Electro-Thermal Model Extraction for MMIC Power Amplifiers

Germán Torregrosa-Penalva[1], Alberto Asensio-López[2], Álvaro Blanco-del-Campo[2]
[1]Universidad Miguel Hernández, Área de Teoría de la Señal y Comunicaciones,
Avenida de la Universidad, Elche (Alicante), 03202, Spain, +34966658955.
[2]Universidad Politécnica de Madrid, Grupo de Microondas y Radar,
Depto. de Señales, Sistemas y Radiocomunicaciones, E.T.S.I. Telecomunicación,
Ciudad Universitaria, Madrid, 28040, Spain.
gtorregrosa@umh.es

***Abstract*—**
This paper presents a simple procedure to extract an electro-thermal model for MMIC power amplifiers. The model accounts for the DC and RF performance of MMIC complex structures formed by multiple transistors combined in different amplifying stages. All the steps taken to perform the thermal and electrical experimental characterization to obtain the model are explained. The extracted model was validated by comparing measured and simulated data of a commercial GaAs FET MMIC power amplifier. It was also used to predict the hot spot temperature and position over a wide range of working conditions.

I. Introduction

The thermal and electrical performance of microwave power amplifiers is known to depend strongly on the materials involved in their mounting structure [1]. Thermal models are usually limited to the determination of the hot spot transistor temperature on the amplifier while assuming constant electrical properties under different temperature conditions [2]. On the other hand, models employed to assess the electrical characteristics of a given transistor cannot normally account for thermal interactions between neighboring devices on the same die forming a single amplifier. Moreover, electro-thermal models as in [3] and [4] intended for complex MMIC structures (formed by the combination of multiple transistors) are difficult to apply to commercial devices unless the amplifier design, its properties (electrical as well as thermal) and its mounting structure are precisely known.

In this paper it is presented an experimental procedure to derive a simplified electro-thermal model proposed for complex commercial MMIC power amplifiers. The model is build up through a straight forward thermal and electrical experimental characterization, requiring basic instrumentation and avoiding the use of unsafe operating conditions. The thermal behavior of the device under test is obtained making use of the procedure proposed in [5], as this non-invasive method is capable of including the effects of the mounting structure. The current model presented in [6] is used to match the DC characteristics of the transistor devices that form the amplifier under varying ambient temperatures. The coupling between the thermal and the electrical characteristics is done following the matrix thermal resistance approach suggested in [7]. The electro-thermal static model derived in this way is able to evaluate the thermal impact of the solder employed to attach the amplifier to its carrier. The internal temperature of the different transistor devices that form the MMIC amplifier can be also obtained accounting for the thermal interactions between them under a wide range of bias and ambient temperature conditions. The dynamic RF behavior of the MMIC amplifier is also introduced to provide the internal temperature change experimented by the transistors in the MMIC amplifier for different RF output power levels.

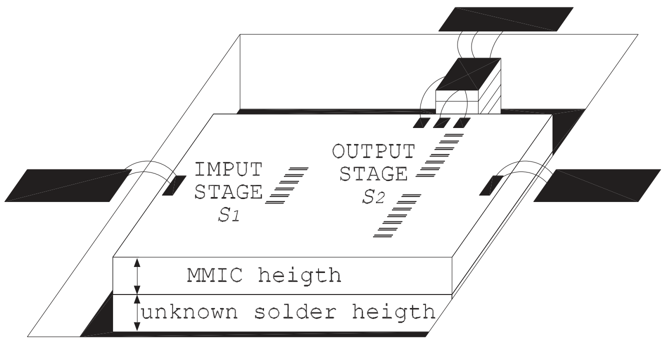


Fig. 1. Drawing of a commercial MMIC power amplifier formed by N transistor devices in two independent amplifying stages.

The technique suggested in this paper, which is described in sections II through V, was tested on a commercial GaAs FET MMIC X band power amplifier. The results obtained as well as the comparison between experimental and simulated data are given in section VI.

II. Model Extraction Overview

The proposed extraction method gives a simple way of obtaining a model useful for commercial MMIC amplifiers as the one depicted in fig. (1), formed by multiple temperature dependent and thermally coupled heat sources.

The process of obtaining an electro-thermal model for MMIC power amplifiers is divided into five steps:

1) Firstly, a thermal characterization of the amplifier is performed to measure the thermal coupling between amplifying stages. This allows the precise determination of the geometrical unknowns in the MMIC mounting structure (such as the solder height in fig. (1)).
2) Next, the thermal resistance matrix is calculated.
3) A current model for the single transistor device forming the complete MMIC amplifier is determined from DC measurements.

4) An iterative calculation follows, establishing the internal temperature and currents on the different transistor devices.
5) Finally the RF performance of the MMIC amplifier is included to give the dynamic internal temperature behavior of every transistor in the MMIC amplifier.

III. Thermal Characterization

MMIC power amplifiers are formed by N transistor devices combined to provide the required gain and output power. The amplifiers electrical performance is dependent on the internal temperature of the different devices. In turn, this temperature is determined by the thermal interaction between the transistors, and by the thermal properties of the solder employed to mount the amplifier. Thus, a thermal model characterization accounting for these effects is necessary to provide accurate results.

A. Thermal Model Extraction

In a MMIC amplifier formed by two separate independent amplifying stages, S_1 and S_2, the average internal temperature on each stage can be calculated using the expression

$$\begin{pmatrix} T^{S_1} \\ T^{S_2} \end{pmatrix} = \begin{pmatrix} R_{S_1S_1} & R_{S_1S_2} \\ R_{S_2S_1} & R_{S_2S_2} \end{pmatrix} \cdot \begin{pmatrix} P_{dis}^{S_1} \\ P_{dis}^{S_2} \end{pmatrix} + T_{amb}\,, \tag{1}$$

where $R_{S_1S_2}$ and $R_{S_2S_1}$ are the thermal coupling terms between amplifying stages, and $P_{dis}^{S_1}$ and $P_{dis}^{S_2}$ their corresponding dissipated power.

The thermal characterization of the MMIC amplifier is performed following the indirect electrical method proposed in [5]. The electrical method presented in [5] is a non-invasive procedure which requires the amplifier to operate under typical bias points and ambient temperatures. The use of this method is limited to MMIC amplifiers that allow independent bias conditions for different amplifying stages within the same amplifier. It uses the drain current consumption of one of the amplifying stages as an internal temperature sensor to experimentally determine the thermal coupling term between different amplifying stages, $R_{S_1S_2}$. This term is dependent on the thermal and geometrical properties of the layers involved in the mounting structure of the device being modelled.

The analytical simulation approach suggested in [2] can be employed to obtain the unknown height of the material used to sold the MMIC amplifier, so that a similar thermal coupling term $R_{S_1S_2}$ (as the one resulted from the thermal characterization performed) can be simulated. This guarantees a precise knowledge of the MMIC amplifier mounting structure characteristics from a thermal point of view. It also makes possible the determination of the self thermal resistance terms $R_{S_1S_1}$ and $R_{S_2S_2}$ through

$$R_{S_1S_1} = \frac{1}{N_{S_1} l_g l_f} \sum_{i=1}^{N_{S_1}} \int_{x_f^i}^{x_f^i + l_f} \int_{y_f^i}^{y_f^i + l_g} T\left(x, y\right) dx dy \tag{2}$$

where $T_{amb} = 0°\text{C}$, $P_{dis}^{S_2} = 0\text{W}$, $T\left(x, y\right)$ is the internal temperature on the top surface of the MMIC amplifier, N_{S_1} the number of transistor devices combined to form the stage S_1, l_g and l_f the gate's length and width, and $\left(x_f^i, y_f^i\right)$ the coordinates of each S_1 transistor i.

B. Thermal Resistance Matrix

The internal temperature of every transistor device on a MMIC amplifier can be related to their corresponding dissipated power by a thermal resistance matrix as reported in [7]. This temperature can be obtained using (3).

$$\begin{pmatrix} T_{FET}^1 \\ T_{FET}^2 \\ \vdots \\ T_{FET}^N \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{1N} \\ R_{21} & R_{22} & \cdots & R_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ R_{N1} & R_{N2} & \cdots & R_{NN} \end{pmatrix} \cdot \begin{pmatrix} P_{dis}^1 \\ P_{dis}^2 \\ \vdots \\ P_{dis}^N \end{pmatrix} + T_{amb} \tag{3}$$

The elements in the $N \times N$ matrix are calculated with (4) by means of thermal simulations performed using the MMIC mounting structure previously determined.

$$R_{ij} = T_{FET}^i \quad \text{with} \quad \begin{cases} P_{dis}^j = 1.0\text{W} \\ P_{dis}^k = 0\text{W} & \forall k \neq j \\ T_{amb} = 0°\text{C} \end{cases} \tag{4}$$

IV. FET Current Model

The single transistor device DC current model is obtained by fitting the parameters of the model used, [6], to the measurements performed on a single MMIC amplifying stage (under different ambient temperatures for a wide range of bias conditions, $I_D^{S_1} = f\left(V_D, V_G, T_{amb}\right)$). Before fitting the model parameters, the transformation

$$I_{DFET} = \frac{I_D^{S_1}}{N_{S_1}} \tag{5}$$

is used to obtain the current of a single transistor device, while the transformation given by

$$T_{FET} = T^{S_1} = T_{amb} + R_{S_1S_1} P_{dis}^{S_1} \tag{6}$$

is employed to determine the internal temperature of a single transistor device for each bias and ambient temperature condition.

V. Iterative Process

The thermal characterization described in section III is performed assuming an equal dissipated power for all the transistors that form an amplifying stage. On the other hand, the DC current model for a single transistor device derived in section IV is obtained assuming the same internal temperature for all the transistors that form a single amplifying stage. Nevertheless, neither the DC current consumption profile is constant for all the transistors nor is their internal temperature uniform.

In order to correctly solve the electro-thermal problem as indicated by

$$T_{FET}^i = f\left(P_{dis}^i\left(T_{FET}^i\right)\right)\,, \tag{7}$$

the iterative process shown in fig. (2) is followed to finally obtain, for some given static bias and ambient temperature conditions, the non-uniform internal temperature for each transistor device and their corresponding non-uniform dissipated power.

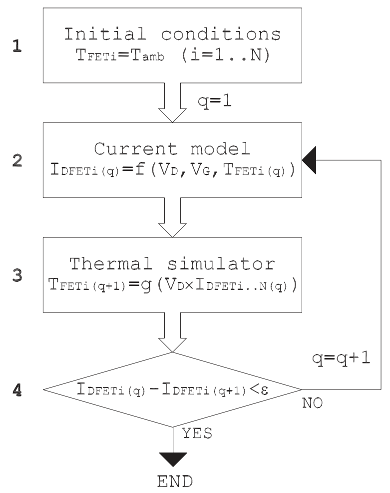


Fig. 2. Electro-thermal simulation process description.

VI. Measurements and Results

The procedure described in previous sections was used to derive an electro-thermal model for a commercial X band MMIC power amplifier. The amplifier is formed, as shown in fig. (1), by two different independent amplifying stages. The input stage is formed by $N_{S_1} = 12$ FETs in parallel, while the second stage is formed by two separate sets of $N_{S_2}/2 = 14$ FET devices.

The thermal conductivity and height of the layers in the MMIC mounting structure are given in table I.

TABLE I

MMIC mounting structure characteristics

Layer	θ_{th} (W/cm/K)	Heigth (μm)
AsGa	0.44	100
Epoxy	0.016	unknown
Carrier	3.9	3000

A. Thermal Characterization

Fig. (3) shows the thermal resistance coupling term $R_{S_1S_2}$ between the input and output stages measured employing the method suggested in [5].

From the thermal measurements performed, the thermal coupling term was estimated to be $R_{S_1S_2} \approx 5.12$°C/W. This value was used to determine a height of the epoxy attachment layer of $h_a = 85.2\mu$m.

B. Static Conditions

The internal temperature on the top surface of the MMIC amplifier was obtained for the following working conditions: $V_{DMMIC} = 8.05$V, $I_{DMMIC} = 272$mA and $T_{amb} = 25.0$°C. Two different kind of simulation were performed: constant dissipated power for the transistors that form the amplifier and non-uniform current consumption when the electro-thermal model is used.

The temperature of the coldest and hottest FET devices as well as their corresponding drain current consumption are given in table II for both sets of simulations. Fig. (4) shows the internal temperature profile for the MMIC input and output stages provided by the electro-thermal simulation.

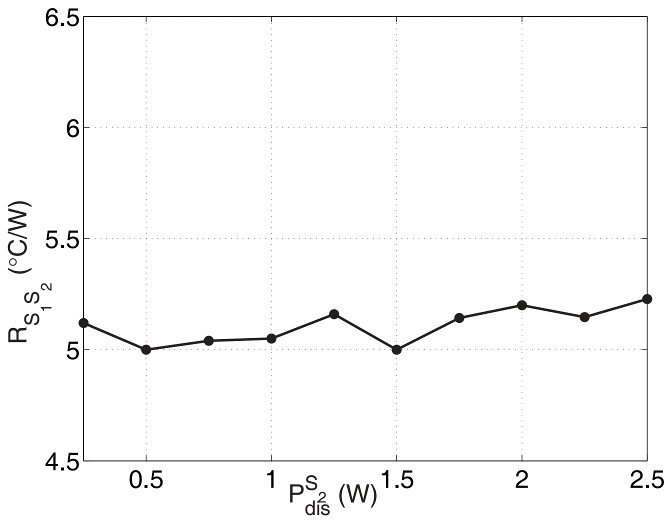


Fig. 3. Thermal resistance coupling term between amplifying stages measured for $T_{amb} = -10.0$°C and $P_{dis}^{S1} \sim 1.2$W@$V_D = 8.0$V.

TABLE II

MMIC transistors internal temperature

Simulation	Coldest FET		Hottest FET	
	T ($°C$)	I_D (mA)	T ($°C$)	I_D (mA)
Uniform drain current	75.45	6.8	96.71	6.8
Electro-thermal	77.54	7.36	95.03	6.59

The electro-thermal model was validated by simulating and measuring the complete MMIC drain current consumption for different bias and ambient temperature conditions. The results given in fig. (5) show good agreement between measurements and simulations.

C. RF Operation

RF measurements, such as those depicted in figure 6.a, can be easily included in the electro-thermal model to give additional insight to the thermal behavior of the MMIC amplifier under dynamic conditions. Fig. 6.b shows that the minimum hot spot internal temperature is not met for maximum efficiency of the complete MMIC amplifier.

VII. Conclusions

This paper proposes a complete procedure to obtain an electro-thermal model for MMIC power amplifiers (formed by multiple temperature dependent heat sources). The experimental thermal characterization is performed following an indirect electrical method that permits the estimation of geometrical unknowns in the MMIC mounting structure. The proposed method is used to accurately predict the static behavior of a commercial X-band MMIC amplifier. RF measurements are used to determine the MMIC internal temperature variation under dynamic conditions.

Acknowledgment

This work was supported by project TIC2002-04569-C02-01 of the Spanish Ministry of Science and Technology.

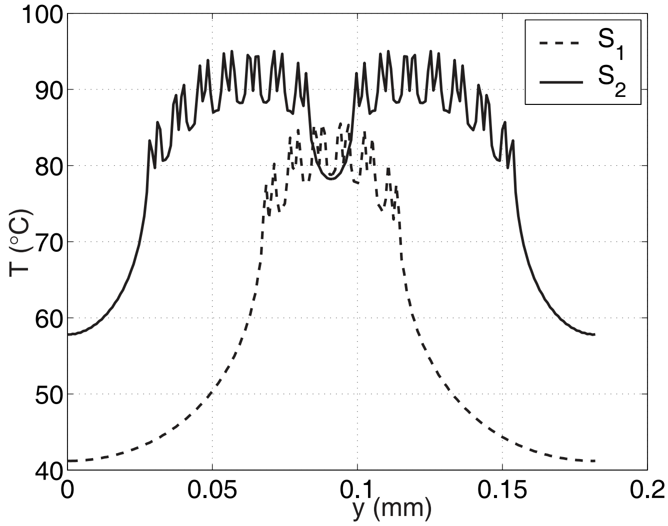


Fig. 4. Internal temperature on the MMIC transistor heat sources for $V_{DMMIC} = 8.05$V, $I_{DMMIC} = 272$mA and $T_{amb} = 25.0$°C.

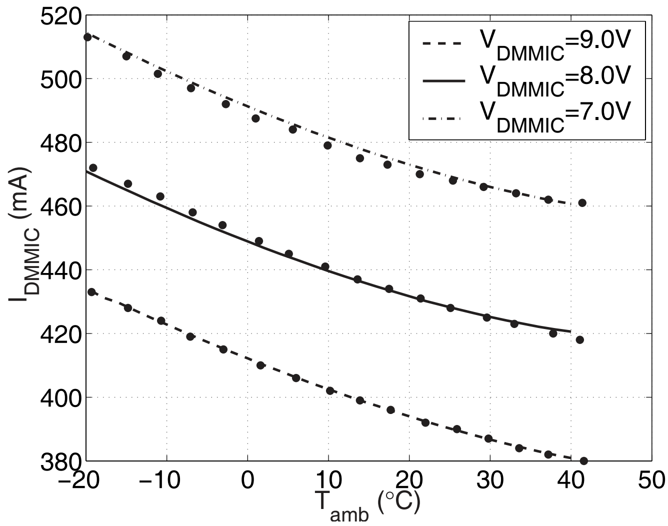
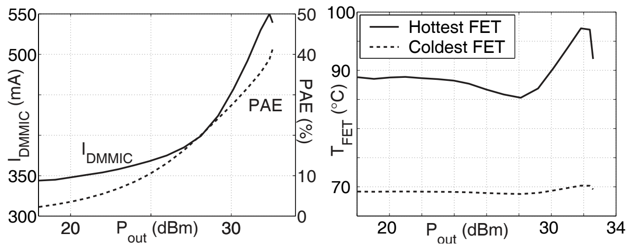


Fig. 5. MMIC power amplifier drain current consumption measured (circles) and simulated for different bias and ambient temperature conditions.



(a) Drain current and power added efficiency at $f = 9.2$GHz.

(b) Temperature of the hottest and coldest FETs in the MMIC.

Fig. 6. Internal temperature behavior under different RF output power levels for $V_{DMMIC} = 8.0$V, $V_{GMMIC} = -1.1$V, $I_{DMMIC} = 344$mA and $T_{amb} = 5.0$°C.

REFERENCES

[1] K. Nishiori, K. Ishida, Y. Kitaura, and N. Uchitomi, "Thermal analysis of GaAs power monolithic microwave IC's mounted with epoxy attachment," *IEEE Trans. on Components, Packaging, and Manufacturing Technology*, vol. 20, no. 2, pp. 220-224, June 1997.

[2] J. Albers, "An exact recursion relation solution for the steady-state surface temperature of a general multilayer structure," *IEEE Trans. on Components, Packaging, and Manufacturing Technology-Part A*, vol. 18, no. 1, pp. 31-38, March 1995.

[3] W. Batty, A. J. Panks, and C. M. Snowden, "Fully coupled electro-thermal simulation of MMICs and MMIC arrays based on a physical model", *1999 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, pp. 693-696, June 1999.

[4] M. Pesare, A. Giorgio, and A. G. Perri, "Electrothermal model of multilayer structure for the design of GaAs integrated circuit devices", *2000 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, pp. 146-149, June 2000.

[5] G. Torregrosa-Penalva, A. Asensio-López, Á. Blanco-del-Campo, and F. J. Ortega-González, "Precise and simple DC-electrothermal characterization of MMIC power amplifiers", *2003 IEEE Nineteenth Annual Semiconductor Thermal Measurement and Management Sym. Dig.*, pp. 112-118, March 2003.

[6] A. J. McCamant, G. D. McCormack, and D. H. Smith, "An improved GaAs MESFET model for SPICE", *IEEE Trans. on Microwave Theory and Techniques*, vol. 38, no. 6, pp. 822-824, June 1990.

[7] W. Batty, A.J. Panks, S. David, R.G. Johnson, and C.M. Snowden, "Electro-thermal modelling and measurement of thermal time constants and natural convection in spatial power combining grid arrays", *2000 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1937-1940, 2000.