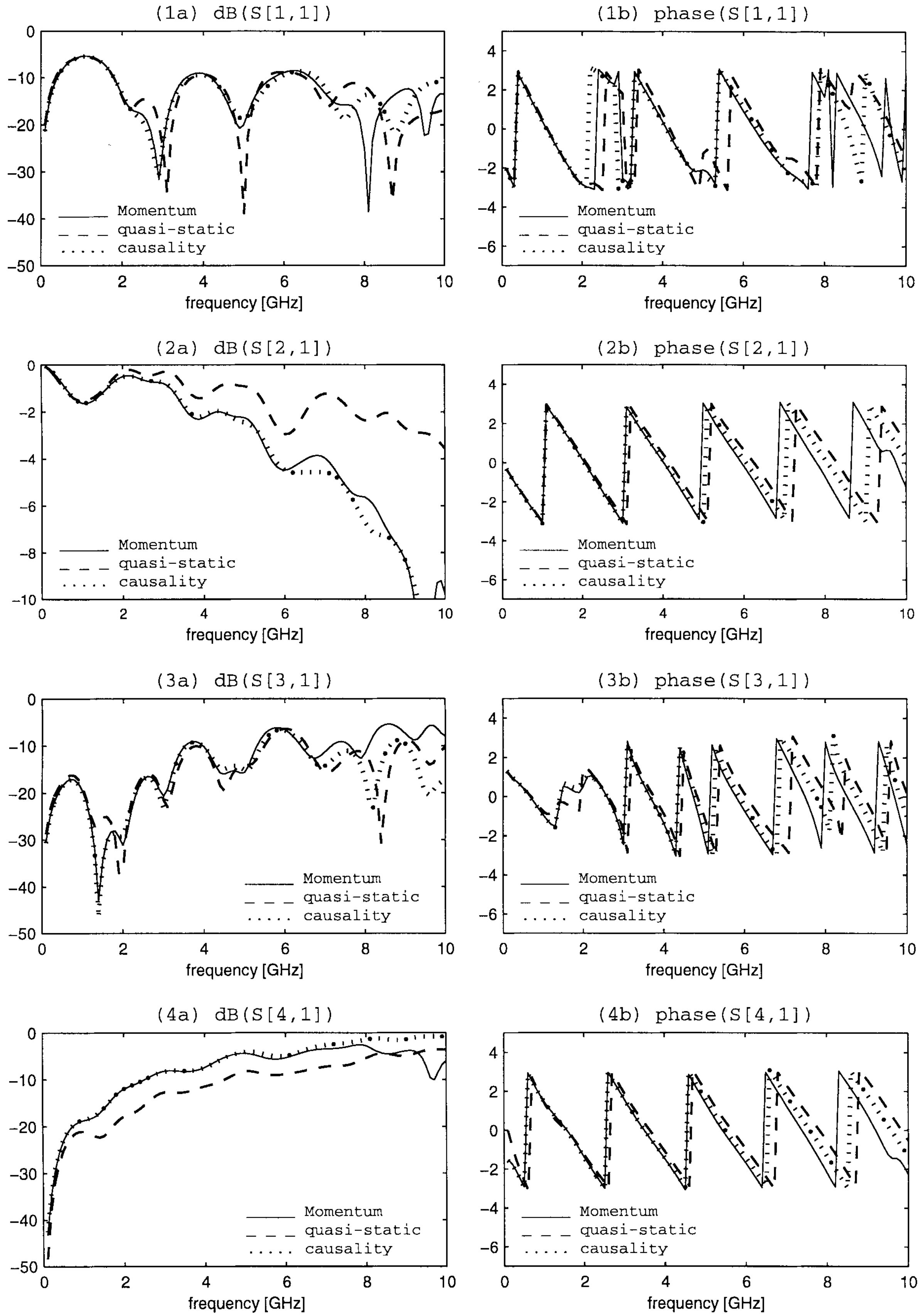
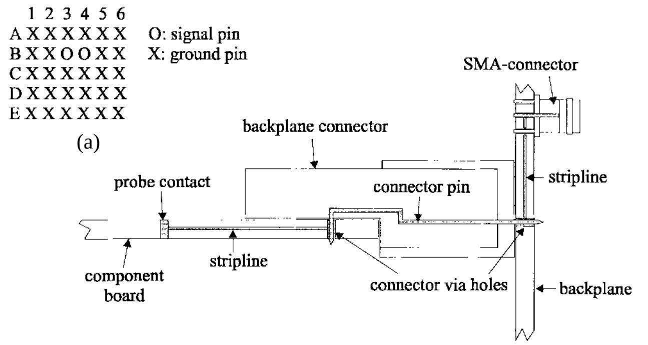
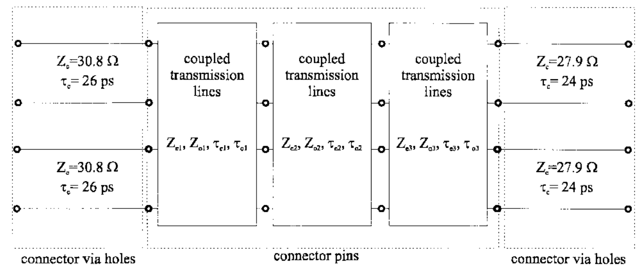



Fig. 4. Comparison of the simulated (HP-Momentum) and modeled $S$-parameters of the structure of Fig. 3. Two models are considered—the quasi-static model and the model obtained with the described algorithm. 1: reflection. 2: transmission. 3: backward crosstalk. 4: forward crosstalk. [(a) Amplitude in dB. (b) Phase].




(b)

Fig. 5. Backplane connector mounted on a component board and a backplane board. (a) Connector signal/ground configuration: pin's $B3$ and $B4$ are signal pin's; all other pin's are short-circuited to ground. (b) Interconnection configuration: signal via hole, stripline, connector via hole, connector pin, connector via hole, stripline, and SMA connector.




| section | $Z_c$ (Ω) | $Z_o$ (Ω) | $\tau_c$ (ps) | $\tau_o$ (ps) |
|---|---|---|---|---|
| 1 | 68.0 | 58.0 | 17 | 20 |
| 2 | 60.3 | 42.6 | 39 | 35 |
| 3 | 70.6 | 50.4 | 35 | 33 |

Fig. 6. Circuit model for the connector via holes and the two connector pin's of the configuration of Fig. 5.

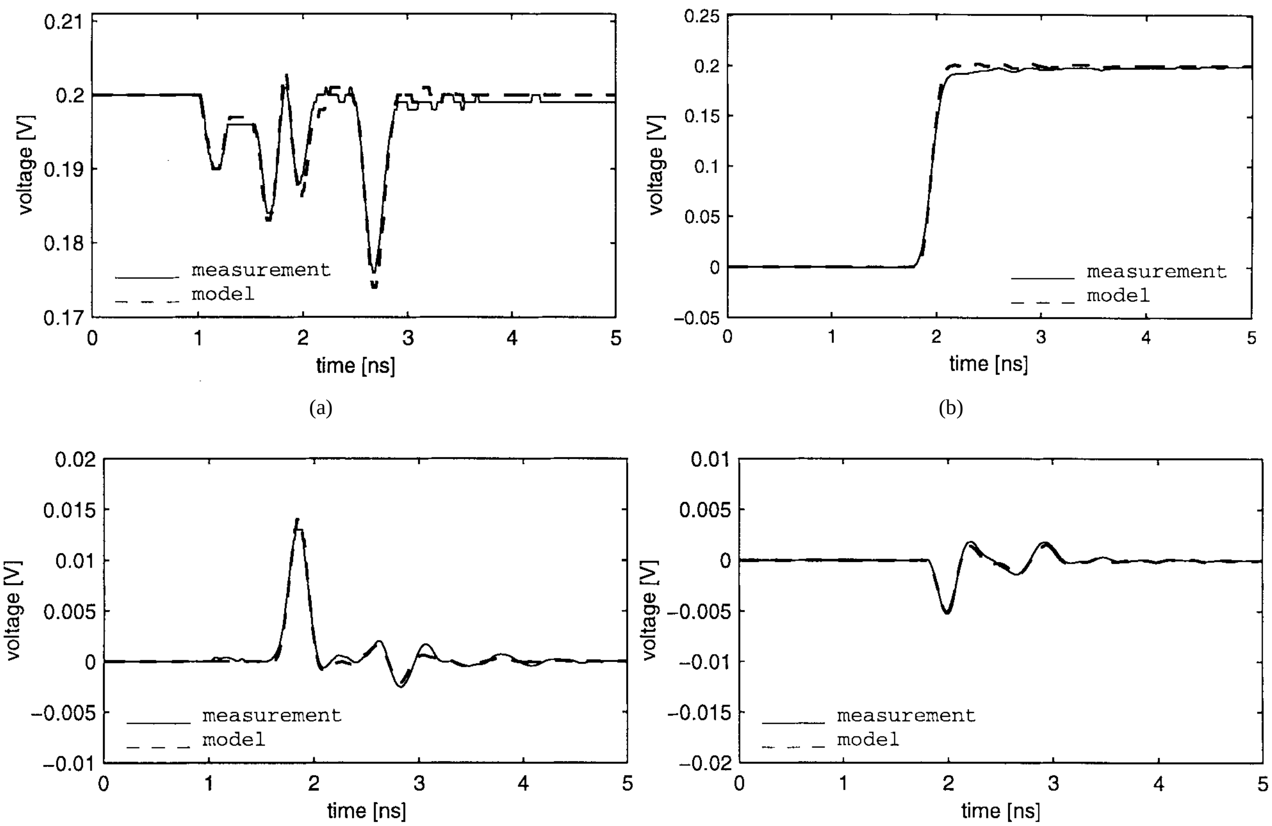



Fig. 7. Comparison of measurement and model in the time domain. (a) Reflection, (b) transmission, (c) backward, and (d) forward crosstalk.

starting the modeling procedure with a higher rise time than the rise time for which the model is derived. In this way, a low-frequency model for the discontinuity is obtained. This model can be used as a starting topology to derive the desired high-frequency model. If it is not clear how the topology must be extended, several topology extensions must be evaluated. The topology for which the noncausal part of the step response is minimal must be chosen to work further with. Since the behavior of the discontinuities are de-embedded from the reflection and transmission measurement of the structure under test, it is extremely important that an accurate model is obtained for the discontinuities, especially for the first ones. A wrong model causes errors which propagate through the modeling of the interconnection structure. Applying the modeling procedure with injection of a signal at both sides of the structure can be used to improve the accuracy of the obtained model for an electrically long interconnection structure.

## III. Experimental Results

To illustrate the algorithm, two examples are considered. First, the method described is used to characterize the nonuniform symmetrical coupled microstrip line, which is constructed by cascading uniform line sections. The structure is also described in [10]. The $S$-parameters of the structure are calculated with the EM-field simulator HP-Momentum.[1] Fig. 4 compares simulated and modeled $S$-parameters of the structure of Fig. 3. Two models are considered. The first one is a low-frequency quasi-static model, which consists of cascaded coupled transmission-line sections from which the circuit parameters are determined with a quasi-static EM solver [11]. The quasi-static model does not include field effects at the location of the discontinuities. The second model is obtained with the described algorithm starting from the simulated $S$-parameters. The algorithm is applied with a smooth step signal with rise time $t_r = 100$ ps. Fig. 4 shows that the derived model is valid up to 7 GHz and that the field effects of the discontinuities must be considered in the equivalent-circuit model.

The second example is shown in Fig. 5. The DUT consists of two connector pin's of a multipin's backplane connector placed on a component board and a backplane board. Striplines on both printed circuit boards are making contact with the connector pin's. In order to connect the striplines with the measurement instrument, the component board is provided with planar contacts for coplanar probes, while the backplane board has SMA connectors. Measurements are performed with the HP8510 network analyzer from 50 MHz to 20.05 GHz using a SOLT calibration. The obtained circuit model for the connector via holes and the connector pin's is shown in Fig. 6. The connector via holes are modeled with a transmission line, while the connector pin's are modeled by three coupled transmission lines. Fig. 7 compares measured and modeled reflection, transmission, backward, and forward crosstalk for an incident step signal with a rise time of 150 ps. As can be concluded from these pictures, not only reflection, but also transmission (rise-time degradation) and crosstalk are accurately modeled.

## IV. Conclusion

An algorithm is presented for the circuit modeling of coupled interconnection structures. Based on the principle of causality, a hybrid circuit-model equivalent consisting of lumped elements, transmission lines, and coupled elements is derived for the structure under test. The simulation and measurement examples show that reflection, transmission, and crosstalk properties of the interconnection are accurately modeled.

## References


[1] A. J. Baden Fuller and A. M. Parker, "Computer optimization of circuits applied to the modeling of microwave IC passive components," *Proc. Inst. Elect. Eng.*, vol. 133, pt. H, pp. 411–418, Oct. 1986.

[2] J. M. Jong and V. K. Tripathi, "Time-domain characterization of interconnect discontinuities in high-speed circuits," *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. 15, pp. 497–504, Aug. 1992.

[3] A. K. Agrawal, K. M. Lee, L. D. Scott, and H. M. Fowles, "Experimental characterization of multiconductor transmission lines in the frequency domain," *IEEE Trans. Electomagn. Compat.*, vol. EMC-21, pp. 20–27, Feb. 1979.

[4] A. K. Agrawal, H. M. Fowles, and L. D. Scott, "Experimental characterization of multiconductor transmission lines in inhomogeneous media using time-domain techniques," *IEEE Trans. Electomagn. Compat.*, vol. EMC-21, pp. 28–32, Feb. 1979.

[5] J. M. Jong, B Janko, and V. K. Tripathi, "Equivalent circuit modeling of interconnects from time-domain measurements," *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. 16, pp. 119–126, Feb. 1993.

[6] J. C. Rautio, "Synthesis of lumped models from $N$-port scattering parameter data," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 535–537, Mar. 1994.

[7] L. A. Hayden and V. K. Tripathi, "Characterization and modeling of multiple line interconnections from time domain measurements," *Trans. Microwave Theory Tech.*, vol. 42, pp. 1737–1743, Sept. 1994.

[8] C. E. Abernethy, A. C. Cangellaris, and J. L. Prince, "A novel method of measuring microelectronic interconnect transmission line parameters and discontinuity equivalent electrical parameters using multiple reflections," *IEEE Trans. Comp., Packag., Manufact. Technol. B*, vol. 19, pp. 32–39, Feb. 1996.

[9] S. Sercu and L. Martens, "A new algorithm for experimental circuit modeling of interconnection structures based on causality," *IEEE Trans. Comp., Packag., Manufact. Technol. B*, vol. 19, pp. 289–295, May 1996.

[10] J. M. Jong, L. A. Hayden, and V. K. Tripathi, "Time domain measurements, characterization and modeling of interconnects," in *40th ARFTG Conf. Dig.*, Orlando, FL, Dec. 3–4, 1992, pp. 96–103.

[11] F. Olyslager, D. De Zutter, and K. Blomme, "Rigorous analysis of the propagation characteristics of general lossless and lossy multiconductor transmission lines in multilayered media," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 79–88, Jan. 1993.


[1] Momentum, Hewlett-Packard EEsof, Santa Rosa, CA.

# Coax Via—A Technique to Reduce Crosstalk and Enhance Impedance Match at Vias in High-Frequency Multilayer Packages Verified by FDTD and MoM Modeling

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***Abstract*—Large-scale crosstalk at vias and poor via electrical performance are major drawbacks in state-of-the-art high-frequency multilayer first- or second-level integrated-circuit/monolithic-microwave integrated-circuit (IC/MMIC) packages. The coax via design modeled in this paper breaks new ground in achieving more than 30-dB ultrawide-band crosstalk reduction and providing an enhanced impedance match.**

## I. Introduction

The multilayer integrated-circuit (IC) package known as a single-chip module (SCM) or multichip module (MCM) used in high input/output (I/O) digital applications—whether organic, alumina, or glass/ceramic based—is now being aggressively sought after as the circuit carrier of choice in integrating microwave, RF wireless, and high-speed digital circuits driven by the underlying cost factors associated with those markets. Although manufacturing such a high-frequency package with good material and dimensional tolerances is proving to be less difficult at frequencies well into the gigahertz range, it is a real challenge to be able to design the package electrically against distortion—namely, crosstalk. Constant-impedance TEM stripline transmission used in the inner layers is extremely effective in achieving negligible crosstalk [1]. Quasi-TEM microstripline transmission used on the top layer causes significant crosstalk [2], but can be circumvented by either placing shielding grounded vias (see Fig. 1) between lines or going directly from device/chip pad into an inner layer. The third and only other (yet most problematic) crosstalk hot spot occurs at signal via-hole transitions. Here, the physical discontinuity causes several unwanted modes that cause severe coupling to other vias and lines. No amount of optimization of the via dimensions, materials, or dielectric constants

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