An Integrated Environment for the Simulation of Electrical, Thermal and Electromagnetic Interactions in High-Performance Integrated Circuits

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Abstract- Joint computer simulation of circuit, thermal and electromagnetic interactions in high performance integrated circuits and systems, is of particular importance for the modeling of electronic packaging since these are complex coupled systems where all these aspects interact in a dynamic sense. This paper describes a computer environment that supports the simultaneous simulation of thermal, electromagnetic and circuit interactions in complex microwave circuits. Locally referenced modules have been used to enable disparate modeling tools to interact, and suggest possible paths to include mechanical interactions in the future. Two methods are presented for the simulation of electro-thermal interaction. The first one is based on coupling electrical and thermal environments using a lumped-parameter model of the heat dissipation dynamics. The second technique, consisting of the run-time coupling of a circuit simulator and a finite-element thermal solver, is based on an application program interface (API) that synchronizes the transfer of information between the two. Through this technique, simultaneous simulation of electrical, thermal and electromagnetic interactions has been achieved.

Keywords- Circuit simulation; harmonic balance; thermal modeling.

I. INTRODUCTION

The performance and characteristics of semiconductor components in electronic packages can be considerably affected by temperature variations, and for this reason accurate circuit simulation requires that the dynamic temperature effects induced by the heat dissipated in the circuit be taken into account. Modeling electro-thermal interactions in integrated circuits has been addressed in a variety of ways [1-5]. Existing methods can be broadly classified into two groups: “relaxation” methods, which simulate the thermal and electrical problems separately and periodically exchange temperature and power information until thermal and electrical convergence is reached; and direct or fully coupled methods, where a single circuit simultaneously handles both electrical and thermal states. In the later, the thermal model is integrated into the circuit simulator, thus the representation of the thermal environment is rather simple. Direct coupled methods have better convergence properties than relaxation methods. This paper discusses the interfacing of an independent thermal solver [6] with a circuit simulator [7] using both a direct coupled electro-thermal model and a relaxation-based simulation of a steady-state microwave circuit. The thermal solver provides unconstrained three-dimensional modeling of the thermal environment.

II. DIRECTLY COUPLED CHARACTERIZATION OF HEAT DISSIPATION IN A CIRCUIT SIMULATOR

One way of incorporating thermal effects in a circuit simulator is to make the thermal model look like an electrical circuit — the thermal and electrical problems are then solved simultaneously as if they were one large electrical problem. This strategy is based on transforming the thermal problem into an equivalent electrical problem, and its limitations are exacerbated by issues related to grounding and floating circuits. The later problem has been

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addressed by the concept of local reference nodes, initially developed for integrated circuit and field analysis of distributed microwave circuits [8]. This concept can be adapted to represent electro-thermal interactions by using thermal terminals, including a local reference node for thermal ground. This is depicted in Fig. 1, where a nonlinear electro-thermal device including both electrical and thermal terminals is shown. Power dissipated in the active device is represented as a heat current source referenced to thermal ground. The state variable at the thermal terminals is device temperature and the associated error function is derived from heat current. The network representation allows efficient simulation of electro-thermal interactions in steady-state: temperature is calculated simultaneously with the electrical quantities since it becomes an additional element of the system state vector.

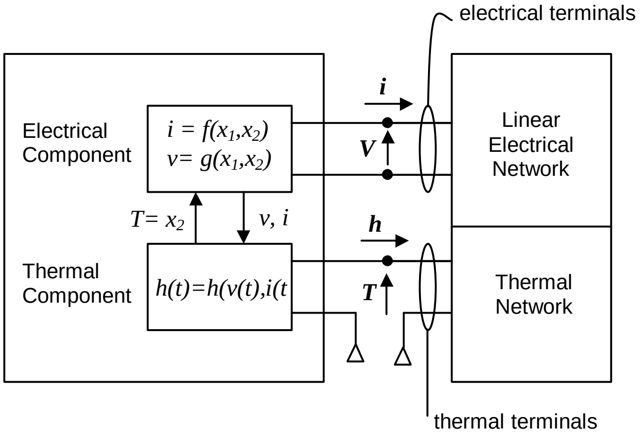

Figure 1. Nonlinear electro-thermal device, where the thermal network uses a local reference node (indicated by triangle symbols) for thermal ground.

Directly coupled simulation relies on the adequate representation of the heat dissipation characteristics of the circuit by a network parameter model. Here the later is extracted using a systematic testing procedure applied to an independent finite element method-based thermal solver. The procedure begins by identifying thermal terminals that interface heat dissipating electrical components with the model of the thermal load. In circuits where the thermal behavior is linear or quasi-linear, the thermal load corresponding to the die can be represented by a thermal admittance matrix, Y_{TH}, so that

$$\begin{bmatrix} \boldsymbol{Y}_{\mathrm{E}} & 0 \\ 0 & \boldsymbol{Y}_{\mathrm{TH}} \end{bmatrix} \begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{T} \end{bmatrix} = \begin{bmatrix} \boldsymbol{i} \\ \boldsymbol{h} \end{bmatrix} \tag{1}$$

where $\boldsymbol{Y}_{\mathrm{E}}$ corresponds to the electrical modified nodal admittance matrix, $\boldsymbol{X}$ is the vector of electrical state variables, $\boldsymbol{T}$ the vector of unknown temperatures, and $\boldsymbol{i}$, $\boldsymbol{h}$ are the corresponding electrical and thermal current vectors. $\boldsymbol{Y}_{\mathrm{TH}}$ is estimated as follows. Vectors of random heat current values (forming a matrix $\boldsymbol{H}_{nxm} = [\boldsymbol{h}]$) are applied to the thermal environment through the thermal solver. This yields a vector $\boldsymbol{T}$ at the thermal terminals for each vector $\boldsymbol{h}$. By repeating this procedure m times ($m>n$, where n is the number of heat sources), matrices $\boldsymbol{H}_{nxm} = [\boldsymbol{h}]$ and $\boldsymbol{Q}_{nxm} = [\boldsymbol{T}]$ are generated and $\boldsymbol{Y}_{\mathrm{TH}}$ can be calculated in a minimum mean-square error sense:

$$\begin{aligned} &\boldsymbol{Y}_{\mathrm{TH}(nxn)}\boldsymbol{Q}_{nxm} = \boldsymbol{H}_{nxm} \quad \Leftrightarrow \\ &\boldsymbol{Y}_{\mathrm{TH}(nxn)} = \boldsymbol{H}_{nxm}(\boldsymbol{Q}^T\boldsymbol{Q})^{-1}_{mxm}\boldsymbol{Q}^T_{mxn} \end{aligned} \tag{2}$$

This formulation renders the thermal load as a multi-port linear element, as shown in Fig. 2. The corresponding thermal capacitors were calculated from the geometry, mass density and specific heat of the die materials.

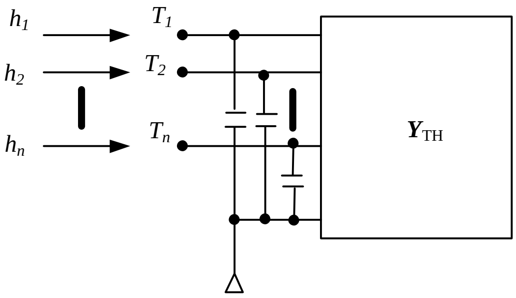

Figure 2. Thermal admittance element

III. CHARACTERIZATION OF HEAT DISSIPATION BASED ON A RELAXATION TECHNIQUE

An alternative approach is based on the run-time coupling of the circuit simulator and the thermal environment. This can be achieved by an applications programming interface (API) that controls the flow of information between the circuit simulator and the thermal solver. Conceptually, the thermal network is connected to the circuit simulator as depicted in Fig. 1, but now the execution is sequential: a vector of temperatures in the active devices is calculated for each vector of dissipated power, and the circuit simulator waits while temperatures are calculated by the thermal solver. Thus, for each iteration of the circuit simulator, several thermal iterations might be required since temperature becomes an additional state variable for the circuit. The trade-offs of this approach are clear: a more accurate representation of the thermal behavior of the system is available, at the expense of a substantial increase in computation time.

IV. RESULTS

The techniques outlined above have been tested by evaluating thermal dissipation in a 2x2 grid amplifier [9]. The layout of the circuit is shown in Fig. 3 and transistors are located at the intersections of the grid.

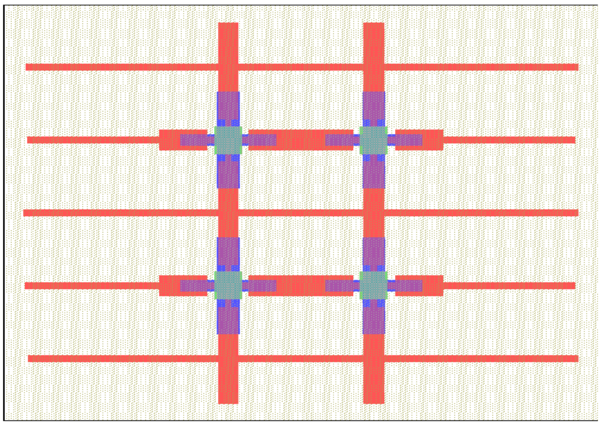

Figure 3. 2x2 Grid amplifier layout

A scaled model (10:3) was built using copper tape, surface mount resistors and platinum resistance-temperature device sensing elements to record temperature. After extracting a thermal admittance matrix as described in Section II, predicted temperature variations were compared to measurements with results shown in Fig. 4. The measured and calculated thermal profiles track each other closely.

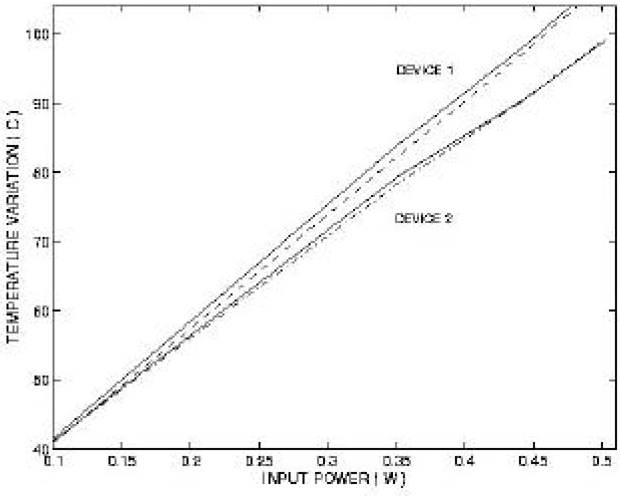

Figure 4. Thermal behavior of the grid amplifier circuit: measurements- solid lines; predictions- dotted lines.

The electrical and thermal waveforms of the original grid amplifier were then simulated using the thermal characterization procedure described Section II and a harmonic balance circuit simulator. The input to the grid amplifier is an incident electric field, interfaced with the circuit simulator through a virtual multi-port element that implements local reference nodes [7]. The results, shown in Fig. 5, illustrate an important point: the sources of heat current in a microwave circuit have a period corresponding to the RF signal, thus a self-consistent electro-thermal simulation must permit tightly integrated modeling of the thermal network with the electrical network. The temperature variations shown indicate the effect of thermal damping as there is very little variation of temperature at the RF frequency. Nevertheless, the variation is still present.

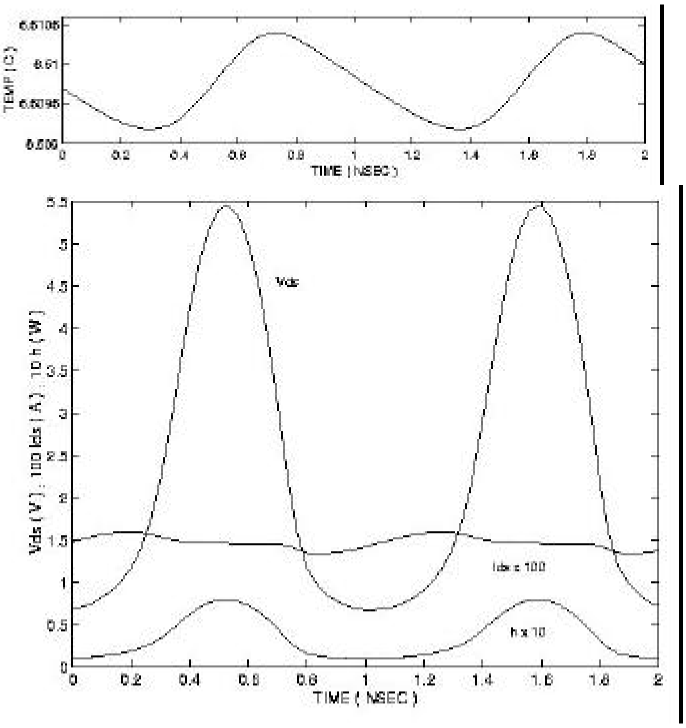

Figure 5. Coupled electro-thermal harmonic balance simulation of the grid amplifier: electrical and thermal waveforms for one of the devices: drain source voltage, Vds; drain source current, Ids; heat flow, h; and temperature increase above ambient.

The grid amplifier was also simulated by the relaxation technique described in Section III. Again, the input was incident field, and harmonic balance analysis was performed. Since the frequency of the RF signal is very high compared to the time constant of the thermal system, the oscillatory behavior in the temperature response was neglected and therefore only the DC solution was considered for the state variable associated to temperature. Results are shown on Fig. 6.

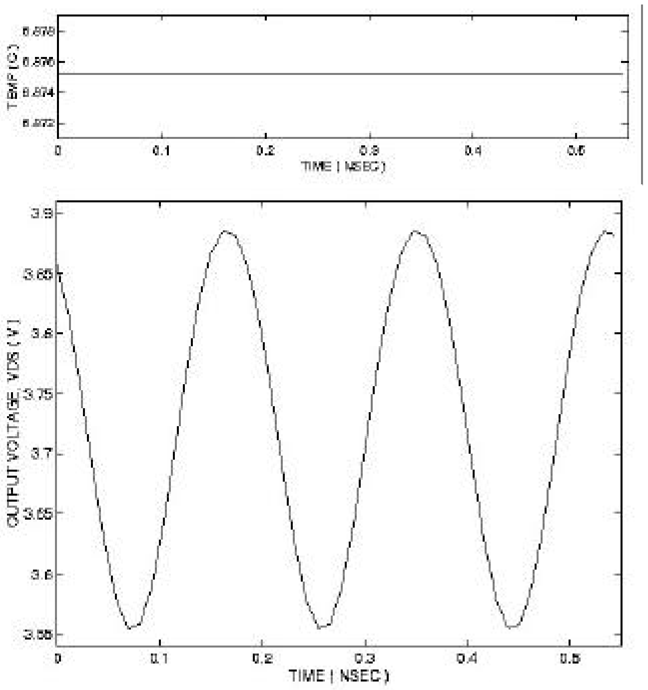

Figure 6. Integrated electro-thermal harmonic balance simulation of the grid amplifier based on relaxation technique: drain source voltage, Vds, for one of the devices, and temperature increase above ambient are shown.

V. DISCUSSION AND CONCLUSIONS

Two techniques for the steady-state coupled simulation of the electro-thermal behavior of active integrated circuits have been proposed. In the coupled method, the thermal behavior of the system is represented by a thermal admittance matrix extracted by a least-squares technique from a FEM thermal model of the circuit layout. On the other hand, the relaxation technique uses a more accurate description of the thermal dissipation network, at the expense of a significant increase in computation time. In a steady state simulation, it is a simple matter to include tight coupling of the thermal network with electro-thermal active devices, as few thermal evaluations are necessary.

VI. REFERENCES

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