

Compact Electrothermal Modeling of an X-band MMIC

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Abstract—Compact electrothermal modeling of lumped electrical devices and compact thermal modeling of volumetric materials enables efficient electrothermal modeling of microwave circuits. The compact thermal model of the body of an X-band MMIC is based on analytical solutions of the heat diffusion equation in thermal sub-volumes. The model is uncompromisingly accurate and captures thermal nonlinearities. The model considers complex MMIC features such as surface metallization and vias, as well as the mounting configurations including lead-frame, carrier, and printed circuit board. This is coupled with electrothermal models of transistors and of resistors. The models are incorporated in a multi-physics simulator that uses the same model in both transient and harmonic analysis of an X-band LNA MMIC. Steady-state thermal measurements are used to validate the simulations.

Index Terms—MMIC, electrothermal effects, circuit simulation, modeling.

I. INTRODUCTION

Co-simulation of the thermal and electrical characteristics of active microwave circuits is notoriously slow with important electrical transients being in the picosecond range while package-level thermal transients can be a second or longer. In the region close to heat generating devices such as transistors and resistors the thermal transients are taken as milliseconds and simulation schemes have evolved that simulate the electrical circuit at picosecond or smaller time-steps while updating the thermal environment every millisecond or so. However in the active device region, the heat generating mechanisms are at the electrical signal rate in the micron and sub-micron longitudinal dimensions of the active channels of transistors the thermal environment is changing at the rate of the electrical signal. There can be tight coupling of the temperature and active device performance, for example through temperature-mobility. While this effect can be viewed as relatively small the effect on performance can be significant in terms of some levels of performance such as intermodulation distortion with a two-tone signal or adjacent channel distortion with digitally-modulated signals. In the latter case distortion that is -80 dBc is important, this is 1 part in 10,000 in terms of voltage levels. So even very low levels of introduced distortion are important and the

electro-thermal interactions must be captured at the period of the carrier signals or at least at the envelope rate.

Thermal simulations are traditionally performed using Finite Element Modeling (FEM) of 3D structures. These are compute intensive as volumetric discretization is involved. It is computationally prohibitive to use FEM thermal simulations in conjunction with electrical simulations. As a result considerable effort has been expended in developing compact thermal models that can be computed many orders of magnitude faster than can FEM schemes. The simplest thermal model is to use simple arrangements of thermal resistances and capacitances together with a circuit-based thermal source, typically a controlled voltage or current source, whose amplitude is proportional to the power dissipated in electrical devices. Electrothermal circuit simulation has been performed previously utilising compact thermal models based on simplified package structures. These often represented multi-finger devices by only a single, average heat dissipating area and ignored all device fine structure such as die surface metallisation. Examples are APLAC by Veijola *et al.*, with a simple thermal description based on heat dissipating spheres; simulation of IGBTs in circuit simulator SABER, utilising the approximate thermal model of Hefner and Blackburn for die, carriers and heatsinks; and SISSI by V. Szekely *et al.*, based on a thermal RC-ladder network obtained from simulated or measured time constant spectra. Various thermal resistance calculation techniques using Green's function, Fourier series, conformal mapping, extraction using deconvolution from numerically generated and measured thermal responses, and numerical techniques have been applied to individual circuit components, devices, heat sinks, packages.

In this paper we describe a compact thermal model of a MMIC body. The model is in effect a boundary-element equivalent of a volumetric model. Transformations enable the volume to be described by an analytical thermal impedance matrix model while still capturing full thermal capacitance. The thermal impedance matrix is reduced to capture the interactions from one point on the discretized surface to another. Complex MMIC features such as surface metallization and via holes, and package and

mounting configurations, such as epoxy or solder attach to lead-frame paddle or carrier. It is critical to realize that the compact thermal model captures nonlinear-thermal effects as well as thermal capacity effects. The electrothermal model of the MMIC is based on the Curtice Cubic model with temperature coefficient parameters that capture the effect of temperature on mobility and on threshold voltage. The thermal terminals of the electro-thermal GaAs pHEMT model are connected to the thermal model of the MMIC body. The result is un-compromised electrothermal co-simulation of an X-band LNA MMIC. Results are in part verified using calibrated thermal images of a MMIC taken with an infra-red camera.

II. GLOBAL STATE VARIABLE BASED MODELING

The electrothermal modeling presented in this paper is implemented in a global state variable based multidomain simulator, *fREEDA*TM¹. This simulator uses state variables to model various nonlinear devices. The state variable based parameterized nonlinear devices can be described with the following set of equations:

$$\mathbf{v}_{NL}(t) = u[\mathbf{x}(t), \frac{d\mathbf{x}}{dt}, \dots, \frac{d^m\mathbf{x}}{dt^m}, \mathbf{x}_D(t)] \quad (1)$$

$$\mathbf{i}_{NL}(t) = w[\mathbf{x}(t), \frac{d\mathbf{x}}{dt}, \dots, \frac{d^m\mathbf{x}}{dt^m}, \mathbf{x}_D(t)] \quad (2)$$

where $\mathbf{v}_{NL}(t)$, $\mathbf{i}_{NL}(t)$ are vectors of voltages and currents at the common ports, $\mathbf{x}(t)$ is a vector of state variables and $\mathbf{x}_D(t)$ a vector of time-delayed state variables, i.e., $\mathbf{x}_{D_i}(t) = x_i(t - \tau_i)$. The time delays τ_i may be functions of the state variables. All the vectors in Eq. (1) and Eq. (2) have a same size n_d equal to the number of common (device) ports. The general formulation to solve the system of linear and nonlinear devices is described in [1]. To incorporate the thermal effects into the circuit simulator, the thermal model is made to look like an electrical circuit. The thermal and electrical circuits are then solved simultaneously as if they were one large electrical circuit. The concept of local reference groups' [2] helps to integrate the thermal network and guarantees no mixing of the electric and thermal currents. A general integration of an electrothermal network is shown in Fig. 1. Power dissipated in the active devices are represented as a heat current sources referenced to thermal ground. The thermal ground is taken as 0 K, and is treated in the circuit simulator as a local reference node. Thus, the entire thermal network is treated by the circuit simulator as a single local reference group. At the interface between the thermal component and thermal network are temperature, T 's, and heat flow, P 's, variables. The error function at the thermal network interface is $P=0$, which is equivalent to the error function of $I=0$ in the electrical network. The

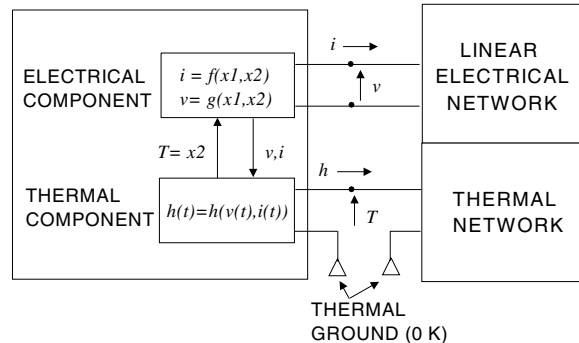


Fig. 1. An electrothermal element connected to linear and thermal networks.

temperature rise of thermal network can be described by the equation:

$$\Delta\theta_i = \sum R_{TH_{ij}}(s)P_j \quad (3)$$

where $\Delta\theta_i$ is the Laplace transformed temperature rise of the element i above its initial temperature, $\sum R_{TH_{ij}}$ is the thermal impedance matrix in the Laplace s -space and the P_j are the transformed time-dependent fluxes due to power dissipation devices $j = 1, 2, \dots, M$. The power dissipated by the nonlinear devices i.e. the heat currents into the thermal model are calculated by self-consistent electrical device models. These heat currents are picked as state variables of the thermal model. The thermal impedance network is calculated using the thermal impedance matrix model described in the next section.

III. THERMAL IMPEDANCE MATRIX MODEL

The construction of the thermal impedance matrix model, and its partial implementation in *fREEDA*TM, has been described at length in [3]. The model solves the non linear, time dependent heat diffusion equation in complicated thermal systems, by transformation of the equation to linear form, domain decomposition, and analytical solution of the transformed equation in regular subvolumes in complex frequency space, s .

The subvolume solutions take the form of s -space thermal impedance matrices, relating the transformed temperature rises of the heating elements and discretised interface elements, to corresponding power dissipations, as described in Eq. (3). The non linear, volumetric thermal problem is thus reduced to the discretised interfaces between subvolumes and the interface with the already non linear electrical model. Linear subsystems only have to be solved once, by thermal precomputation.

Explicit forms for the thermal impedance matrices are

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SPOT	Simulated Temperature(C)	Measured Temperature(C)
DC PAD	46.99	46.4
Transistor 1	41.36	40.7
Transistor 2	44.78	43.1

TABLE I
TEMPERATURES AT VARIOUS SPOTS ON THE MMIC.

given in [3] and are of the general form,

$$R_{TH_{ij}}(s) = \sum_{mn} \left\{ \begin{array}{l} \coth(\gamma_{mn}D) \\ \operatorname{cosech}(\gamma_{mn}D) \end{array} \right\} \times \quad (4)$$

$$\frac{-4/(\kappa LW \gamma_{mn})}{(1 + \delta_{m0})(1 + \delta_{n0})} \frac{I_{mn}^i I_{mn}^j}{I_{00}^i I_{00}^j},$$

where $m, n = 0, 1, 2, \dots$,

$$\lambda_m = \frac{m\pi}{L}, \mu_n = \frac{n\pi}{W}, \gamma_{mn} = \left(\lambda_m^2 + \mu_n^2 + \frac{s}{k} \right)^{1/2}, \quad (5)$$

L, W, D are the subvolume dimensions in the x -, y - and z -directions respectively; the subvolume has thermal conductivity, κ , diffusivity, k ; and I_{mn}^i are area integrals over heating element and discretised interface element domains, D_i ,

$$I_{mn}^i = \iint_{D_i} \cos \lambda_m x \cos \mu_n y \, dx dy. \quad (6)$$

The s -space thermal impedance matrices are matrices of transfer functions representing the impulse responses of the thermal subsystems. They can be used directly in frequency space, by the evaluation $s \rightarrow j\omega$, to generate network parameters, for instance in harmonic balance simulation, or they can employ numerical Laplace inversion of $R_{TH_{ij}}(s) \frac{1}{s}$, to give system step response, for instance in convolution transient simulation.

In the simulations described here, the limit $s \rightarrow 0, t \rightarrow \infty$, was taken, to generate time-independent, steady-state thermal impedance matrices for thermal subsystems. These thermal impedance matrices described thermal N-ports corresponding to subvolumes of the modelled MMIC. Combination and reduction of N-ports, to form a global thermal impedance matrix describing the composite structure, was achieved by matrix manipulation on subsystem thermal impedance matrices. This was then implemented in *fREEDA*TM in terms of thermal conductances, current sources and current controlled voltage sources [3], allowing self-consistent electrothermal co-simulation.

IV. MEASUREMENTS AND RESULTS

The electrothermal model described in the above sections was verified with thermal images of a high dynamic range Filtronics X-band MMIC LNA, shown in Fig. 2.

This MMIC was glued with a thermally conductive epoxy to a Kovar substrate, which is screwed onto a carrier block, acting as the heat sink. The thermal images of

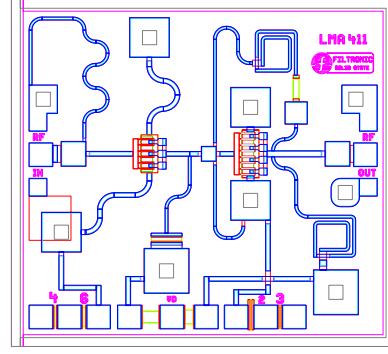


Fig. 2. Layout of LMA411 X-band MMIC.

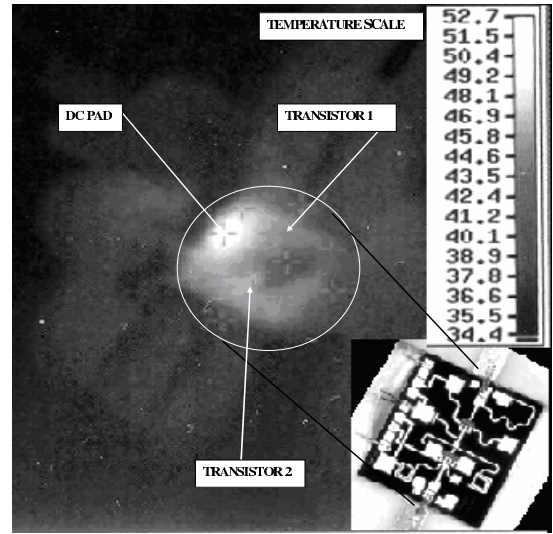


Fig. 3. Thermal Image of the X-band MMIC.

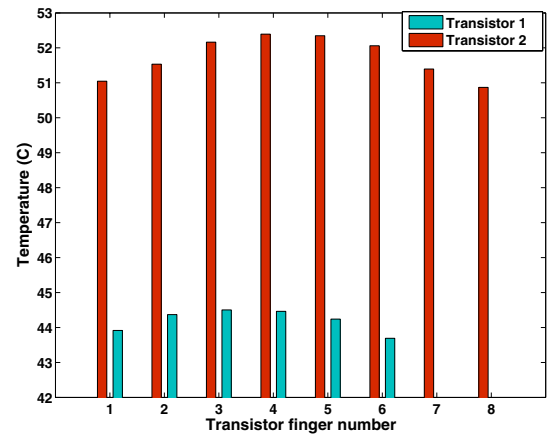


Fig. 4. Simulated temperatures of transistor fingers.

the MMIC were captured using the infra red AFEM/Thermovision 900 SW/TE camera with a pixel size of $50\mu\text{m}$. The MMIC was painted with a specially prepared black ink with known emissivity.

The GaAs die was modeled as an N-port with surface heating elements representing the 6 gates of transistor 1, 8 gates of transistor 2, and 2 power dissipating TaN resistors. In addition, three ‘pixel’ elements were constructed, receiving zero power but delivering temperature response over $50\mu\text{m} \times 50\mu\text{m}$ ‘pixel’ areas, to mimic the resolution limitations of the thermal camera. These heating elements gave rise to a 19×19 global thermal impedance matrix for the mounted and metallised die. The GaAs die N-port also contained surface discretisation for connection of surface metallisation. Metal elements were included to describe DC pads, and vias and via caps in the vicinity of transistor 2. These metal elements were in turn represented as thermal N-ports with discretised bases, and interface nodes connected to the corresponding discretised areas on the surface of the GaAs. Explicit reference to the interface nodes was eliminated by N-port reduction, based on manipulation of the corresponding subsystem thermal impedance matrices.

The base of the GaAs die was also discretised, as were the top and bottom surfaces of the epoxy subvolume, and the top of the Kovar layer. Explicit reference to the interface nodes was similarly eliminated.

The heat sources of the GaAs die are the 2 pHEMTs, modeled using the Curtice-cubic model, and the TaN bias resistors. The vias near the source terminals of second stage pHEMT were modeled using a 2-port interface element, connected in parallel with the GaAs die. This is a good approximation of the embedded thermal subvolumes. The heat dissipation of the spiral inductors and other surface metallization was ignored.

Figure 3 shows the thermal image of the MMIC, with the temperature of the heat sink set to 35C. Thermal camera emissivity calibrations and corrections were taken care of with a reference image of the MMIC, with no DC power. Also, during the correction process, the unevenness of the black ink, on certain areas of the MMIC, was taken into account. This unevenness of the black ink, reduces the emissivity of area, leading to erroneous temperature readings. Hence even though the thermal image shows temperature readings above 50C, the actual temperature readings of the various spots on the MMIC are shown in Table I. This table shows the comparison between the measured temperatures and simulated temperatures of the ‘pixel’ elements at a heat sink temperature of 35C. The simulated temperatures are in excellent agreement with the measured temperatures. As seen in Figure 4, individual transistor finger temperatures are higher than the ‘pixel’ element temperatures. The ‘pixel’ elements help calculate the average temperature over the resolution or ‘pixel’ size

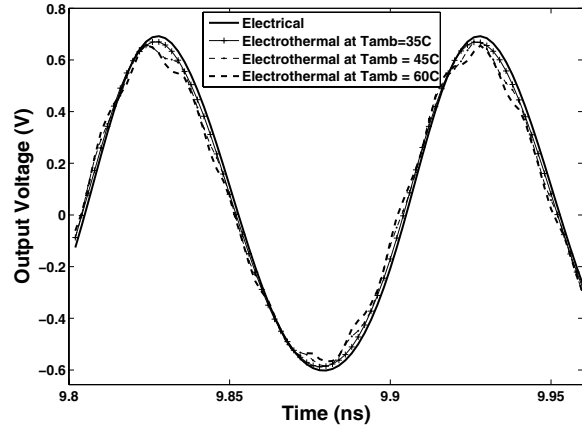


Fig. 5. Output voltage at elevated temperatures.

of the thermal camera. The transistor temperatures, are used by the electrothermal pHEMT model, to perform a coupled electrothermal simulation. Figure 5 shows the output voltage of the MMIC with an electrical model at room temperature, and an electrothermal model at the temperature provided by the thermal model. If self-heating and mutual thermal interactions are ignored the output voltage is overestimated. At high ambient/heat sink temperatures the output voltage is significantly overestimated. Hence self-heating and mutual thermal interactions cannot be ignored in evaluating the performance of the MMIC.

V. CONCLUSION

A fully-coupled electrothermal simulation of an X-band MMIC LNA has been demonstrated. The thermal impedance model is a highly accurate model which describes thermal interactions, based on analytical solutions of the heat diffusion equation in thermal subvolumes. The concept of a universal error function has been demonstrated in the state variable based circuit simulator. The electrothermal steady-state simulations of the X-band MMIC under DC bias, have been validated with thermal images. This model will help predict effects of temperature rise due to self-heating and mutual interactions on the performance of MMICs.

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