“The Three Musketeers of Large-Signal RF and Microwave Design - Measurement, Modeling and CAE”

Marc Vanden Bossche, Frans Verbeyst, and Jan Verspecht

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The Three Musketeers of Large Signal RF and Microwave Design
-Measurement, Modeling and CAE-

Marc Vanden Bossche, Frans Verbeyst, Jan Verspecht

HPEEsof – NMDG, Lammerstraat 20, B-9000 Ghent, Belgium – Europe

1 Abstract

This paper explains and illustrates that the voltage–current behavior of nonlinear devices, components and systems is the basis for a framework for the large signal RF and microwave design and manufacturing process. This framework spans measurement, modeling and CAE technology in a coherent way.

2 Introduction

In the RF / microwave design and manufacturing cycle nonlinear behavior has become very crucial. Today it is still a concern to be kept under control. Tomorrow it will be the feature for increased functionality at a lower cost.

To quantify nonlinear behavior all kinds of measures did arise like spectral regrowth, ACPR, IP3. Unfortunately a solid theoretical foundation complemented with a practical approach is missing. As a result the system level engineer still copes with nonlinearities differently than the process engineer who is responsible for the basic building block.

First this paper argues that the measurement concepts, the models of components and the simulation tools must be brought together under one framework. This framework must be applicable from the device level up to the system level, from the R&D lab up to the manufacturing floor. It is explained how this impacts, shortens and simplifies the design and manufacturing process. Finally the paper gives an overview of the state of the art of the different technologies.

3 A framework for the large signal design process

Presently the effectiveness of the design and manufacturing process is negatively impacted by the iterations required at the different levels in the chain from device to system level and by the difficulties to exchange specifications between the different levels.

For example, it is the task of the process engineer to improve and innovate semiconductor technology to meet the present and future market requirements. But this engineer faces the challenge to translate high level specifications, like the 3G specifications, into concrete physical device and process parameters.

The device-modeling engineer faces a similar problem. Once the performance of the transistors on wafer is verified with a process that does not address high-level performance factors at all, the device-modeling engineer extracts transistor models from measurements. Usually the measurements consist of DC voltage and current measurements and S-parameters at different bias points and frequencies. Because of the growing need to deal properly with nonlinearities, large signal models have to be derived from these measurements.

But the circuit designer is not really interested in S-parameters at different bias points. His concern is the large signal voltage–current behavior of the model. Therefore the model has to be verified with a different type of measurements using signals closer related to the application. Loadpull measurements are for example one way to verify some large signal performance of the model. Unfortunately when there is a difference between the measurements and model prediction, these measurements cannot be used to improve the model. Therefore evolving and new process technologies are the privilege of design houses that can afford device modeling engineers and equipment working together with the circuit engineers to adapt transistor models based on experiences at the circuit level. It is very difficult to work with the foundries to solve this problem.

These difficulties occur at and between different levels of the design and manufacturing process.

To shorten the design and manufacturing process and to accelerate the integration of complete systems on chip, there is a need for a framework dealing with nonlinear behavior from device to system level and that spans the measurement, modeling and simulation technology in a coherent way.

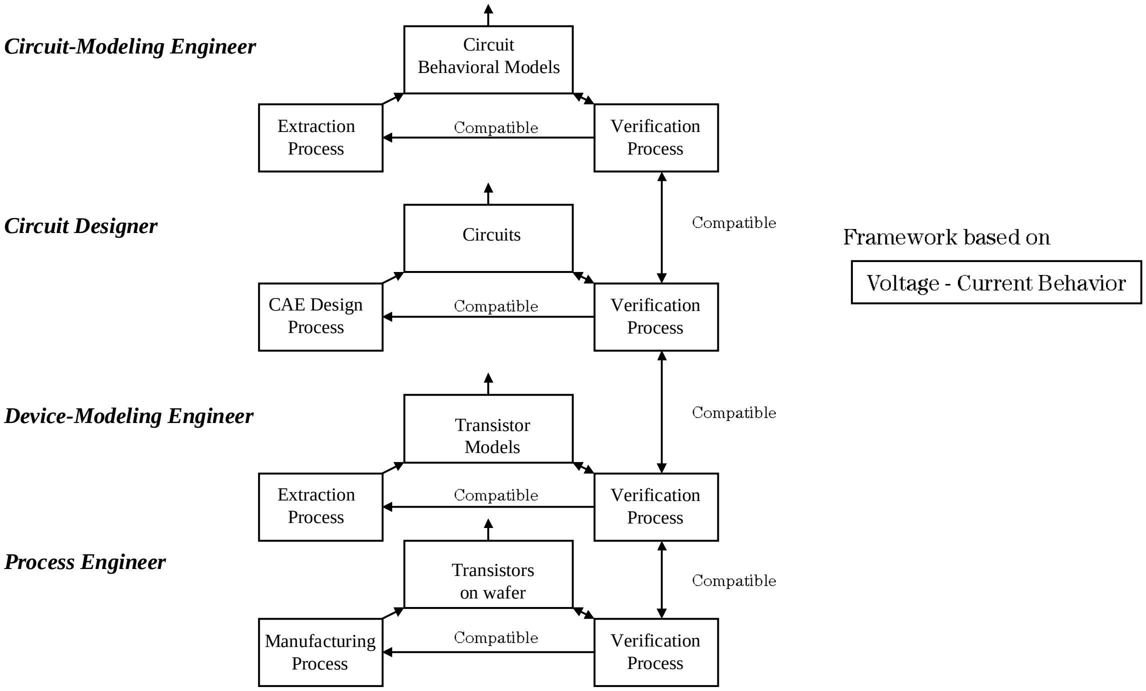

Figure 1 A framework for large signal design creates unification from device to system level

The positive impact on the design and manufacturing cycle of such a framework is illustrated for linear RF and microwave designs. The S–parameters are the linear model that can be measured by the vector network analyzer and can be used by the CAE tools to simulate. S-parameter measurements are consistently used for the verification process.

Because of the coherence of the framework and the applicability from device to system level, it became part of the basic education of the HF electrical engineer and it found a place in test and manufacturing. Design, manufacturing and testing of small-signal amplifiers is a nice example of the benefits of a framework.

A similar framework dealing with nonlinear devices, components and systems will reduce the large signal design and manufacturing cycle in different ways:

- models with higher reliability are made available to the circuit designers faster
- reliable simulation – or measurement – based models are made available to the board designers and system designers faster while keeping computer resource consumption low
- concerns and problems detected by engineers at higher levels can easily propagate down to create immediately improvements at lower levels
- testing the manufactured components can be done coherently with the design methodology
- systems on chip will be realized quicker

4 The three musketeers of large signal RF and Microwave design

The framework consists of measuring, modeling and simulating. The measurements learn the engineer about the behavior. In combination with a device or behavioral model these measurements can be transformed into a mathematical behavioral description. This model is then used in CAE tools to perform predictions of more complex systems. Finally it must be easy to relate the simulation results of these more complex systems with new measurements which can be fed back into the modeling process for improvements if required.

During this process it must be evenly easy to work in a voltage–current formalism as in a wave formalism. Frequency domain and time domain must be easily exchangeable.

4.1 CAE tools

The existing CAE simulators do reflect how one looks at the world and how one thinks that the world operates. The development of the simulators was not constrained by the existing measurement capability. The concrete measurement problem did arise when models had to be created for these simulators.

The fundamental information in present CAE tools are the voltage and current behavior, constrained by the Kirchoff current and voltage laws.

The difference between a time – domain, harmonic balance and circuit envelope simulator is related to the efficiency to represent the voltage and current signals and to reduce the efforts of the nonlinear equations solver.

Using linear transformations it is possible to represent voltages and currents easily in the voltage or current wave formalism, either in the time or frequency domain.

4.2 The measurements

As mentioned the voltage and currents are the fundamental information for the CAE tools. Also device level models are expressed as a voltage – current relationship.

For the framework it is important that the voltage–current behavior can be measured accurately at the ports of components. The ports represent the interaction with the outside world (Figure 2).

Figure 2 Voltage – Current relationship of a component

Similar to the simulator technology measurement technology can be optimized for different types of signals.

Arbitrary broadband signals require fast analogue to digital converters (ADC) and memory to save all the information. Due to limitation of the ADC technology the bandwidth of these signals is restricted. Time domain simulators can deal properly with this type of signals.

Knowing that the signals are periodic, like a sine wave of 1 GHz and its harmonics, synchronous detection techniques can be used to measure amplitudes and phases of all harmonics ([1] until [8]). Harmonic balance simulators are adequate to deal with this type of signals. Broadband high frequency voltages and current behavior of two port devices can be measured accurately with a nonlinear network measurement system.

Modulated signals are a combination of a set of base-band signals and high frequency phasors. By our knowledge today no solutions exist to measure voltage and current waveforms under a modulated excitation.

4.3 The models

This paragraph illustrates how modeling people, from the device level up to the system level, benefit from bridging the gap between the time and frequency domain, between travelling voltage waves and voltage-current, and between simulation and measurement. A number of relevant papers are available ([9] until [16]). Three concrete examples are described in the following.

A first example is illustrated in [14]. This describes how the parameters of classical large-signal transistor models (typically derived from s-parameters) can be optimized importing actual high-frequency voltage-current waveform measurements (performed with an NNMS measurement system) into a commercial simulator. The standard simulator optimizer is used in order to tune the parameters such that the simulated waveforms accurately fit the measured waveforms. The result is a very reliable model, provided that the large signal measurements performed are close to the signals encountered during the design and the actual “day-in-the-live” of the device.

A new and promising approach is illustrated by the second example [17]. A model topology is now chosen, based upon neural network technology, which allows direct parameter extraction based upon voltage-current waveform measurements. Model verification is done performing a set of independent measurements and comparing model and verification measurement results. This is illustrated by figure 3.

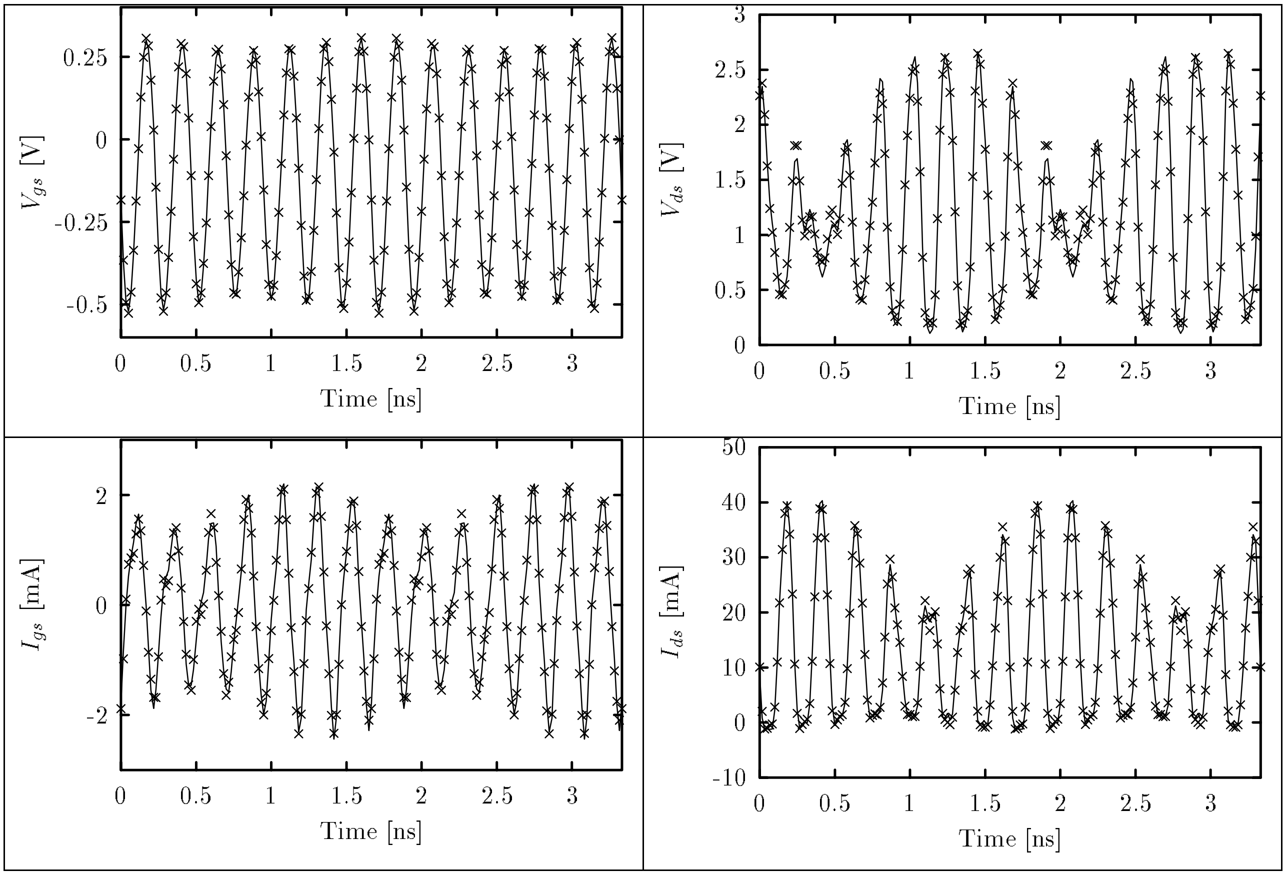

Figure 3 Comparison of the measured (x) and fitted neural network model (—): $V_{gs}(t)$, $V_{ds}(t)$, $I_{gs}(t)$, $I_{ds}(t)$ *of an InP HEMT excited by a two-tone signal (*V_{gsDC}*= -0.1 V,* V_{dsDC}*= 1.2 V,* f_1*= 4.2 GHz,* f_2*= 4.8 GHz)*

Note that this kind of modeling can easily be applied to a circuit containing more than one transistor. Main assumption is that the whole device is behaving as a lumped quasi-static non-linearity.

A third example [16] uses essentially the same measurement information in order to extract the parameters of a so-called “frequency domain black-box behavioral model”. This is a model relating the spectral representations of voltage and current (respectively incident and scattered travelling waves). These models can accurately describe any microwave device, circuit, and even system, provided that the drive is periodic. Note that, despite the fact that the model is a frequency domain model, the comparison can be made in time-domain (Figure 4). This is possible since information on both amplitude and phase of all spectral components is present (in the measurement as well as in the model).

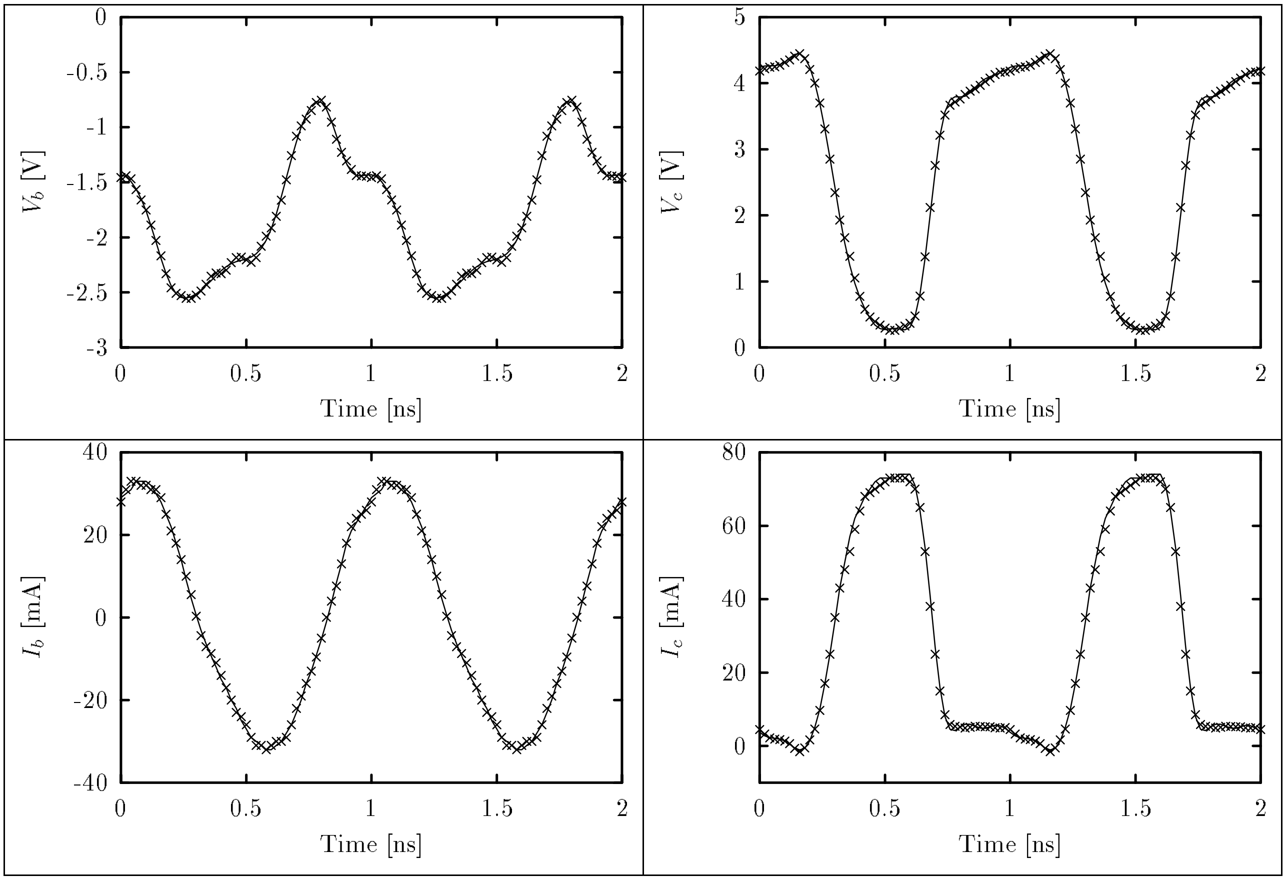

Figure 4 Comparison of the measurement (x) and extracted frequency domain black-box model (—): $V_b(t)$, $V_c(t)$, $I_b(t)$, $Ic(t)$ *of a silicon power stage excited by a 1 GHz signal*

All modeling approaches mentioned above deal easily with a whole range of terminations (mainly limited by the range of the tuning circuits used during the measurements).

5 Conclusions

Modeling, measuring and simulation are the three musketeers for effective RF and microwave design. It is important for the three musketeers to speak the same language across the whole design cycle, from device level up to system level. This is achieved by bridging the gap between time and frequency domain, between travelling voltage waves and current-voltage signal representations and between measurement, modeling and simulation. Although the necessary musketeer dictionary is as yet not complete, a lot of pages are presently ready for print.

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