Chapter 6

Conclusion

In this dissertation an efficient and accurate quasi-static methodology is presented for evaluating frequency dependent resistance and inductance of high-speed digital interconnects and various lossy transmission lines. For circuit performance evaluation and signal integrity analysis in high-speed computer and communication systems, the prediction of parasitic resistance and inductance as well as capacitance is required especially for inter-chip interconnects, e.g., in multichip modules (MCMs), where the conductor loss becomes important as the clock speed increases. Resistance and inductance prediction is required from DC to high frequency where the skin depth is of the order of the cross-sectional dimension of the conductor. At high frequency the standard impedance boundary condition (SIBC) can be incorporated with various electromagnetic field solvers, but it is hard to apply SIBC at low and mid frequency because accuarate surface impedance modeling is difficult at that regime. For unified evaluation of resistance and inductance from low to high frequency, the effective internal impedance (EII) is defined as an approximation to the surface impedance of the isolated conductor, which characterizes the interior of the conductor to represent resistance and internal inductance. Three different models of EII are presented: first, the plane wave model assumes a plane wave is incident onto all conductor surfaces and penetrates into the conductor. Second, the modified plane wave model takes care of the reflection and transmission of the plane wave inside and the interface of the conductor at low frequency and, therefore, accurately accommodates low frequency behavior. Third, the transmission line model divides the conductor into triangular patches near the corner and flat slabs, and EII is defined by solving non-uniform and uniform telegraphist's equation. By combining the boundary element method (BEM) and EII it is demonstrated that these EII models give a good approximation to the surface impedance and are useful as SIBC at high frequency, but at low and mid frequency EII is different from SIBC.

EII should be incorporated with appropriate field solvers to accurately predict resistance and inductance, regardless of the frequency of interest. First, the conformal mapping is combined with EII, which is efficient and reasonably accurate in that it avoids numerically intensive matrix manipulation and considers the geometrical symmetry. It is applied for asymmetric transmission lines, the effect of the conductor thickness is examined, and the effectiveness is shown. But, its application to complicated multi-conductor transmission lines and three dimensional geometries is restricted due to the difficulty of finding the conformal maps. To overcome the limit of the conformal mapping technique the more rigorous, Green's function based surface current integral equation is successfully incorporated with EII for regular two dimensional transmission lines and three dimensional structures. And these are shown to be efficient and accurate through comparison with existing rigorous quasi-static techniques of the volume filament method (VFM) and the partial element equivalent circuit method (PEEC), which are based on the volume current integral equation.

The EII approach fundamentally reduces the computational time and memory by modeling the conductor interior as an impedance shell at the conductor surface and replacing the discretization of the conductor interior with the discretization of the conductor surface. Further computational efficiency can be obtainable by applying numerically fast matrix solvers such as the multipole-accelerated, preconditioned generalized minimal residual (GMRES) algorithm or other iterative solvers exploiting sparsification of the matrix. As a next step in circuit performance evaluation of quantities such as delay, crosstalk, simultaneous switching noise, etc., the proposed technique of calculating frequency dependent resistance and inductance can be interfaced with existing convolution based or SPICE-like time domain circuit simulators, in conjunction with moment-matching methods. One way is to use frequency independent circuit representation, where the frequency dependent series impedance is approximately synthesized using lumped *RL* ladder circuits. The other way is to represent the impulse response of the frequency dependent lines using *Y*-parameters, *S*-parameters, etc. and, then, to simulate in the time domain by matching the nonlinear boundary conditions. In this approach the frequency dependent transmission line is modeled as a macro and it is used in a SPICE-like simulator.

Appendix

Analysis of Coupled Lossy Transmission Lines

Time domain simulation of signal propagation along lossy transmission lines is feasible with various SPICE-like or other simulators. For the circuits with linear loads, the fast Fourier transform (FFT) can be easily adopted to the analysis of the transmission lines. For coupled lossy transmission lines as shown in Fig. 4.10, the telegraphist's equation is solved with appropriate driver and load conditions as in reference [91,92] . And the following transfer functions are driven for an active and a quiet line.

$$\frac{V_{1,2}(x,\omega)}{V_{in}(\omega)} = 0.5\left[\frac{1}{P_1}\frac{e^{-\gamma_1 x}+\rho_{L1}e^{-\gamma_1(2l-x)}}{1-\rho_{S1}\rho_{L1}e^{-2\gamma_1 l}} \pm \frac{1}{P_2}\frac{e^{-\gamma_2 x}+\rho_{L2}e^{-\gamma_2(2l-x)}}{1-\rho_{S2}\rho_{L2}e^{-2\gamma_2 l}}\right], \quad \text{(A.1)}$$

where Z_L is the load impedance, Z_S is the driver impedance, V_1 and V_2 are the voltage of an active and a quiet line, respectively.

$$\rho_{Ln} = \frac{Z_L - Z_n}{Z_L + Z_n} \qquad \rho_{Sn} = \frac{Z_S - Z_n}{Z_S + Z_n} \qquad P_n = 1 + \frac{Z_S}{Z_n} \quad \text{(A.2)}$$

Z_n is the characteristic impedance for even and odd mode of two lines,

$$Z_1 = \sqrt{\frac{(R_{11}+R_{12})+j\omega(L_{11}+L_{12})}{j\omega(C_{11}-C_{12})}} \qquad Z_2 = \sqrt{\frac{(R_{11}-R_{12})+j\omega(L_{11}-L_{12})}{j\omega(C_{11}+C_{12})}} \quad \text{(A.3)}$$

and γ_n is the propagation constant for even and odd mode of two lines.

$$\gamma_1 = \sqrt{\{(R_{11}+R_{12})+j\omega(L_{11}+L_{12})\}j\omega(C_{11}-C_{12})} \quad \text{(A.4)}$$

$$\gamma_2 = \sqrt{\{(R_{11}-R_{12})+j\omega(L_{11}-L_{12})\}j\omega(C_{11}+C_{12})}\,.$$

And through a fast Fourier transform (FFT) time domain signal profile is obtained.

BIBLIOGRAPHY

[1] A. Cangellaris, "A note on the calculation of the current distribution in lossy microstrip structures," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 81-83, April 1991.

[2] G. L. Matthaei, K. Kiziloglu, N. Dagli, and S. I. Long, "The nature of the charges, currents, and fields in and about conductors having cross-sectional dimensions of the order of a skin depth," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1031-1035, August 1990.

[3] R. C. Frye, and H. Z. Chen, "Optimal self-damped lossy transmission line interconnections for multichip modules," *IEEE Trans. Circuits Sys.-II: Analog Digital Signal Process.*, vol. 39, pp. 765-771, November 1992.

[4] J. Jin, *The Finite Element Method in Electromagnetics*. John Wiley & Sons, Inc., 1993.

[5] A. Darcherif, A. Raizer, J. Sakellaris, and G. Meunier, "On the use of the surface impedance boundary concept in shielded and multiconductor cable characterization by the finite element method," *IEEE Trans. Magnetics*, vol. 28, pp. 1446-1449, March 1992.

[6] T. H. Fawzi, M. T. Ahmed, and P. E. Burke, "On the use of impedance boundary conditions in eddy current problems," *IEEE Trans. Magnetics*, vol. MAG-21, pp. 1835-1840, September 1985.

[7] E. M. Deely, "Avoiding surface impedance modification in BE methods by singularity-free representations," *IEEE Trans. Magnetics*, vol. 28, pp. 2814-2816, September 1992.

[8] J. R. Mosig, "Arbitrary shaped microstrip structures and their analysis with a mixed potential integral equation," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 314-323, February 1988.

[9] B. J. Rubin, "An electromagnetic approach for modeling high-performance computer packages," *IBM J. Res. Develop.*, vol. 34, pp. 585-600, July 1990.

[10] J. G. Maloney, and G. S. Smith, "The use of surface impedance concepts in the finite-difference time-domain method," *IEEE Trans. Antennas Prop.*, vol. 40, pp. 39-48, January 1992.

[11] J. H. Beggs, R. J. Luebbers, K. S. Yee, and K. S. Kunz, "Finite-difference time-domain implementation of surface impedance boundary conditions," *IEEE Trans. Antennas Prop.*, vol. 40, pp. 49-56, January 1992.

[12] M. A. Leontovich, "On the approximate boundary conditions for electromagnetic fields on the surface of well conducting bodies," *Investigations of Propagation of Radio Waves*, pp. 5-20, B. A. Vvdensky, Ed. Moscow: Academy of Sciences USSR, 1948.

[13] D. J. Hoppe, and Y. Rahmat-Samii, *Impedance Boundary Conditions in Electromagnetics*. A SUMMA Book, 1995.

[14] S. A. Schelkunoff, "The electromagnetic theory of coaxial transmission lines and cylindrical shields," *B.S.T. Journal*, vol. 13, pp. 532-579, 1934.

[15] T. B. Senior, "Impedance boundary conditions for imperfectly conducting surfaces," *Appl. Sci. Res.*, vol. 8, pp. 418-436, 1960.

[16] K. M. Mitzner, "An integral equation approach to scattering from a body of finite conductivity," *Radio Sci.*, vol. 2, pp. 1459-1470, 1967.

[17] R. Horton, B. Easter, and A. Gopinath, "Variation of microstrip losses with thickness of strip," *Elctrn. Lett.*, vol. 26, pp. 490-491, August 1971.

[18] E. M. Deely, "Surface impedance near edges and corners in three-dimensional media," *IEEE Trans. Magnetics*, vol. 26, pp. 712-714, March 1990.

[19] W. Jingguo, J. D. Lavers, and Z. Peibai, "Modified surface impedance boundary condition applied to eddy current problems," *IEEE Trans. Magnetics*, vol. 28, pp. 1197-1200, March 1992.

[20] W. Jingguo, and J. D. Lavers, "Modified surface impedance boundary condition for 3D eddy current problems," *IEEE Trans. Magnetics*, vol. 29, pp. 1826-1829, March 1993.

[21] E. Tuncer, "Extraction of parameter for high speed digital interconnects," Ph.D. thesis, Graduate School of The University of Texas at Austin, August 1995,

[22] E. Tuncer, B.-T. Lee, and D. P. Neikirk, "Interconnect series impedance determination using a surface ribbon method," *IEEE 3rd Topical Meetings on Electrical Performance of Electronic Packaging*, Monterey, CA, November 2-4, 1994, pp. 249-252.

[23] E. Tuncer, M. S. Islam, B.-T. Lee, and D. P. Neikirk, "Quasi-static conductor loss calculations in transmission lines using a new conformal mapping technique," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-42, pp. 1807-1815, September 1994.

[24] W. T. Weeks, L. L. Wu, M. F. McAllister, and A. Singh, "Resistive and inductive skin effect in rectangular conductors," *IBM J. Res. Develop.*, vol. 23, pp. 652-660, November 1979.

[25] M. J. Tsuk, and J. A. Kong, "A Hybrid method for the calculation of the resistance and inductance of transmission lines with arbitrary cross sections," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1338-1347, August 1991.

[26] H. A. Wheeler, "Transmission-line properties of a strip on s dielectric sheet on a plane," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 631-647, August 1977.

[27] A. R. Djordjevic, and T. K. Sarkar, "Closed-form formulas for frequency-dependent resistance and inductance per unit length of microstrip and strip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 241-248, February 1994.

[28] G. H. Owyang, and T. T. Wu, "The approximate parameters of slot lines and their complement," *IRE Trans. Antennas Prop.*, vol. 55, pp. 49-55, January 1958.

[29] G. Ghione, "A CAD-oriented analytical model for the losses of general asymmetric coplanar lines in hybrid and monolithic MICs," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 1499-1510, September 1993.

[30] L. Lewin, "A method of avoiding the edge current divergence in perturbation loss calculations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 717-719, July 1984.

[31] L. A. Vainshtein, and S. M. Zhurav, "Strong skin effect at the edges of metal plates," *Pis'ma Zh. Tekh. Fiz.*, vol. 12, pp. 723-729, 1986 (Engl. transl. in Sov. Tech. Phys. Lett., 12, 298-299, 1986).

[32] R. E. Collin, *Foundations for Microwave Engineering.* McGraw-Hill, 1992.

[33] E. L. Barsotti, and E. F. Kuester, "A simple method to account for edge shape in the conductor loss in microstrip," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 98-105, January 1991.

[34] C. L. Holloway, and E. F. Kuester, "A quasi-closed form expression for the conductor loss of CPW lines, with an investigation of edge shape effects," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2695-2701, December 1995.

[35] R. Schinzinger, and A. Ametani, "Surge propagation characteristics of pipe-enclosed underground cables," *IEEE Trans. Power Appar. Sys.*, vol. PAS-97, pp. 1680-1688, September/October 1978.

[36] J.-Y. Ke, and C. H. Chen, "Dispersion and attenuation characteristics of copper waveguides with finite metallization thickness and conductivity," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1128-1134, May 1995.

[37] R. Faraji-Dana, and Y. L. Chow, "The current distribution and AC resistance of a microstrip structure," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1268-1277, September 1990.

[38] G. I. Costache, "Finite element method applied to skin-effect problems in strip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1009-1013, November 1987.

[39] W. Heinrich, "Full-wave analysis of conductor losses on MMIC transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1468-1472, October 1990.

[40] H. Klingbeil, and W. Heinrich, "Calculation of CPW A.C. resistance and inductance using a quasi-static mode-matching approach," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1004-1007, June 1994.

[41] R. Schinzinger, and P. A. A. Laura, *Conformal Mapping: Methods and Applications*. Elsevier, 1991.

[42] K. K. M. Cheng, and I. D. Robertson, "Quasi-TEM of V-shaped conductor-backed coplanar waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 43, August 1995.

[43] D. Beatovic, P. L. Levin, S. Sadovic, and R. Hutnak, "A galerkin formulation of the boundary element method for two-dimensional and axi-symmetric problems in electrostatics," *IEEE Trans. Electr. Insulation*, vol. 27, pp. 135-143, February 1992.

[44] T.-N. Chang, and C.-H. Tan, "Analysis of a shielded microstrip line with finite metallization thickness by the boundary element method," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1130-1132, August 1990.

[45] J. M. Chung, Q. Y. Gui, and C. C. Hsiung, "Numerical computation of Schwarz-Christoffel transformation for simply connected unbounded domain," *Computer Methods in Appl. Mech. Engr.*, vol. 105, pp. 93-109, 1993.

[46] E. Costamagna, "On the numerical inversion of the Schwarz-Christoffel conformal transformation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 35-40, January 1987.

[47] L. N. Trefethen, "Numerical computation of the Schwarz-Christoffel transformation," *SIAM J. Sci. Stat. Comput.*, vol. 1, pp. 83-102, March 1980.

[48] D. Homentcovschi, G. Ghione, C. Naldi, and R. Oprea, "Analytic determination of the capacitance matrix of planar or cylindrical multiconductor lines on multilayered substrates," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 363-373, February 1995.

[49] Q. Chen, A. Konard, and P. P. Biringer, "An integrodifferential finite element-Green's function method for the solution of unbounded eddy current problems," *IEEE Trans. Magnetics*, vol. 29, pp. 1874-1877, March 1993.

[50] A. Konard, "Integrodifferential finite element formulation of two-dimensional steady-state skin effect problems," *IEEE Trans. Magnetics*, vol. MAG-18, pp. 284-292, January 1982.

[51] R.-B. Wu, and J.-C. Yang, "Boundary integral equation formulation of skin effect problems in multiconductor transmission lines," *IEEE Trans. Magnetics*, vol. 25, pp. 3013-3015, July 1989.

[52] J.-F. Kiang, "Integral equation solution to the skin effect problem in conductor strips of finite thickness," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 452-460, March 1991.

[53] T. E. V. Deventer, P. B. Katehi, and A. C. Cangellaris, "An integral equation method for the evaluation of conductor and dielectric losses in high-frequency interconnects," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1964-1971, December 1989.

[54] S. Ponnapalli, A. Deutsch, and R. Bertin, "A package analysis tool based on a method of moments surface formulation," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 16, pp. 884-892, December 1993.

[55] N. K. Das, and D. M. Pozar, "Full-wave spectral-domain computation of material, radiation, and guided wave losses in infinite multilayered printed transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 54-63, January 1991.

[56] J. Aguilera, R. Margues, and M. Horno, "Quasi-TEM surface impedance approaches for the analysis of MIC and MMIC transmission lines, including both conductor and substrate losses," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1553-1558, July 1995.

[57] E. Paleczny, D. Kinowski, J. F. Legier, P. Pribetich, and P. Kennis, "Computation of full wave approaches for determination of microstrip conductor

losses for MMIC applications," *Elctrn. Lett.*, vol. 26, pp. 2076-2077, December 1990.

[58] R. Margues, J. Aguilera, F. Medina, and M. Horno, "On the use of the surface impedance approach in the quasi-TEM analysis of lossy and superconductor strip lines," *Microwave Optical Tech. Lett.*, vol. 6, pp. 391-394, June 1993.

[59] A. E. Ruehli, "Inductance calculations in a complex integrated circuit environment," *IBM J. Res. Develop.*, vol. 16, pp. 470-481, September 1972.

[60] P. A. Brennan, N. Raver, and A. E. Ruehli, "Three-dimensional inductance computations with partial element equivalent circuits," *IBM J. Res. Develop.*, vol. 23, pp. 661-668, November 1979.

[61] R.-B. Wu, C.-N. Kuo, and K. K. Chang, "Inductance and resistance computations for three-dimensional multiconductor interconnection structures," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 263-271, February 1992.

[62] T. V. Dinh, B. Cabon, and J. Chilo, "Time domain analysis of skin effect on lossy interconnections," *Elctrn. Lett.*, vol. 26, pp. 2057-2058, December 1990.

[63] D. Zhou, and J. R. Martf, "Skin effect calculations in pipe-type cables using a linear current subconductor technique," *IEEE Trans. Power Delivery*, vol. 9, pp. 598-604, January 1994.

[64] M. Kamon, M. J. Tsuk, and J. K. White, "FASTHENRY: A multipole-accelerated 3-D inductance extraction program," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1750-1758, September 1994.

[65] H. A. Haus, and J. R. Melcher, *Electromagnetic fields and energy.* Englewood Cliffs, NJ: Prentice-Hall, 1989.

[66] C. Hoer, and C. Love, "Exact inductance equations for rectangular conductors with applications to more complicated geometries," *Jl. Res. Natl. Bureau Standards - C. Engr. Instrument.*, vol. 69C, pp. 127-137, April-June 1965.

[67] C. A. Balanis, *Advanced Engineering Electromagnetics*. John Wiley & Sons, 1989.

[68] T. K. Sarkar, Z. A. Maricevic, J. B. Zhang, and A. R. Djordjevic, "Evaluation of excess inductance and capacitance of microstrip junctions," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1095-1097, June 1994.

[69] P. A. Kok, and D. De Zutter, "Scalar magnetostatic potential approach to the prediction of the excess inductance of grounded via's and via's through a hole in a ground plane," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1229-1237, July 1994.

[70] A. E. Ruehli, "Equivalent circuit models for three-dimensional multiconductor systems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 216-221, March 1974.

[71] A. E. Ruehli, N. Kulasza, and J. Pivnichny, "Inductance of nonstraight conductors close to a ground return plane," *IEEE Trans. Microwave Theory Tech.*, vol. 23, pp. 706-708, August 1975.

[72] J. R. Phillips, M. Kamon, and J. K. White, "An FFT-based approach to including non-ideal ground planes in a fast 3-D inductance extraction program," *IEEE 1993 Custom Integrated Circuits Conference*, 1993, pp. 8.3.1-8.3.4.

[73] R. Raghuram, Z. Yang, D. Divekar, and P. Wang, "Inductance computation of multiple arbitrarily shaped planes," *IEEE 3rd Topical Meeting on Electrical Performance of Electronic Packaging*, Monterey, CA, 1994, pp. 216-218.

[74] T. Becks, and I. Wolff, "Analysis of 3-D metallization structures by a full-wave spectral domain technique," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2219-2227, December 1992.

[75] J.-X. Zheng, "A 3-D electromagnetic simulator for high frequency applications," *IEEE Trans. Comp. Packaging Manufact. Tech. -Part B*, vol. 18, pp. 112-118, February 1995.

[76] C.-W. Lam, S. M. Ali, and P. Nuytkens, "Three-dimensional modeling of multichip module interconnects," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 16, pp. 699-704, November 1993.

[77] M. Gribbons, A. C. Cangellaris, and J. L. Prince, "Finite-difference time-domain analysis of pulse propagation in multichip module interconnects," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 16, pp. 490-498, August 1993.

[78] E. Pillai, and W. Wiesbeck, "Derivation of equivalent circuits for multilayer printed circuit board discontinuities using full wave models," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1774-1783, September 1994.

[79] 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, September 1994.

[80] B.-T. Lee, E. Tuncer, and D. P. Neikirk, "3-D series impedance extraction using effective internal impedance," *IEEE 4th Topical Meeting on Electrical Performance on Electronic Packaging*, Portlsnd, OR, October 2-4, 1995, pp. 220-222.

[81] A. E. Ruehli, and H. Heeb, "Circuit models for three-dimensional geometries including dielectrics," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1507-1516, July 1992.

[82] H. Heeb, and A. E. Ruehli, "Three-dimensional interconnect analysis using partial element equivalent circuits," *IEEE Trans. Circuits Systems - 1: Fundamental Theory Appl.*, vol. 39, pp. 974-982, November 1992.

[83] A. C. Cangellaris, J. L. Prince, and L. P. Vakanas, "Frequency-dependent inductance and resistance calculation for three-dimensional structures in high-speed interconnect systems," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 13, pp. 154-159, March 1990.

[84] K. Nakamata, and M. Nishimura, "Frequency analysis of IC package inductance by the partial element equivalent circuit (PEEC) method," *Electronics and Communications in Japan, Part 2*, vol. 75, pp. 81-90, 1992 (transl. from *Denshi Joho Tsushin Gakkai Ronbunshi*, 75-C-II,279-286, June 1992).

[85] B. McCredie, S. Kuppinger, G. Katopis, and W. D. Becker, "A model to hardware comparison of simultaneous switching noise on a CMOS chip," *IEEE 3rd*

Topical Meeting on Electrical Performance of Electronic Packaging, Monterey, CA, November 2-4,1994, pp. 43-45.

[86] N. Hirano, M. Miura, Y. Hiruta, and T. Sudo, "Characterization and reduction of simultaneous swtching noise for a multilayer package," *1994 IEEE 44th Electronic Components and Technology Conference*, 1994, pp. 949-956.

[87] A. Vaidyanath, B. Thoroddsen, J. L. Prince, and A. C. Cangellaris, "Simultaneous switching noise: influence of plane-plane and plane-signal trace coupling," *IEEE Trans. Comp. Packaging Manufact. Tech. - Part B*, vol. 18, pp. 496-502, August 1995.

[88] G. Pan, X. Zhu, and B. K. Gilbert, "Analysis of transmission lines of finite thickness above a periodically perforated ground plane at oblique orientations," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 383-392, February 1995.

[89] C.-P. Chien, A. F. Burnett, J. M. Cech, and M. H. Tanielian, "The signal transmission characteristics of embedded microstrip transmission lines over a meshed ground plane in copper/polymide multichip module," *IEEE Trans. Comp. Packaging Manufact. Tech. - Part B*, vol. 17, pp. 578-583, November 1994.

[90] A. C. Cangellaris, M. Gribbons, and J. L. Prince, "Electrical characteristics of multichip module interconnects with perforated reference planes," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 16, pp. 113-118, February 1993.

[91] H. You, and M. Soma, "Analysis and simulation of multiconductor transmission lines for high-speed interconnect and package design," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 13, pp. 839-846, December 1990.

[92] L.-T. Hwang, D. Nayak, I. Turlik, and A. Reisman, "Thin-film pulse propagation analysis using frequency techniques," *IEEE Trans. Comp. Hybrids Manufact. Tech.*, vol. 14, pp. 192-198, March 1991.

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