Dynamic Electro-Thermal Behavioral Model for RF Power Amplifiers

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Abstract — **Electrical and electro-thermal memory effects influence significantly the performance of RF power amplifiers and predistortion-based linearizers as signal bandwidth and operation power increase. In this paper, we present an electro-thermal behavior model for RF power amplifiers. Input and output time domain waveforms have been used to identify the PA's model parameters. Measurements that have been conducted on a 90-watt peak LDMOS power amplifier were found to be in good agreement with those obtained from a simulation that uses the model developed and implemented in ADS environment.**

I. Introduction

Memory effects on the behavior of RF power amplifiers were the subject of a great number of studies in the last few years as their output power and signal bandwidth continues growing. This rising interest is explained generally by their significant influence on the performance of power amplifiers, and specifically when linearized using predistortion techniques. Consequently, a good knowledge of memory effect sources and the development of an accurate method to capture their effects is a critical step in the design of wideband high power amplifiers. In the literature [1] two categories of memory effects are pointed out: electrical and electro-thermal memory effects. Electrical memory effects are caused by the variation of terminal impedances (biasing and matching circuit's impedances) over the input signal bandwidth around the carrier frequency f_0 and its harmonics $2f_0$, as well as at baseband frequencies. These effects could be minimized, especially in the case of FET based amplifiers, if great attentions are carried on the matching and biasing circuit design. However, transistor temperature-dependent electrical parameters such as gain variation causes unavoidable electro-thermal memory effects.

In the literature, memory effects are measured as being the PA distortion dependency on tone spacing under a two-tone test signal. In fact, it supposes that for a given value of the frequency spacing and within wide-range amplitude, the power amplifier behavior will be similar to that of a signal with a bandwidth equal to the frequency spacing. It is seen as a practical way to get around the difficulties when using other metrics such as ACPR with a modulated signal to study this phenomenon.

Bosch and al. [2] proposed a measurement system using two network analyzers capable of providing information about the memory effects on the fundamental signals. This system does not provide their effects on IMD that are essential in the linearization case. Other systems [3] have been proposed to measure the relative phase of the IMD3 and were based on a reference non-linearity generator (low frequency MESFET). This generator should provide a constant phase IMD3 over a range of wideband modulation frequencies. The dependency of their performances on the quality of the reference non-linearity, which should be an ideal third order distorter, represents the drawbacks of such measurement systems. Vuolevi and al. [1] proposed a measurement setup suitable to a predistortion application based on envelope injection techniques. This technique requires a tedious and lengthy calibration that calls for too many specialized instruments, such as three generators, two vector network analyzers, two spectrum analyzers, down-converters, etc. In addition, its accuracy depends greatly on the quality of the measurement equipment.

In the first section of this paper, we develop a more comprehensive and accurate expression of the junction temperature as a function of the instantaneous dissipated power, as well as the input signal level. This expression will be used in the second section for the construction of an electro-thermal model suitable for RF power amplifiers. In the final section, a brief discussion is proposed to explain how the electro-thermal behavior of the amplifier influences the generation of the inter-modulation distortion (IMD) for different types of drive signals such as WCDMA, GSM etc.

II. Electro-Thermal Model

Vuolevi and al. [1] expressed the junction temperature of the transistor T_j according to the equation (1) in order to explain its dynamic changes with the drive signal. Equation (1) utilizes $Z_{th}(w_1 - w_2)$ as thermal impedance at low frequency and $P_{dissip}(w_1-w_2)$ as the dissipated power at these frequencies.

$$T_j=T_{amb}+R_{th}P_{dissip}(DC)+Z_{th}(w_1-w_2)P_{dissip}(w_1-w_2) \quad (1)$$

The instantaneous dissipated power determines the instantaneous rate of heat that is applied to the transistor. Furthermore, due to the finite mass of the component, thermal impedance includes a capacitive part in addition to the resistive one. Thermal resistance describes just the steady-state behavior, and thermal capacitance is essential for the description of the dynamic behavior. Thermal resistances and capacitances together lead to exponential rise and fall times characterized by thermal RC time constant, similar to the electrical RC constant. The expression of the instantaneous junction temperature of the transistor was developed by making use of the existing duality [4] between heat transfer and electrical phenomena summarized in table1.

TABLE I
THERMAL AND ELECTRICAL QUANTITIES EQUIVALENCE

	THERMAL QUANTITY		ELECTRICAL QUANTITY
P_{dissip}	Power heat flow (W)	I	Current flow (A)
T_j	Temperature (K)	V	Voltage (V)
R_{th}	Thermal resistance (K/W)	R	Electrical resistance (Ω)
C_{th}	Thermal capacitance (J/K)	C	Electrical capacitance (F)

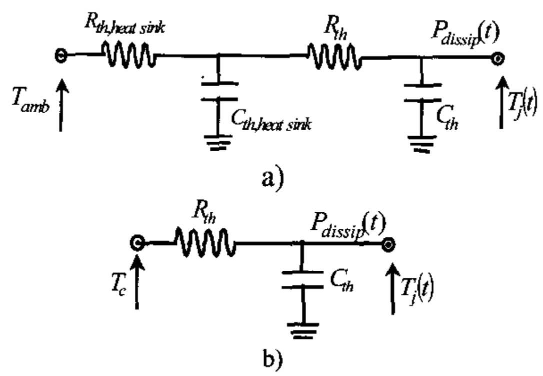

Fig. 1. Transistor thermal model

Figure 1 shows the thermal network models of the transistor including the silicon chip, the package and the heat sink relating the junction and ambient temperatures to the dissipated heat amount. Since thermal constant $R_{th,heat\sin k}\times C_{th,heat\sin k}$ is too large when compared to $R_{th}\times C_{th}$, figure 1-a) was simplified to figure 1-b).

Based on figure 1-b), the instantaneous temperature can be expressed as a solution to the following first order non-homogeneous differential equation:

$$\frac{\partial T_j(t)}{\partial t}+\frac{1}{R_{th}C_{th}}T_j(t)=\frac{1}{R_{th}C_{th}}\left(R_{th}P_{dissip}(t)+T_c\right) \quad (2)$$

where

$$P_{dissip}(t)=V_{DS,dc}\times I_{DS,dc}(t)+P_{RF,in}(t)-P_{RF,out}(t) \quad (3)$$

Or

$$P_{dissip}(t)=(1-\eta(t))\times P_{RFout}(t) \quad (4)$$

and $\eta(t)=$ ***instantaneous power effeciency***

Equation (2) has the form

$$\frac{\partial}{\partial t}T_j(t)+a(t)T_j(t)=b(t) \quad (5)$$

where

$a(t)=\frac{1}{R_{th}C_{th}}$ and $b(t)=\frac{1}{R_{th}C_{th}}\left(R_{th}P_{dissip}(t)+T_c\right)$

The general solution of (5) has the following form

$$T_j(t)=e^{\left(-\int a(t)dt\right)}\left(\int e^{\left(\int a(t)dt\right)}b(t)dt+K\right) \quad (6)$$

This equation is equivalent to

$$T_j(t)=e^{-\frac{t}{\tau}}\left(\int\frac{1}{\tau}e^{\left(\frac{t}{\tau}\right)}\left(R_{th}P_{dissip}(t)+T_c\right)dt+K\right) \quad (7)$$

$R_{th}C_{th}=\tau$ is the thermal time constant.

The integral of the right hand side expression of (7) can be rewritten as follows:

$$T_j(t)=e^{-\frac{t}{\tau}}\left\{\int\frac{\partial e^{\left(\frac{t}{\tau}\right)}\left(R_{th}P_{dissip}(t)+T_c\right)}{\partial t}dt-\int R_{th}e^{\left(\frac{t}{\tau}\right)}\frac{\partial P_{dissip}(t)}{\partial t}dt+K\right\} \quad (8)$$

In the particular case of a step input signal excitation, the instantaneous power is constant, hence the instantaneous dissipated power remains constant. Therefore one can write:

$$P_{dissip}(t) = \begin{cases} P & t_0 \le t \le T \\ P_0 & t < t_0 \end{cases} ;\Rightarrow \frac{\partial P_{dissip}(t)}{\partial t} = 0 \qquad (9)$$

with $\tau \ll T$

In such a case, equation (8) becomes equation (10)

$$T_j(t) = T_{j,s} + (T_{j,0} - T_{j,s}) \times e^{-\frac{\Delta t}{\tau}} \qquad (10)$$

where $T_{j,0} = T_c + R_{th}P_0$, $T_{j,s} = T_c + R_{th}P$

Figure 3 shows the time variation of the junction temperature according to equation (1) for the pulsed signal shown in figure 2.

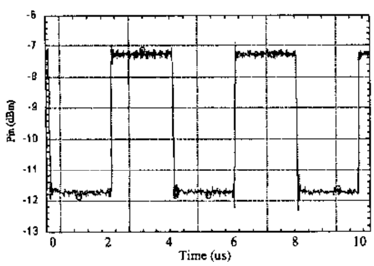

Fig. 2. Input pulsed signal envelope (period 4us, duty cycle = 0.5).

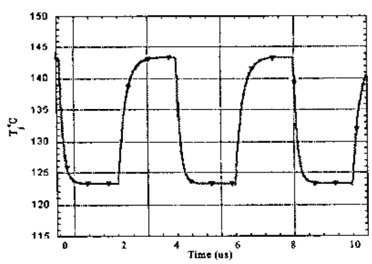

Fig. 3. Junction temperature variation vs. time for pulsed signal (period 4us, duty cycle =0.5).

III. MODEL IDENTIFICATION AND VALIDATION

The instantaneous junction temperature expression defined in the last section was used to complete the free-self-heating behavior model of the power amplifier [5] as shown in Figure 4. In this work, an LDMOS 90 watts peak power amplifier was used. Several experiments were conducted on this amplifier in order to characterize its thermal behavior. Figures 5 and 6 show the measured gain compression, phase and amplitude, versus junction temperature. The amplifier under test was operated in this stage of measurements in its small signal region. Such that This way the measured gain compression results from only the junction temperature variation, and not the electrical non-linearity of the amplifier. These curves will be used in the behavior model to determine the complex gain compression amount corresponding to each input signal level, as a function of its corresponding junction temperature. Figure 7 shows the pulsed measurement results of the drain current versus the input signal for different case temperatures. This curve is used in the amplifier model given in figure 4 for the calculation of instantaneous dissipated power, which in turn will serve to calculate the instantaneous junction temperature. Figure 8 shows the simulated and measured output waveforms of the power amplifier under a 50% duty cycle square input signal. We can observe easily the exponential fall and rise of the signal as a response to the junction temperature exponential variation predicted by equation (10). Moreover, the agreement between the simulated and measured waveforms in figure 8 demonstrates the accuracy of the developed model to predict the electro-thermal behavior of the tested amplifier.

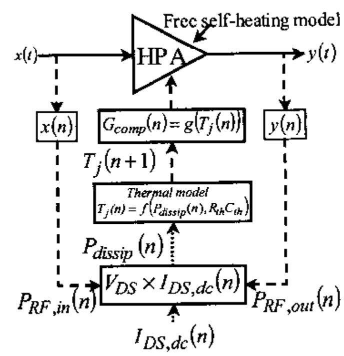

Fig. 4. Dynamic temperature calculation bloc diagram.

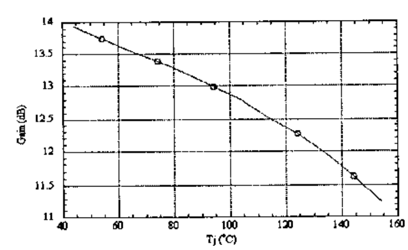

Fig. 5. Measured gain compression vs. junction temperature.

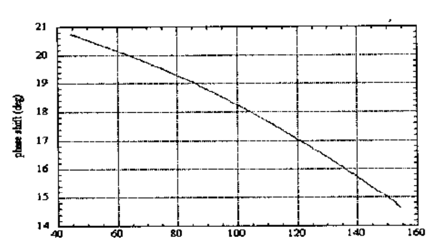

Fig. 6. Measured phase compression vs. junction temperature.

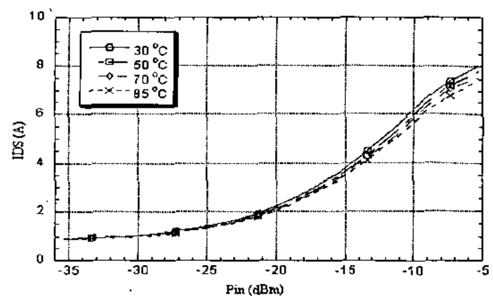

Fig. 7. Pulsed measurements of drain current vs. drive.

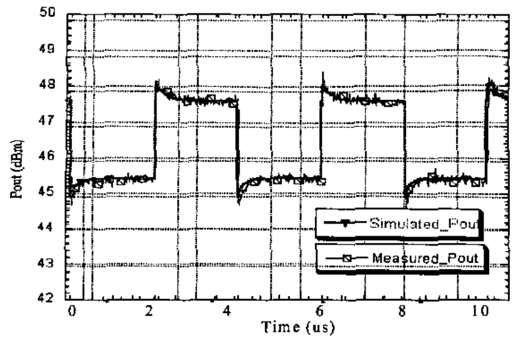

Fig. 9. Measured and simulated output envelope waveforms (period 4us, duty cycle =0.5).

IV. DISCUSSIONS

The temperature changes have repercussions on electrical parameters of the transistor that influence the amplifier behavior. Instantaneous transistor junction temperature variation depends on instantaneous dissipated power, and consequently, on the input signal time variation. As a result, high power amplifiers complex gain (amplitude and phase shifting) dependency on junction temperature can be considered as a source of non-linearity. The combination of this source of non-linearity, with the transistor intrinsic electrical non-linearity versus input signal, explains the influence of the thermal transient behavior on the inter-modulation distortion. This mechanism provides an explanation for the dependency of IMD on tones frequency spacing variation in the case of multi-tones signal excitation, since they can be interpreted as a dynamic variation of junction temperature in time. Thus, the IMD vectors emerging from thermal and electrical non-linearity sources result in a varying IMD vector that depends on frequency tones spacing as transistor thermal behavior does. This leads to the fact that the behavior of the power amplifier under high varying amplitude and wideband signals (high speed signals) may be considered as free of self-heating effects. Indeed, instantaneous junction temperature will not experience a lot of changes, and by consequence thermal non-linearity source influence will be minimized. Furthermore, the instantaneous temperature will be close to that fixed by input average power and consequently to the average dissipated power. Accordingly, electrical memory effects may well be considered as the main source of memory effects in the behavior of power amplifiers under wideband and high varying signals, such as multi-carriers WCDMA. However, in the case of narrow band signals (e.g. GSM signals) with a channel separation as small as 25KHz, the power amplifier dynamic electro-thermal behavior should be well taken into account to assure good performance.

V. CONCLUSION

In this paper a dynamic electro-thermal behavior model for power amplifiers is proposed along with its parameter identification procedure. Implementation of the model within ADS simulator and its validation was carried out for a 90-Watt peak power LDMOS amplifier. Satisfactory results were obtained for pulsed signals.

Based on the model developed, and the experiments conducted, one can conclude that power amplifiers used for multi-carriers 3G applications are almost free from thermal induced memory effects. In contrast, they are sensitive and influenced by electrical induced memory effects.

REFERENCES

[1] J.H.K. Vuolevi, T. Rahkonen, and J. P. A. Manninen, "Measurement technique for characterizing memory effects in RF power amplifiers, " *IEEE Trans. Microwave Theory and Tech*, vol. 49, no. 8, pp. 1383-1389, Aug. 2001.

[2] W. Bosch, and G. Gatti, "Measurement and simulation of memory effects in predistortion linearizers," *IEEE Trans. Microwave Theory and Tech*, vol. 37, no. 12, pp. 1885 - 1890, Dec. 1989.

[3] Y. Youngoo, Y. Jeahyok, N. Joongjin, K. Bumman, and P. Myungkyu, "Measurement of two-tone transfer characteristics of high-power amplifiers," *IEEE Trans. Microwave Theory and Tech*, vol. 49, no. 3, pp. 568-571, March 2001.

[4] K. Skadron, T. Abdelzaher, and M. R. Stan, "Control-theoretic techniques and thermal-RC modeling for accurate and localized dynamic thermal management," *IEEE Proceeding, Eighth International Symp. on High-Performance Computer Architecture*, pp. 12-23, 2002.

[5] S. Boumaiza, and F. M. Ghannouchi, "An accurate complex behaviour test bed suitable for 3G power amplifiers characterization," *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, pp. 2241-2244, June 2002.