Behavioral modeling of GaN-based power amplifiers: impact of electrothermal feedback on the model accuracy and identification

BEHAVIORAL MODELING OF GaN-BASED POWER AMPLIFIERS: IMPACT OF ELECTROTHERMAL FEEDBACK ON THE MODEL ACCURACY AND IDENTIFICATION

Roberto Quaglia, Vittorio Camarchia, Federica Cappelluti, Simona Donati Guerrieri, Eduardo G. Lima, Giovanni Ghione, and Marco Pirola
Department of Electronics (DELEN), Politecnico di Torino, Corso Duca Degli Abruzzi, 24, 10129 Torino, Italy; Corresponding author: vittorio.camarchia@polito.it

ABSTRACT: *In this article, we discuss the accuracy of behavioral models in simulating the intermodulation distortion (IMD) of microwave GaN-based high-power amplifiers in the presence of strong electrothermal (ET) feedback. Exploiting an accurate self-consistent ET model derived from measurements and thermal finite-element method simulations, we show that behavioral models are able to yield accurate results, provided that the model identification is carried out with signals with wide bandwidth and large dynamics.*

Key words: *behavioral model; GaN HEMT; power amplifiers; electrothermal models*

1. INTRODUCTION

Next-generation RF power amplifiers (PAs) based on GaN High-Electron Mobility Transistors (HEMTs) take advantage of the high breakdown voltage typical of wide-bandgap semiconductors to reach record power densities, one order of magnitude larger than those achievable by state-of-art GaAs technology. As shown in [1], device self-heating and the related slow memory effects affect the device performances, above all in terms of linearity under multitone or variable envelope excitation, thus requiring the development of modeling tools able to accurately describe the electrothermal (ET) interaction and its effect at physical, circuit, and system level. In particular, the accurate and efficient system-level modeling of the PA linearity (that is significantly influenced by thermal memory effects, see [1]) is a key issue for the reliable simulation of modern radio frequency (RF) communication systems (which aim to increase the bandwidth efficiency through the use of complex modulated signals characterized by a strongly varying envelope), with an aim at improving the PA linearity through the use of baseband predistortion stage, whose design requires a very accurate PA model in the presence of complex input signal.

Within the framework of physics-based and circuit-level models, the simulation of thermal-induced nonlinearities requires a detailed system-level description of heat diffusion dynamics (and not only the knowledge of the average or dc device temperature) and a self-consistent solution of the electrical and thermal equations. In this context, we have previously developed a compact self-consistent ET model [1] for GaN-based Pas, suitable for the prediction of long-memory thermal effects on nonlinear distortion. However, the computational intensity and the very structure of physics-based or circuit-level models prevents their use in system-level simulations; behavioral-models based on external terminal measurements are, as well known, far better suited, provided that they are able to accurately reproduce nonlinear distortions induced by low frequency memory effects in the presence of complex, variable-envelope input signals.

The development of PAs behavioral models has been widely addressed in the literature, but little attention has been given so far to the issue of ET dynamic feedback, and to the influence of such a feedback on the model performances. Typical approaches (see e.g., [2] and references therein) include memory-less AM-AM AM-PM models or models based on Volterra-like expansions [3], the latter being able to describe short-memory effects but yet not suitable for the inclusion of long memory-phenomena. Recently, a possible approach to the behavioral ET simulation of PAs has been proposed in [2], exploiting a behavioral electrical model coupled to dynamic thermal reduced model. However, the evaluation of the device thermal impedance still poses some problems, as it requires either numerical calculations, based on a precise knowledge of the device geometry and materials, or dedicated (and difficult) dynamic thermal measurements.

Based on the above discussion, in this article we take into consideration an overall behavioral model (or black-box model), wherein temperature effects are embedded but not explicitly considered by exploiting temperature as a separate control variable, and we assume that the model is derived from standard electrical measurements (though with complex input signals, not only single- or two-tone inputs). The purpose of the article is to assess, on the basis of a case study, whether such a behavioral model is able to accurately describe nonlinear distortions in high-power devices affected by significant ET feedback. To be able to fully control and separate the effect of the ET feedback, we have exploited, as the *physical* PA, the self-consistent ET compact model (SCET) presented in [1]. The model was in turn extensively tested on experimental data and, as shown in [1], is able to accurately predict the influence of long thermal memory on the nonlinear distortion.

Concerning the behavioral models, we consider two different models exploiting a Wiener-like and a memory-polynomial (MP) approach, respectively. The models are indentified on the basis of numerical simulations carried out on the SCET compact model; as already stressed, this allows to readily assess the separate effect of the electrical and thermal memory on the device performances, thus helping to clarify the impact of each mechanism on the accuracy of the considered behavioral models, in particular, with reference to the parameter extraction procedure.

2. SELF-CONSISTENT ELECTROTHERMAL CIRCUIT MODEL

The reference circuit level model, SCET, couples a temperature-dependent nonlinear equivalent circuit based on a cubic Curtice FET compact model [4], to a compact dynamic thermal model extracted through a Wiener behavioral approach from full-scale 3-D finite-element method (FEM) simulations. The model was extracted and validated on the basis of pulsed dc and small-signal experimental measurements of a Selex-SI coplanar AlGaN/GaN HEMT on SiC substrate, with 1-mm total gate periphery (10×100 μm). The model was then validated against large-signal measurements, proving its accuracy in the prediction of gain and nonlinearities. Further details on the modeling approach and validation may be found in [1]. The ability of the model to accurately reproduce slow memory effects on IM3 generation make it well suited for the development and analysis of behavioral approaches presented in the following sections.

3. BEHAVIORAL MODELS

3.1. Wiener Model

The relationship between the PA baseband input and output complex envelopes is described through the classical Wiener-like approach, exploiting the cascade of a linear filter followed by a static nonlinearity [5], as shown in Figure 1.

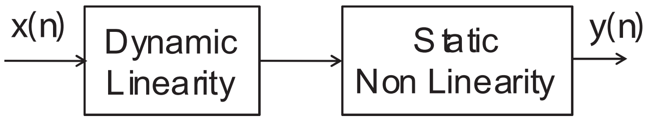

Figure 1 Diagram of the Wiener baseband model

In the present implementation, the static nonlinearity is modeled by an odd-order polynomial, whereas a finite impulse response (FIR) filter models the dynamic linear behavior. The corresponding constitutive equation is:

$$y(n) = \sum_{p=1}^{P} a_{2p-1}\left[\left|\sum_{m=0}^{M} h_m x(n-m)\right|^{2(p-1)} \sum_{m=0}^{M} h_m x(n-m)\right].$$

The coefficients a_{2p-1} and h_m of the Wiener model have been fitted on complex-envelope time-domain input–output measurements.

3.2. Memory Polynomial

The MP model is a particular case of the Parallel Hammerstein model [6]: every branch includes an odd monomial static nonlinearity followed by a FIR filter for the dynamic linear response.

The scheme of the MP model is shown in Figure 2; the corresponding model equation is:

$$y(n) = \sum_{p=1}^{P}\sum_{m=0}^{M} b_{p,m} x(n-m)|x(n-m)|^{2(p-1)},$$

where $x(n)$ is the baseband input instantaneous sample, $y(n)$ is the baseband output instantaneous sample, P is the number of branches, $M + 1$ is the number of taps in every FIR filter, $b_{p,m}$ are the coefficients of the model. The MP model is linear in its parameters therefore the extraction from an envelope time domain measure can be carried out by a Least Squares Method [7].

3.3. Extraction Strategy

Because of the intrinsic nonextrapolative feature of black-box system-level models, the parameters extraction must be carried out by applying proper excitation signals to the device, to cover the entire operation range in terms of frequency bandwidth and voltage/current range. The development of an overall behavioral approach relies on the idea that the proper choice of electrical excitation signals used for the model extraction is expected to capture in a direct way also the temperature operation range of interest. In what follows, we show that the overall approach can be successful if the model is extracted with excitation signals characterized by a high dynamic content (large frequency bandwidth) and a randomly generated large amplitude variation. The requirement of a high dynamic content reflects the long-memory feature of the device thermal behavior.

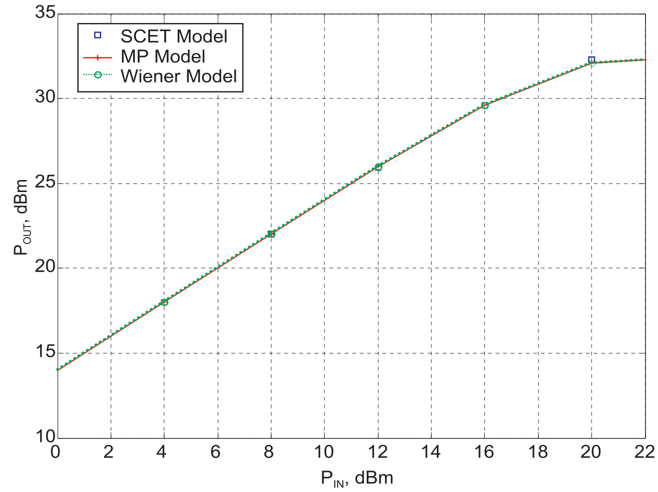

Figure 3 Class A PA. Single-tone simulation results: comparison between SCET and Wiener behavioral model extracted with a single tone stimulus. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

4. RESULTS

4.1. Class A PA

The PA has been modeled both with the Wiener and the MP approaches. The complex envelopes of PA input and output signals have been collected and elaborated by the extraction algorithm. The implemented Wiener model has a maximum polynomial order of nine and a FIR filter with two taps. For the sake of comparison, the same polynomial order and memory depth has been used for the MP model that has five branches. The extracted models have been validated against envelope single-tone and two-tone simulations.

As a first test, the Wiener model has been extracted by employing a single tone excitation signal. As shown in Figure 3, the model reproduces with good accuracy the PA behavior at fundamental frequency.

However, as shown in Figure 4, the accuracy results to be very poor when IMD products are considered, especially for closely spaced tones. This is interpreted as a consequence of the wide bandwidth inherent to the thermal feedback, as confirmed from the results in Section 4.2. On the other hand, if the bandwidth of the

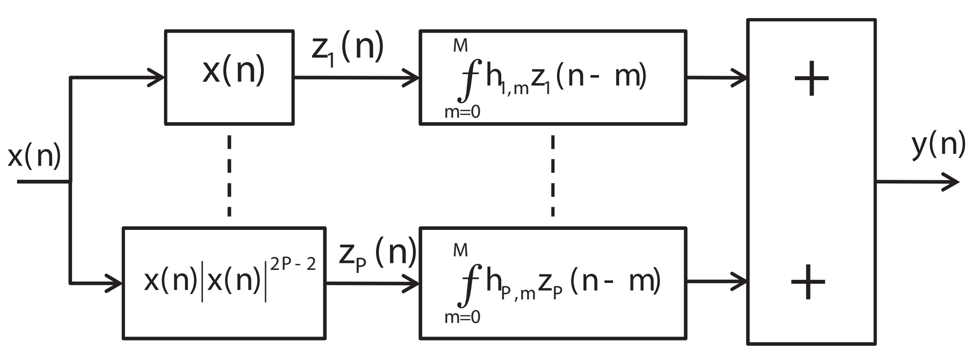

Figure 2 Diagram of the memory polynomial baseband model

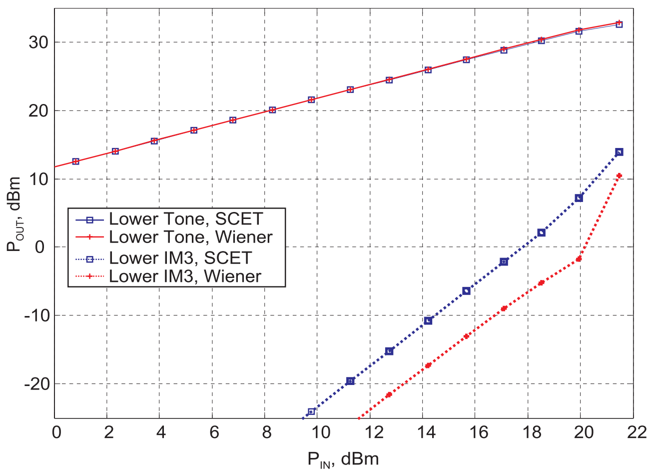

Figure 4 Class A PA. Two-tone simulation for 20 MHz of tone spacing: comparison between SCET and Wiener behavioral model extracted with a single tone stimulus. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

stimulus used during the extraction procedure is wide enough (in our approach, a random modulated signal was used with 100 MHz of bandwidth), the situation changes significantly. The two-tone P_{IN}–P_{OUT} simulation curves (with tone spacing of 30 MHz), see Figure 5, show the good agreement of both behavioral models with respect to the reference SCET model, in terms of fundamental tones and 3rd order intermodulation products (IM3). A slightly better accuracy is provided by the MP model in terms of IM3. Based on this, we have exploited the MP model to carry out two-tone simulations with different tone spacing. The results, reported in Figure 6, show that the behavioral model reproduces with good quantitative accuracy the IM3 dependence on the tone spacing.

To further assess the importance of the test signal bandwidth used for the model identification, a second MP model has been extracted with a narrow band random modulated signal (10 MHz): in this case the two-tone simulation (tones spacing of 30 MHz) shows the poor accuracy in reproducing the IM3s (note that the

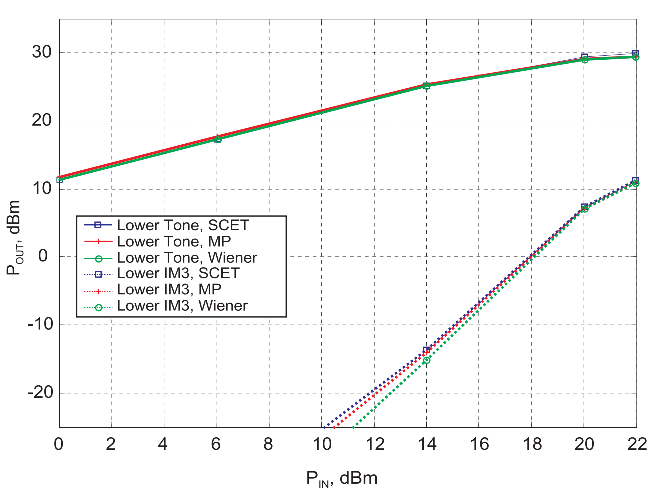

Figure 5 Class A PA. Two-tone simulation with 30 MHz of tone spacing: comparison between SCET and the two behavioral models, extracted with a wide band (100 MHz) test signal. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

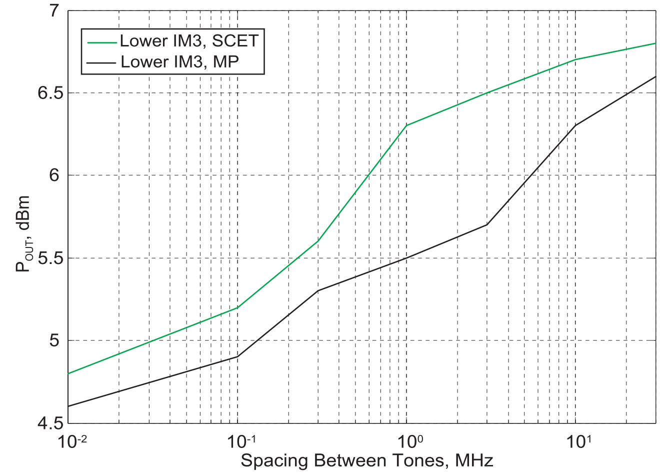

Figure 6 Class A PA. Two tone simulation results: lower IM3 vs. spacing comparison between SCET and MP behavioral model extracted with a wide band (100 MHz) test signal. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

average error against the SCET model is about ten times larger than in the previous case), whereas the P_{IN}–P_{OUT} at the fundamental tone frequencies still is accurate (see Fig. 7).

4.2. Assessing Memory Effects

To further assess the impact of long-memory effects on distortion and provide insight on whether they are related to the thermal or electrical response, the thermal part of the SCET model has been turned off, obtaining a purely electrical isothermal model of the PA. In this case, even if the parameter extraction is carried out with a narrow-band signal (about 10 MHz), the MP model results to be quite accurate both in terms of fundamental tones and IM3 or of the PA in the presence of wideband (30 MHz) excitation (see Fig. 8).

5. CONCLUSIONS

We have presented a discussion on the suitability of black-box behavioral models, directly identified from measured electrical performances, when applied to the modeling of high-PAs in which

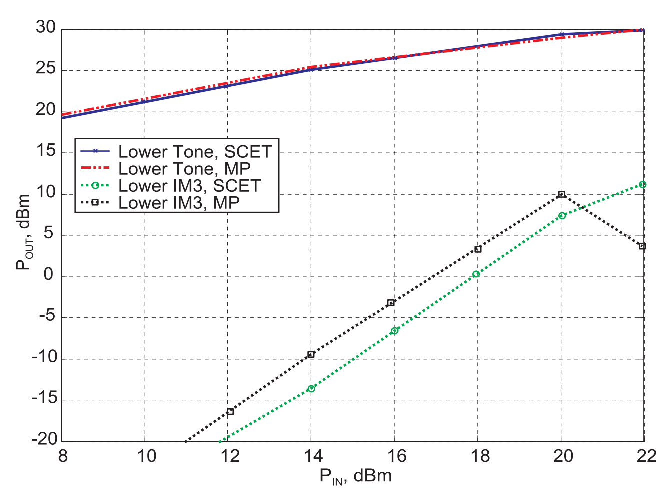

Figure 7 Class A PA. Two-tone simulation with 30 MHz of tone spacing: comparison between SCET and MP behavioral model extracted with a narrow band (10 MHz) test signal. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

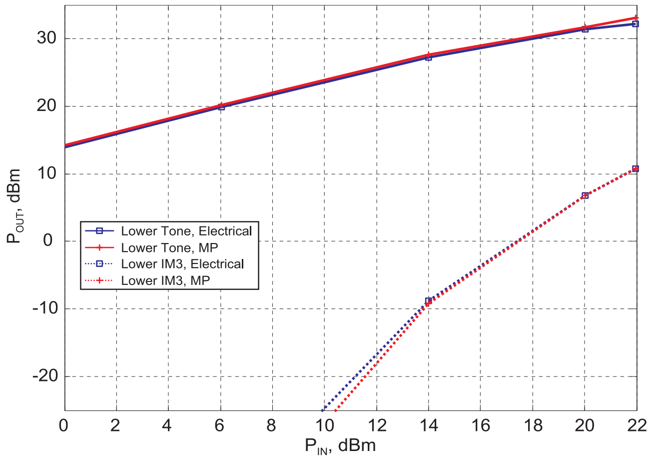

Figure 8 Class A PA. Two-tone simulation with 30 MHz of tone spacing: comparison between electrical isothermal model and MP behavioral model extracted with a narrow band (10 MHz) test signal. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

intermodulation performances are strongly affected by long-memory thermal effects resulting from ET feedback. The presented results on class-A PAs show that black-box approaches yield accurate results in terms of intermodulation distortion, provided that test signals with wide bandwidth (compatible with the low-pass behavior of the thermal dynamics) and suitably large dynamic range are exploited in the parameter model extraction.

ACKNOWLEDGMENTS

The work was partly supported by the NOE NEWCOM++ and by the PRIN 2007 M3ICGAN projects.

REFERENCES

1. V. Camarchia, F. Cappelluti, M. Pirola, S.D. Guerrieri, and G. Ghione, Self-consistent electrothermal modeling of Class A, AB, and B power GaN HEMTs under modulated RF excitation, Microwave Theory Tech 55 (2007), 1824–1831.
2. J. Mazeau, R. Sommet, D. Caban-Chastas, E. Gatard, R. Quere, and Y. Mancuso, Behavioral thermal modeling for microwave power amplifier design, Microwave Theory Tech 55 (2007), 2290–2296.
3. C. Florian, F. Filicori, D. Mirri, T. Brazil, and M. Wren, CAD identification and validation of a non-linear dynamic model for performance analysis of large-signal amplifiers, IEEE MTT-S Int Microw Symp Dig Philadelphia 3 (2003), no. 8–13, 2125–2128.
4. W.R. Curtice and M. Ettenberg, A nonlinear GaAs FET model for use in the design of output circuits for power amplifiers, IEEE Trans Microw Theory Tech MTT-33 (1985), 1383–1394.
5. M. Schetzen, Nonlinear system modeling based on the Wiener theory, Proc IEEE 69 (1981), 1557–1773.
6. J. Kim and K. Konstantinou, Digital predistortion of wideband signals based on power amplifier models with memory, Electron Lett 37 (2001), 1417–1418.
7. V. Camarchia, P. Colantonio, S.D. Guerrieri, R. Giofrè, E.G. Lima, L. Piazzon, M. Pirola, R. Quaglia, Base-band predistortion linearization scheme of high efficiency power amplifiers for wireless applications, Integrated Nonlinear Microwave and Millimeter-Wave Circuits, INMMIC 2008 Workshop, 2008, pp 119–122

AN ADAPTIVE SPECTROELLIPSOMETER FOR ECOLOGICAL MONITORING

F. A. Mkrtchyan, V. F. Krapivin, V. I. Kovalev, and V. V. Klimov
A.V. Kotelnikov's Institute of Radioengineering and Electronics, Russian Academy of Sciences (IRE RAS), 1 Vvedensky Square, Fryazino, Moscow Region 141190, Russia; Corresponding author: ferd47@mail.ru (or) ferd@ms.ire.rssi.ru

ABSTRACT: *In this article, the creation of multichannel polarization optical instrumentation and the use of spectroellipsometric technology for the real-time ecological control of aquatic environment is discussed. It was shown that spectroellipsometric devices give high precision of measurements of water quality characteristics. Spectroellipsometric multichannel measurements in an aquatic environment are conducted by the algorithms for the recognition and identification of pollutants. Some results of an adaptive spectroellipsometer applications are given.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 2792–2795, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24730

Key words: *spectroellipsometric system; polarization optics; aquatic environment; ecological monitoring; recognition; identification; solution; pollutants*

1. INTRODUCTION

The creation of multichannel polarization optical instrumentation and the use of spectroellipsometric technology are very important for the real-time ecological control of aquatic environment.

Ellipsometers are very sensitive and precise tools for measuring the parameters of different environments. With fast and precise ellipsometric measurements, it should be possible to extract both fast and slow components of the optical parameter changes connected with different influences of the ambient atmosphere on the object under study. Also, ellipsometric devices are precise real-time detection systems for optical monitoring of the pollutant in the aquatic environment. It should be mentioned that efficient solution of this multiparametric problem greatly depends on the precision and simplicity of ellipsometric devices.

This report is aimed to describe the following:

- A technology of combined use of spectroellipsometry and algorithms of identification and recognition that allowed the creation of a standard integral complex of instrumental, algorithmic, modular, and software tools for the collection and processing of data on the aquatic environment quality with forecasting and decision-making functions.
- A compact measuring-information multichannel spectroellipsometric system for the monitoring of aquatic environment quality, which is based on the combined use of spectroellipsometry and training, classification, and identification algorithms
- This spectroellipsometric system will differ from modern worldwide analogs by the use of a new and very promising method of spectroellipsometric measurements, an original element base of polarization optics and a complex mathematical approach to estimate the quality of a water object subjected to anthropogenic influence.
- The main advantage of an adaptive spectroellipsometric system consists in the update database of spectral images of water solutions.