Modelling of Large Non-Linear Systems Integrating Thermal and Electromagnetic Models

M. B. Steer*, C. E. Christoffersen*, H. Gutierrez*, S. Nakazawa*, M. Abdullah*, and T. W. Nutesson

*Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7911. m.b.steer@ieee.org

The Aerospace Corporation, Chantilly Virginia, U.S.A.

ABSTRACT

The integration of thermal and electromagnetic modeling with traditional circuit simulation is becoming necessary for the analysis of large microwave and millimeter-wave systems. Issues relating to the abstraction required to interface these analyses are discussed particularly as they relate to spatial power combing systems.

INTRODUCTION

Modeling large nonlinear systems and considering thermal and electromagnetic effects is the grand challenge of microwave computer engineering of the latter half of the 1990's. Computing power and the levels of abstraction that microwave modelers are comfortable with are reaching the critical threshold. To date limited treatment of thermal effects and of electromagnetic interactions have been considered. Incorporation of thermal effects has been limited to fixing the temperature of an active device throughout the simulation, or the use of elaborate electro-thermal active device models but with minimal treatment of the thermal environment. Electromagnetic—circuit interactions have been considered at several levels. From the earliest days of microwave computer aided engineering two port and three port models of regular structures such as transmission lines or transmission line junctions have been incorporated in circuit simulators in a straightforward manner. This has involved a direct conversion to a nodal description by setting one of the port terminals, at each and every port, to a global reference node. In the modeling of high speed signal propagation in high speed digital circuits the electromagnetic environment (generally transmission lines and coupled transmission line structures) has been represented as large RLC networks or by an equivalent pole-zero description. The more general microwave problem of strong electromagnetic interactions with nonlinear circuits has been modeled by integrating nonlinear devices in a time-domain field simulator such as the FDTD technique. The lumped elements have been incorporated as equivalent current and voltage sources, or, the field mesh has been merged with the mesh of an active device simulator [1], [2], [3]. There are also commercial products that allow the interfacing of a electromagnetic derived models with circuits but for now only fairly simple systems with a few ports can be handled. The incorporation of electromagnetic field theoretic derived models into a general purpose circuit simulator has only recently been addressed [1], [4], [5], [6].

THERMAL— CIRCUIT INTEGRATION

There are two key ingredients in integrating a thermal analysis with circuit simulation. The first of these is the development of physically based electro-thermal models of microwave transistors [7]. The model is an important milestone as the electrical and thermal problems are solved concurrently. However it is not practical to concurrently solve the electro-thermal problem of an entire circuit at the device physics level. The second key ingredient is the development of strategies for integrating thermal analysis and circuit analysis at levels above that of individual transistors [8]. Because of the excellent work done in different disciplines (electrical engineering and mechanical engineering respectively) the high end electrical and thermal simulators are not easily integrated. However it seems only reasonable for a designer to expect to use the best of both worlds.

The structure of the integrated electro-thermal simulator is outlined in Figure 2. Here a physically consistent electro-thermal active device model handles coupling of electrical and thermal quantities inside active device. A thermal resistance model is used to handle the bulk semiconductor region outside of the active device region. The thermal capacity here is negligible. This thermal model could handle an entire MMIC. The active device generates heat and with the local thermal model injects heat into the rest of the thermal network. The thermal simulator handles heat spreader etc. and thermal quantities have a large time constant (100's of µs). At the interface between the circuit simulator and the thermal simulator there are temperature, T, and heat flow, H, variables. The heat flow at this interface is balanced by adjusting T. Thus analysis proceeds with V, T as state Variables and with error functions: $\Sigma H = 0$, $\Sigma I = 0$. V and T are adjusted to minimize the error functions

ELECTROMAGNETIC— CIRCUIT INTEGRATION

One of the first problems that must be addressed is that in general spatially distributed structures do not have a common reference node. Port descriptions make the most sense in developing linear models of these structures but then this is fundamentally incompatible with most circuit simulators and with circuit theory. Circuit theory has evolved to include a common reference node to which all voltages in the circuit are referred. However in spatially distributed systems it is not feasible to define nodal and voltages or a single reference point. Consider the microwave structures shown in Figure 1. Both of the structures shown here have nonlinear devices embedded in a structure for which an electromagnetic model can be derived. The active devices in the case of Figure 1(a) are separated by each other over a considerable difference. The node voltages at each transistor pair can only be refereed locally and so it is convenient to define a local reference node. Thus in Figure 1(a) there are four local reference nodes. This enables a port-based description to be converted to a nodal admittance description but now this has four redundant rows and columns as opposed to the single redundant row/column in conventional circuits. Thus to analyze this structure a modification to standard modified nodal admittance analysis is necessary. To recap the issue here. A single common reference node implies that the "nodal" voltages at one transistor pair has a specific voltage relationship with the "nodal" voltages at another transistor pair. However, the voltage between any two points, or equivalently the line integral of the electric field, depends on the path of integration. Since the electric field is not conservative in this spatially distributed system voltage has no meaning when referred over a distance. The second structure in Figure 1 is of a finline structure with dual Vivaldi antennas separated by a MMIC. Thus one antenna is the input to the circuit and the other is the output. It is possible to analyze this structure to yield two port parameters. It would be easy to imagine that the common metal structure is a common ground. However a common ground implies that charges can instantaneously redistribute and so clearly this is not possible. The very operation of this circuit relies on the input and output ports being totally independent. A further example of the problem here is to imagine a time domain field simulation. All four terminals at the input and output are then instantaneously isolated.

The solution to this problem that we have developed is a based on two developments. First, in [6] a technology for integrating port-based electromagnetic field models with nonlinear devices was introduced. Second in [9] a multiport network was used to enable electromagnetic models of individual interconnects to be assembled in a larger structure. This assemblage accounted for the interactions of the structures through the use of electromagnetic ports with electric and magnetic currents. The work currently being undertaken develops a network based model of the electromagnetic environment, whereby sections of the large electromagnetic structure are interfaced to each other at "electromagnetic terminals" and to the conventional nodal-based circuit at the ports. The electromagnetic simulator produces the multi-port admittance matrix of the passive grid structure for inclusion in a microwave circuit simulation program. The admittance matrix produced is port based due to the lack of a global reference node in the spatially distributed structure.

DISCUSSION

The work presented here is an approach to handling large systems such as quasi-optical amplifiers using full electromagnetic modeling. The interconnectivity of electromagnetic blocks could be handled using an electromagnetic simulator or in a circuit simulator. We have chosen to perform the interconnectivity in a circuit simulator because of the excellent methodology that has been developed for the analysis of circuits. The essence of a circuit simulator is enforcing Kirchoff's current law. In the extension we have developed additional quantities were introduced at the "electromagnetic interfaces." A circuit simulator enforces balancing of the electromagnetic quantities (the coefficients of the weighted basis functions) at the interface.

A complete integrated circuit / electromagnetic and thermal simulation was performed for the 2 X 2 grid oscillator shown in Figure 3(a). The thermal simulator used here is L-Edit/Therm© from Tanner Research. The thermal profile of the oscillator is shown in Figure 3(b) and the circuit and thermal waveforms are shown in Figure 4. The nonsymmetric thermal profile is because the active devices are oscillating at different amplitudes and phases although at the same frequency.

ACKNOWLEDGEMENTS

This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) through the MAFET Thrust III program as DARPA agreement number DAAL01-96-K-3619.

REFERENCES

[1] P. Ciampolini, P. Mezzanotte, L. Roselli and R. Sorrentino, "Accurate and efficient circuit simulation with lumped-element FDTD technique," *IEEE Trans. Microwave Theory Tech.*, Vol. 44, Dec. 1996, pp. 2207--2215.

[2] V. A. Thomas, M. E. Jones, M. Piket-May, A. Taflove and E. Harrigan, "The use of SPICE lumped circuits as sub-grid models for FDTD analysis," *IEEE Trans. Microwave Theory and Techn.*, Vol. 45, May 1994, pp. 141-143.

[3] C.-N. Kuo, B. Houshmand, and T. Itoh, "Full-wave analysis of packaged microwave circuits with active and nonlinear devices: an FDTD approach," *IEEE Trans. Microwave Theory and Techn.*, Vol 45, May 1997, pp. 819-826. \

[4] T.W. Nuteson, G.P. Monahan, M.B. Steer, K. Naishadham, J.W.Mink, K. Kojucharoff and J. Harvey, "Full-wave analysis of quasi-optical structures," *IEEE Trans. Microwave Theory Techniques*, May 1996, pp. 701-710.

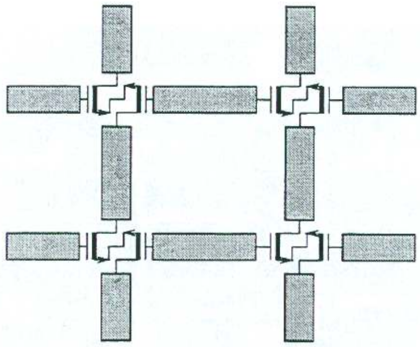
[5] J. Kunisch and Ingo Wolf, "The compression approach: a new technique for the analysis of distributed circuits containing nonlinear elements," *in IEEE MTT-S Int. Microwave Symp. Workshop WSK*, 1992, pp. 16--31.

[6] J. Kunisch and Ingo Wolf, "Steady-state analysis of nonlinear forced and autonomous microwave circuits using the compression approach," *International J. Microwave and Millimeter-Wave Computer-Aided Engineering*, Vol. 5, No. 4, 1995, pp. 241-225.

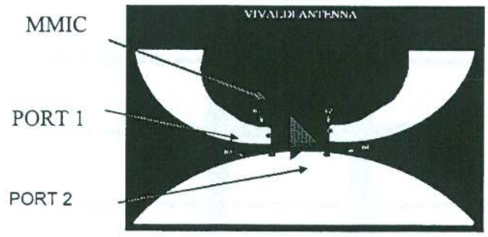
[7] R. G. Johnson, C. Snowden, R. D. Pollard, "Physics-based electro-thermal model for microwave and millimetre wave HEMTs," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, June 1997, pp. 1485-1488.

[8] M.B. Steer, M. N. Abdullah, C. Christoffersen, M. Summers, S. Nakazawa, A. Khalil, and J. Harvey, "Integrated electro-magnetic and circuit modeling of large microwave and millimeter-wave structures," *Proc. 1998 IEEE Antennas and Propagation Symposium,* June 1998, pp 478-481.

[9] R. P. Parrikar and K. C. Gupta, "Multiport network model for CAD of electromagnetically-coupled microstrip patch antennas," *Proc. 1996 IEEE Antennas and Propagation Society Int. Symp. Dig.*, Vol. 2, 1996, pp. 1058-1061.



(a)



(b)

Figure 1. Spatially distributed microwave structures: (a) a 2 X 2 quasi-optical grid amplifier; and (b) a dual Vivaldi antenna system with inserted MMIC amplifier, the metal areas in white.

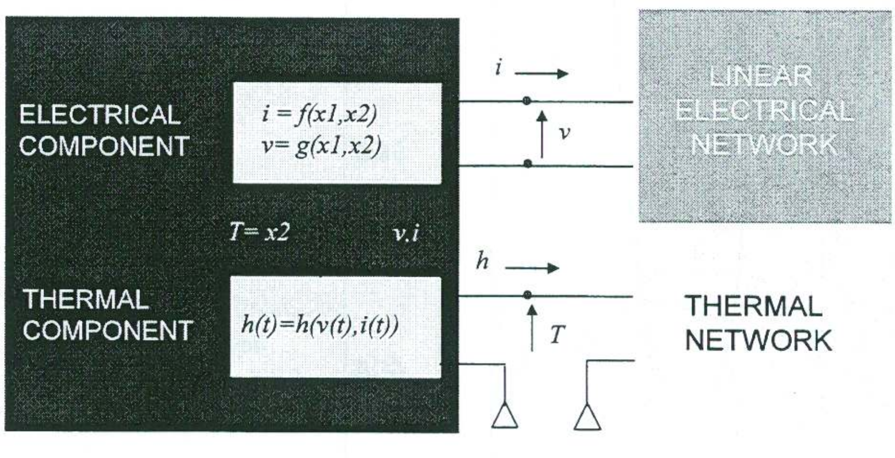


Figure 2 Circuit level model of integrated electrothermal network.

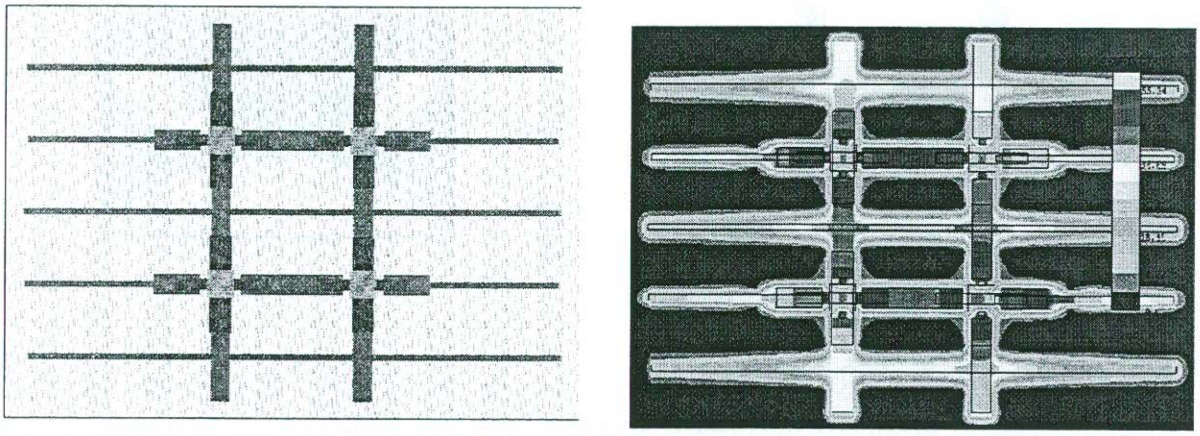


Figure 3. Integrated elecromagnetic, circuit and thermal simulation of a grid oscillator: (a) Layout of 2X2 grid oscillator; and (b) thermal profile of oscillator.

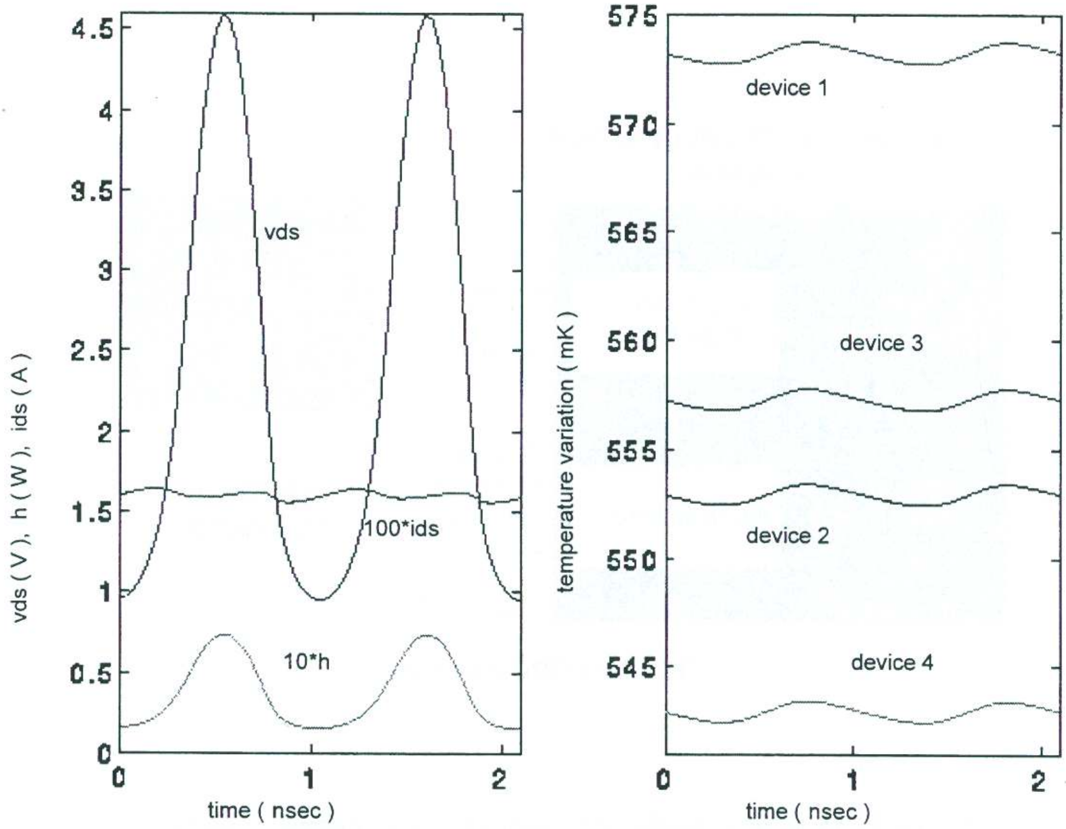


Figure 4. Voltage and temperature waveforms at one of the unit cell amplifiers in the grid oscillator.