International Journal of Microwave and Wireless Technologies, 2009, 1(6), 489–495.
doi:10.1017/S1759078709990602

Implementation of electrothermal system-level model for RF power amplifiers in Scilab/Scicos environment

FLORENT BESOMBES[1,2], RAPHAËL SOMMET[2], JULIE MAZEAU[1], EDOUARD NGOYA[2] AND JEAN-PAUL MARTINAUD[1]

This paper presents a behavioral electrothermal model implementation for high RF power amplifiers dedicated to the simulation of radar application in the Scilab/Scicos environment. This model, based on the direct coupling between a behavioral electrical model and a physics-based reduced thermal model, allows to predict nonlinear effects, high-frequency memory effects, and thermal effects due to the amplifier self-heating. System model implementation in Scilab/Scicos platform allows fast time domain simulation with very good convergence properties.

Keywords: Behavioral electrothermal model, Power amplifier, Reduced thermal model, Ritz vector approach, System environment, Scilab/Scicos simulation platform

Received 30 June 2009; Revised 16 September 2009; first published online 19 January 2010

I. INTRODUCTION

Nowadays, system-level simulation is an efficient answer to problems encountered in complex microwave circuit simulation. However, in order to minimize computational resources and to conserve a good accuracy, black-box simulation requires accurate behavioral models of the microwave elementary subsystems which constitute the system.

The RF power amplifier is a key element of transmission–reception modules. The use of high power creates nonlinearities and material self-heating inside the component. Interaction of these effects leads to amplitude and phase distortions on the transmitted signal. Within the context of development of active electronically scanned array radar such as those developed by Thales Airborne Systems, the amplifier position, downstream of the amplitude, and the phase control, does not allow in correcting these distortions. This is the reason why behavioral modeling of RF power amplifiers represents an important research axis. Many works [1–5] have already been performed in order to obtain a system-level model allowing a tradeoff between an accurate prediction of performances and the simulation time.

The black-box model presented in this paper, takes into account the coupling between nonlinear effects, high-frequency memory effects, and thermal effects due to the amplifier self-heating. Its integration in Scilab/Scicos environment allows in performing fast transient simulation with very good precision and convergence properties.

[1]THALES Airborne Systems, 2 avenue Gay Lussac, 78851 Elancourt, France.
[2]XLIM CNRS, 7 rue Jules Vallès, 19100 Brive La Gaillarde, France.
Corresponding author:
F. Besombes
Email: florent.besombes@xlim.fr

II. Scilab/Scicos SIMULATION PLATFORM

A) Introduction

Scicos is a part of the scientific software package Scicoslab providing many capabilities available in Simulink [6, 7]. It has been developed at INRIA Rocquencourt for about 15 years by project-team METALAU. Based on an open formalism motivated by synchronous languages extended to continuous time dynamics, Scicos can be used to model and simulate hybrid dynamical systems.

B) Scicos environment

Scicos is a complete environment which allows construction of models, simulation, and code generation. It includes:

- *A block diagram editor*: Scicos contains a graphical editor that can be used to build block diagram models of dynamical systems. The blocks can come from various palettes provided by Scicos or can be defined by user. These new blocks can be defined in C, Fortran, or Scilab.
- *A compiler*: Scicos compiler defines scheduling tables based on the model description. These tables, usually compiled by the Scicos editor, can then be used by the simulator and the code generation function.
- *A simulator*: Scicos simulator runs simulation using the scheduling tables and other information provided by the compiler. This is a hybrid simulator able to deal with both discrete and continuous time systems, and events. For the continuous time part, it uses the ODE solver LSODAR or the DAE solver DASKR depending on the nature of the continuous time system considered. Moreover it includes a code generator. Scicos can generate

C code to represent the behavior of some subsystems. These subsystems must not include continuous time components.

C) Scicos and Scilab

Scicos is a Scicoslab toolbox and runs in the Scilab environment. The access to Scilab functions when designing simulation models is of great importance: Scicos user often needs to use Scilab functions such as those dedicated to database interpolation, as it will be seen thereafter, in the development of simulation models. Scilab programming language can be used for batch processing of multiple simulation tasks. More generally, models designed by Scicos can be used as functions in Scilab. Scilab graphical facilities can also be used for post-processing simulation results.

D) Scicos formalism

Scicos is a tool for designing reactive systems. Scicos models are designed using a block diagram editor, but an underlying language exists providing a well-defined formalism. This formalism is very simple because it deals exclusively with the reactive part of the design; it does not provide a complete programming language. The blocks are considered as atoms in Scicos; Scicos simulator considers them almost as black boxes. It knows some of their properties but not the underlying code. The code realizing the behavior of a block (called the simulation or computational function) can be written in C, Fortran, or Scilab. In Scicos formalism, the execution of simulation functions is considered instantaneous so Scicos can be considered as a synchronous language or more specifically as an extension of it to handle continuous time systems. The existence of a unique universal time is assumed in the formalism.

E) Create new Scicos block

In addition to the available blocks, Scicos allows user to create and use new blocks. Various ways are possible:

- New blocks can be based on existing blocks using the super blocks construction and masking. This function allows to group different existing blocks together in order to create a new function (see Section III.E). However, super blocks are just graphical facilities, they do not reduce time calculation.
- Scicos also makes different generic blocks available for users in order to create Scilab, Fortran, or C basic functions. The major drawback of these blocks is that they are unsuitable with complex functions such as the amplifier behavior description.
- Finally, Scicos blocks can be defined using C or Scilab programs and loaded in Scilab (see Section III.C). Such new blocks require a good understanding of how Scicos works and the data structures used.

F) Scicos block structure

The Scicos blocks are built around two functions: an interfacing function expressed in Scilab language and a computational function written in C, Fortran, or Scilab.

The interfacing function is used during model construction by interfacing with the block diagram editor. It contains routines used notably for initializing the block data structure, defining the block geometry and the number of inputs and outputs, and handling the interface with the user.

The computational function is used during simulation and contains the routines for computing in particular the outputs and the state blocks.

III. INTEGRATED ELECTROTHERMAL BEHAVIORAL MODEL

The system-level model implemented in Scilab/Scicos environment is the result of a fruitful collaboration between Thales Airborne Systems and Xlim laboratory.

The electrothermal behavior prediction of the RF power amplifier is possible, thanks to the coupling of an electrical model with a thermal model (Fig. 1).

A) Electrical system-level model

The studied amplifier is a narrow band device working around the central carrier frequency f_o. Input and output complex envelope signals are linked by a transfer function using the truncated first-order modified Volterra series [5]. This formalism is particularly well suited to narrow band highly nonlinear devices. These series have been extended to take into account the temperature, considering thermal effects as independent of frequency [8]. They lead to the following expression of S_{21} transmission parameter with $a_1(t)$, the input power wave:

$$\tilde{S}_{21}(|\tilde{a}_1(t)|, T, \Omega) = \tilde{S}_{21stat}(|\tilde{a}_1(t)|, T) + \frac{1}{2\pi}\int_{BW} \tilde{S}_{21dyn}(|\tilde{a}_1(t)|, \Omega)e^{j\Omega t}\, d\Omega. \quad (1)$$

In case of radar applications, the use of the model is limited to pulsed continuous wave (CW) signal. Therefore, only the carrier frequency is considered so the second term in (1) is simplified. Expression (1) can be expressed as follows:

$$\tilde{S}_{21}(|\tilde{a}_1(t)|, T, \Omega)) = \tilde{S}_{21stat}(|\tilde{a}_1(t)|, T) + \tilde{S}_{21dyn}(|\tilde{a}_1(t)|, \Omega). \quad (2)$$

The static transmission parameter S_{21stat} describes the amplifier nonlinear behavior at the central carrier frequency f_o for a working temperature T inside the component. Its

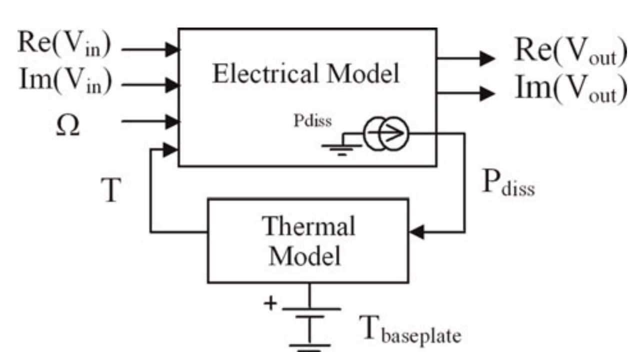

Fig. 1. Electrothermal behavioral model.

https://doi.org/10.1017/S1759078709990602 Published online by Cambridge University Press

expression is the following:

$$\tilde{S}_{21stat}(|\tilde{a}_1(t)|, T) = \tilde{S}_{21stat\_Tamb}(|\tilde{a}_1(t)|, T_{amb}) + \alpha(|\tilde{a}_1(t)|, T), \quad (3)$$

$$\alpha(|\tilde{a}_1(t)|, T) = \tilde{S}_{21}(|\tilde{a}_1(t)|, T, \Omega_o) - \tilde{S}_{21}(|\tilde{a}_1(t)|, T_{amb}, \Omega_o). \quad (4)$$

The differential gain α represents gain variations brought by temperature variations inside the components. This term is equal to zero at the ambient temperature T_{amb}.

The dynamic gain $S21_{dyn}$ represents the gain variation due to the displacement of the carrier frequency in the device bandwidth BW (HF memory). Its expression is

$$\tilde{S}_{21dyn}(|\tilde{a}_1|, \Omega) = \tilde{S}_{21}(|\tilde{a}_1|, T_{amb}, \Omega) - \tilde{S}_{21}(|\tilde{a}_1|, T_{amb}, \Omega_o). \quad (5)$$

The dissipated power calculated by the electrical model can be expressed by

$$P_{diss}(|\tilde{a}_1(t)|, T, \Omega) = P_{in} - P_{out} + P_{dc} = \frac{1}{2}|\tilde{a}_1(t)|^2(1 - |\tilde{S}_{21}(|\tilde{a}_1(t)|, T, \Omega)|^2) + V_{ceo}I_{co}(|\tilde{a}_1(t)|, T, \Omega). \quad (6)$$

The continuous power P_{dc} is only the bias power at the collector assuming the base bias current negligible compared to the collector bias current ($I_{bo} \ll I_{co}$). The V_{ceo} collector voltage being constant, the power P_{dc} depends only of current I_{co} which varies with the input signal magnitude, the temperature, and the carrier frequency. The bias current I_{co} can be expressed by the summation of two independents terms as the S_{21} parameter expression: a static term representing the thermal influence at frequency f_o and a dynamic differential term HI_{co} representing the spectral dispersion. The current I_{co} can be expressed as follows:

$$I_{co}(|\tilde{a}_1(t), T, \Omega|) = I_{co}(|\tilde{a}_1(t), T, \Omega_o|) + HI_{co}(|\tilde{a}_1(t), T_{amb}, \Omega|). \quad (7)$$

This model can be driven by input signal of type CW, pulsed CW, and chirp.

B) Electrical model extraction

The static terms $S_{21stat}(|a_1|, T_{amb})$, $\alpha(|a_1|, T)$, and $I_{co}(|a_1|, T)$ are extracted, thanks to an isothermal single-tone harmonic-balance simulation of the circuit model. The extraction is performed at central carrier frequency f_o for various temperatures T within the device (Fig. 2).

The identification of the dynamic terms $S_{21dyn}(|a_1|, f)$ and $HI_{co}(|a_1|, f)$ is performed, thanks to a single-tone harmonic-balance simulation for a fixed temperature ($T = T_{amb}$) inside the amplifier and for various frequencies within the component bandwidth (Fig. 3). The terms a_1 and b_2, respectively, represent the input and output power waves.

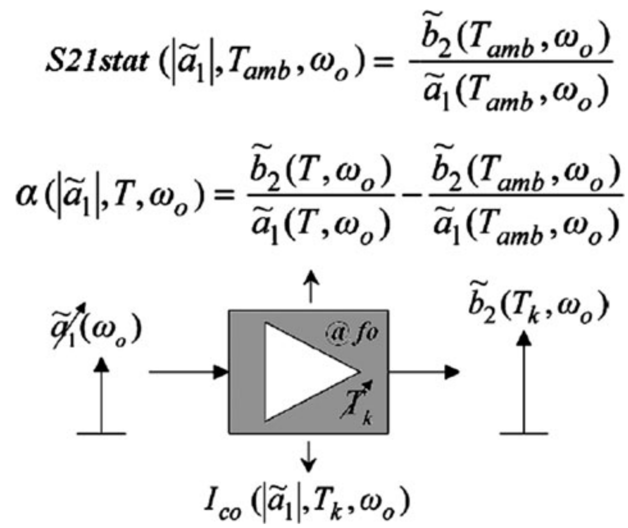

Fig. 2. Identification of static terms.

This database is fully representative of the amplifier behavior. It defines the domain of validity for each parameter, carrier frequency, input power wave magnitude, temperature, and device bias point.

These data can be obtained by measurements although isothermal measurements are difficult to perform for the extraction of the static terms. For the dynamic terms identification, it is imperative to use short pulse duration (≈2 μs) in comparison with the main thermal time constant (≈30 μs) in order to avoid self-heating effects.

C) Electrical model integration

The electrical model implementation in Scicos has been performed, thanks to the creation of a block called "BET model" (Fig. 4). This block is defined with two functions: the interfacing function, which describes notably the block geometry; the computational function, written in Scilab language, which reproduces the amplifier behavior from data files resulting from isothermal simulations of circuit model. The data files are splined under Scilab (*Splin* and *Splin2D*). These two functions, defined in Scilab, are then loaded into Scicos to obtain the full electrical model.

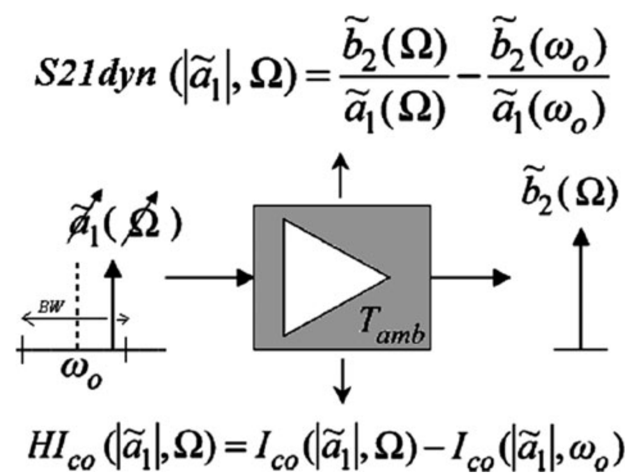

Fig. 3. Identification of dynamic terms.

https://doi.org/10.1017/S1759078709990602 Published online by Cambridge University Press

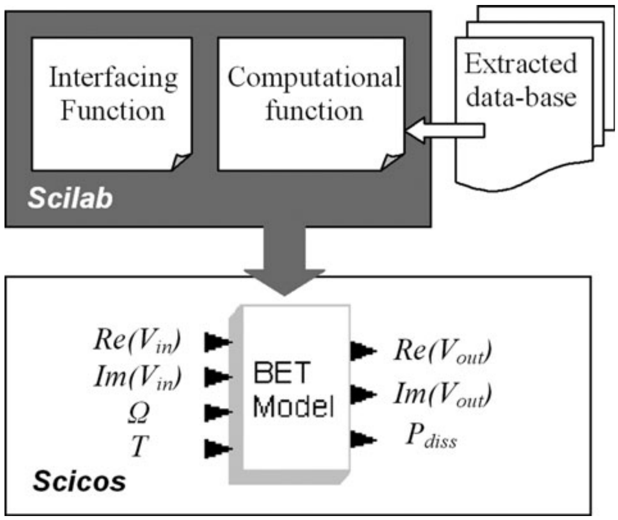

Fig. 4. "BET model" block.

The input variables of the BET model are the voltage V_{in} (real and imaginary parts) corresponding to the input signal envelope, the carrier frequency f, and the temperature T received from the thermal model. The block delivers the output power P_{out} and the dissipated power P_{diss} (Fig. 4).

The BET model allows in evaluating nonlinear and high-frequency memory effects. The amplifier self-heating is computed by the thermal model described in the next section.

D) Thermal model

The thermal model allows in predicting the transient thermal behavior of the amplifier. This physics-based model is obtained from a three-dimensional (3D) thermal simulator based on a finite element method (FEM).

First, a coarse grain thermal analysis is performed in order to evaluate the coupling between the different stages of the amplifier. Simplifications can often be applied to multistage amplifiers, without affecting the accuracy of the results: neglecting the inter-stage coupling effects, simplifying the layer structure and the dissipation volumes in the transistor [8].

Thanks to the FEM, a linear system with characteristic matrices of the heat equation is extracted:

$$\begin{aligned} E\dot{T} &= AT + Bu(t), \\ Y &= CT, \end{aligned} \tag{8}$$

E and $(-A)$ represent, respectively, the heat capacity and the heat conductivity matrices of the system composed of n linear equations determined by the mesh of the structure. B represents the distribution of the dissipated power and T the distribution of the temperature. Y is the output temperature extracted from the solution T through the C product.

Applying Fourier transform to the previous system leads to the transfer function

$$H(\omega) = Y(\omega)/U(\omega) = C(j\omega\, E - A)^{-1}B. \tag{9}$$

Unfortunately, this function cannot be directly computed and used in a simulator system because of its important dimension and the great difficulty to invert high-dimensional matrices.

Thus, a model order reduction technique based on the Ritz vector approach [9, 10] has been developed. This method enables the reduction of system dimensions and the extraction of an equivalent operating temperature for the amplifier with the use of C. This approach is very efficient to cope with linear problems, but a linear system requires the heat conductivity of the used materials to be constant.

The Ritz vector approach is a projection method which relies on the generation of an orthogonal and E-orthonormal basis Φ_m constituted of m vectors $(m \ll n)$. Rewriting the original system in the new coordinate results in a smaller system

$$\begin{aligned} I_R\dot{T}_R &= A_R T_R + \Phi_R^T Bu(t), \\ Y &= CT_R. \end{aligned} \tag{10}$$

The "R" subscript indicates the reduced system. The previous equations represent the system implemented as presented in Fig. 5 of the next section.

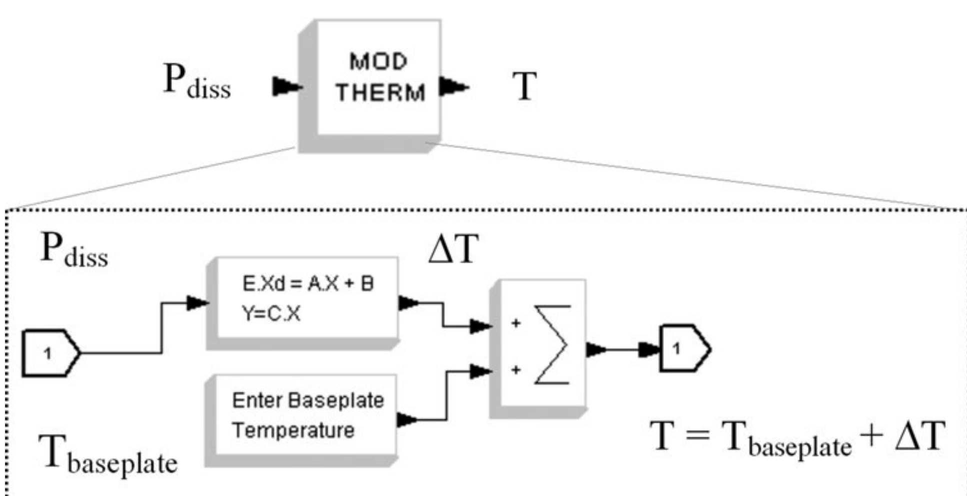

Fig. 5. "MOD THERM" super block.

https://doi.org/10.1017/S1759078709990602 Published online by Cambridge University Press

The accuracy of the transient regime depends on the time constant number (it means the number of Ritz vectors m) which can be freely chosen by the designer.

E) Thermal model integration

The thermal model implementation in Scicos platform is realized, thanks to the "MOD THERM" super block (Fig. 5) which is built around three blocks:

- The "$EX_d = AX + BY = CX$" block allows to solve the linear system of matrices extracted from 3D thermal simulation of the equivalent power amplifier structure. This block calculates the working temperature variations ΔT knowing the dissipated power inside the amplifier.
- The "enter baseplate temperature" block has been created to take into account the amplifier baseplate temperature $T_{baseplate}$.
- "Summation" block, available in Scicos linear palette, allows determining the working temperature T doing the summation of the baseplate temperature $T_{baseplate}$ with the temperature variation ΔT.

The behavior of "MOD THERM" super block is equivalent to a thermal impedance. It means it determines the amplifier working temperature T for a dissipated power P_{diss} and a given baseplate temperature $T_{baseplate}$.

IV. BET MODEL IN Scicos/RESULTS

Results plotted in Fig. 6 allow in comparing the behavioral electrothermal model (BET model) stemming from Scicos simulation, and the circuit model simulation for a power amplifier based on (AsGa/GaInP) HBT technology. The generated power reaches 8 W in X-band (harmonic-balance simulation under Agilent ADS simulator). The $S21$ parameter is represented in module and phase versus the input power, for various values of the temperature, and various values of the carrier frequency.

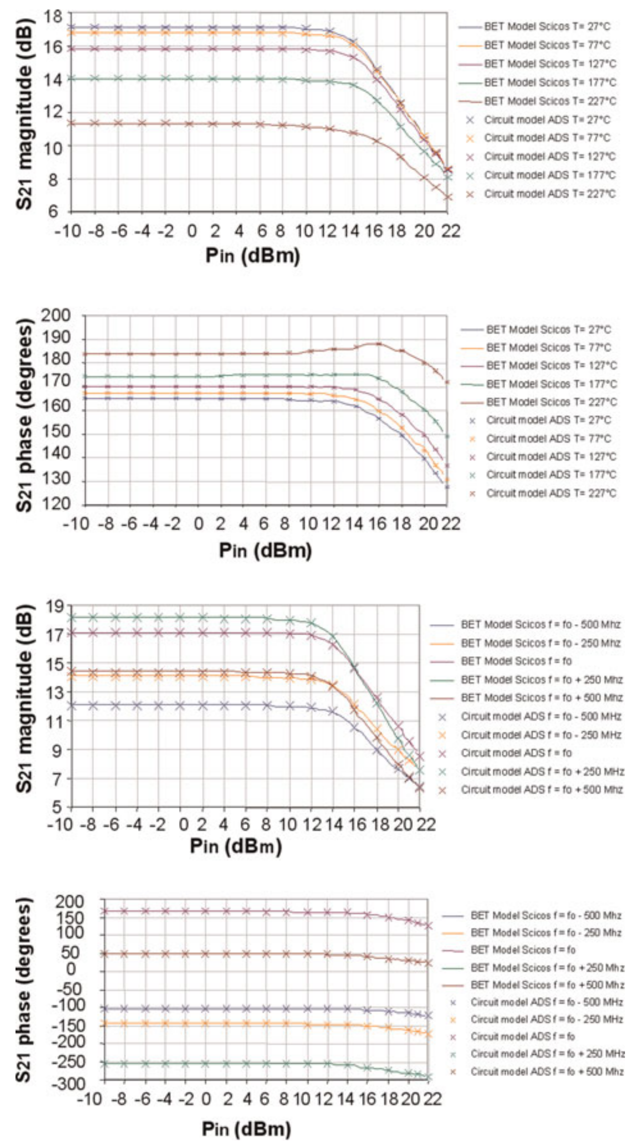

Fig. 6. Comparison of $S21$ (magnitude and phase) calculated by the BET model in Scicos and the circuit model ADS for various temperatures and carrier frequencies.

Figure 7 shows the implementation of the BET model in Scicos simulation platform. The electrical and thermal models that have been developed separately are associated in the same Scicos simulation interface. The so-created BET model is driven by a pulsed envelope signal V_{in} generated by two Scicos block "pulse generator". The carrier frequency is given by a "constant" Scicos block. In this case, the carrier frequency assumes to be constant (pulsed CW signal). However, the BET model is able to consider a varying carrier frequency during the simulation to handle frequency modulated signal (chirp signal for example).

The model computes the output envelope signal V_{out} and the dissipated power P_{diss}. Constantly, P_{diss} is injected into the thermal model translating the evolution of the working temperature T.

The output power time-domain response, the dissipated power, and the amplifier working temperature are plotted for various input power levels (Fig. 8), when the model is driven by a 96 μs long pulse.

The results show a very good agreement between the BET model and results stemming from the circuit model ADS simulation with a mean square error lower than 10^{-3}.

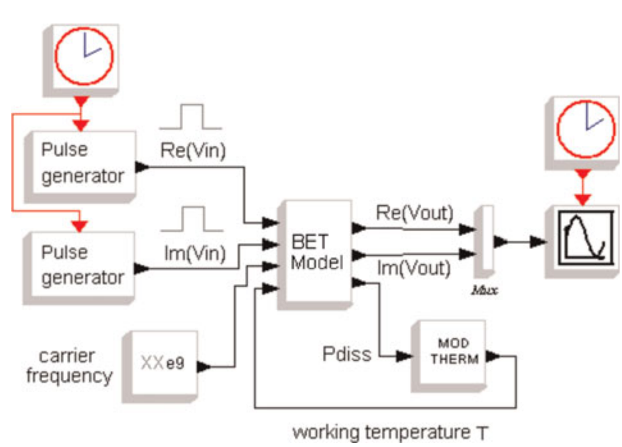

Fig. 7. BET model in Scicos environment.

https://doi.org/10.1017/S1759078709990602 Published online by Cambridge University Press

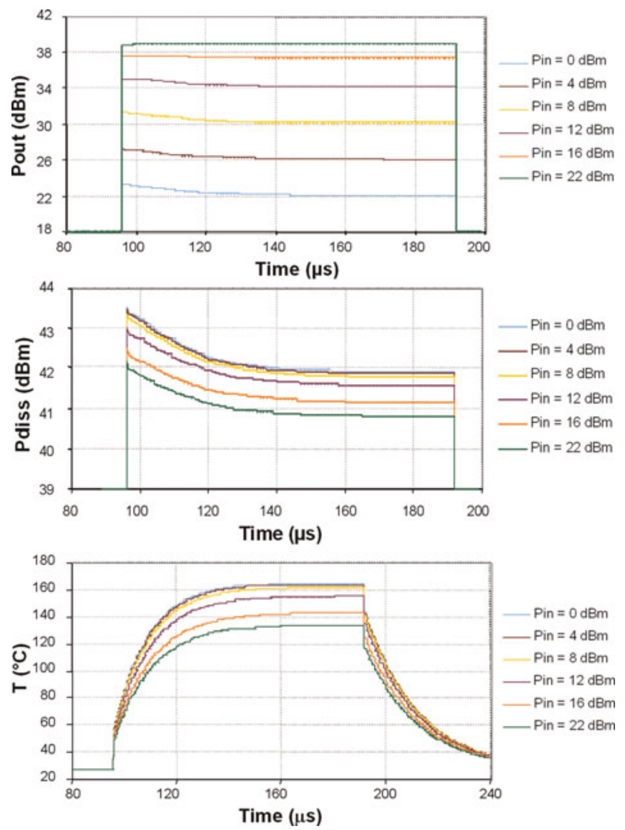

Fig. 8. Output power, dissipated power, and working temperature calculated by the BET model in Scicos for various input powers (pulse duration of 96 µs).

V. CONCLUSION

In this paper, we have proposed an integrated solution in the open source environment Scilab/Scicos for a BET model. The use of this solution has revealed a great improvement in time domain simulation and very good convergence properties. The computation time has been divided by (at least) 1000 in comparison to an envelope simulation of the circuit model as in ADS software.

This work has been performed in the framework of the French MoD (Ministry of Defense) project SCERNE [11] (XLIM, IMS, INRIA, THALES, and IPSIS consortium) for the development of an extraction/simulation tool of "fine-grains" behavioral model and its integration in radar simulator ASTRAD and network antenna simulator SAFAR.

REFERENCES

[1] Pedro, J. C.; Maas, S. A.: A comparative overview of microwave and wireless power-amplifier behavioral modeling approaches. IEEE Trans. Microwave Theory Tech., **53** (4) (2005), 1150–1163.

[2] Ngoya, E.; Le Gallou, N.; Nebus, J. M.; Buret, H.; Reig, P.: Accurate RF and microwave system level modeling of wideband nonlinear circuits, in IEEE MTT-S Int. Microwave Symp. Digest, Boston, MA, vol. **1**, 2000, pp. 79–82.

[3] Root, D.-E.; Verspecht, J.; Sharrit, D.; Wood, J.; Cognata, A.: Broad-band poly-harmonic distortion (PHD) behavioral models from fast automated simulations and large-signal vectorial network measurements. IEEE Trans. Microwave Theory Tech., **53** (11) (2005), 3656–3664.

[4] Mirri, D.; Iuculano, G.; Filicori, F.; Pasini, G.; Vannini, G.; Gabriella, G. P.: A modified Volterra series approach for nonlinear dynamic systems modeling. IEEE Trans. Circuits Syst. I: Fundam. Theory Appl., **49** (8) (2002), pp. 1118–1128.

[5] Le Gallou, N.: Modélisation par séries de Volterra dynamiques des phénomènes de mémoire nonlinéaires pour la simulation système d'amplificateurs de puissance, Ph.D. dissertation, XLIM Research Institute, Limoges University, Limoges, France, 2001.

[6] Nikoukhah, R.: SCICOS, a dynamic systems modeler and simulator, in Proc. 23rd IASTED Int. Conf. on Modelling, Identification, and Control (MIC '04), Grindelwald, Switzerland, February 2004, paper 412–133, pp. 263–268.

[7] Nikoukhah, R.; Steer, S.: SCICOS, a dynamic system builder and simulator, in IEEE Int. Conf. on Computer-Aided Control System Design, Dearborn, MI, 1996, pp. 430–435.

[8] Mazeau, J.; Sommet, R.; Caban-Chastas, D.; Gatard, E.; Quéré, R.; Mancuso, Y.: Behavioral thermal modeling for microwave power amplifier design. IEEE Trans. Microwave Theory Tech., **55** (11) (2007), pp. 2290–2297.

[9] Sommet, R.; Lopez, D.; Quéré, R.: From 3-D thermal simulation of HBT devices to their thermal model integration into circuit simulators via Ritz vectors reduction techniques, in 8th Intersociety Thermal and Thermomechanical Phenomena in Electronic Systems Conf., San Diego, CA, 2002, pp. 22–28.

[10] Hsu, J. T.; Vu-Quoc, L.: A rational formulation of thermal circuit models for electrothermal simulation. ii. Model reduction techniques [power electronic systems]. IEEE Trans. Circuits Syst. I: Fundam. Theory Appl., **43** (9) (1996), pp. 733–744.

[11] Mons, S. *et al.*: SCERNE – Simulation de Chaînes d'Emission Réception de Nouvelle gEnération, in 16th "Journées Nationales Microondes" Conference, Grenoble, 2009.

Florent Besombes received a master's degree in high-frequency and optical telecommunications in 2007 from the Limoges University, France. He is currently working toward a Ph.D. degree at the XLIM laboratory in the high frequency components circuits signals and systems department, Limoges University in collaboration with THALES Airborne Systems, Elancourt, France. His research interests are dedicated to electrothermal system-level models of power amplifiers for radar applications.

Julie Mazeau received a master's degree in high-frequency and optical telecommunications from the University of Limoges, Limoges, France, in 2003, and a Ph.D. degree about "electro-thermal system-level model of power amplifiers for radar applications" at the Research Institute XLIM, University of Limoges in collaboration with THALES Airborne Systems, Elancourt, France, in 2007. She joined the advanced technologies team at THALES Airborne Systems, Elancourt, France. She is in charge of microwave modeling and design for active antenna T/R modules.

https://doi.org/10.1017/S1759078709990602 Published online by Cambridge University Press

Raphaël Sommet received a French Aggregation in applied physics degree and a Ph.D. degree from the University of Limoges, Limoges, France, in 1991 and 1996, respectively. From 1997, he has been a permanent researcher with the C2S2 team "Nonlinear Microwave Circuits and Subsystems," XLIM Research Institute, Centre National de la Recherche Scientifique (CNRS), University of Limoges. His research interests concern HBT device simulation, 3-D thermal FE simulation, model-order reduction, microwave circuit simulation, and generally the coupling of all physics-based simulation with circuit simulation.

Edouard Ngoya received a Ph.D. degree in electronics from the University of Limoges in 1988. He worked as R&D engineer with CAROLINE and RACAL-REDAC in 1988 and 1989. In 1990 he joined the French Centre National de la Recherche Scientifique (CNRS) as a senior researcher at XLIM-University of Limoges. He has initiated key circuit simulation and modeling techniques and contributed to the development of several ADE tools for nonlinear RF and microwave circuits. His current domains of interest include full-chip RFIC simulation techniques, analog system bloc-level modeling, and PA linearization techniques.

Jean-Paul Martinaud received a Ph.D. degree in applied mathematics from the University Pierre et Marie Curie PARIS VI, France, in 1984. He is currently dean expert of hardware modeling at THALES Airborne System and responsible of electromagnetism modeling and simulation tools development in the antennas and circuits application domain.

https://doi.org/10.1017/S1759078709990602 Published online by Cambridge University Press