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Linking X Parameters to Physical Simulations For Design-Oriented Large-Signal Device Variability Modeling

Simona Donati Guerrieri[#1], Fabrizio Bonani[#2], Giovanni Ghione[#3],
[#]Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy
[1]simona.donati@polito.it, [2]fabrizio.bonani@polito.it, [3]giovanni.ghione@polito.it

***Abstract*— We propose various techniques extending X parameters to include the effect of active microwave device variability by exploiting TCAD simulations. We discuss two possible implementations into Agilent ADS. Both approaches are validated against full microwave amplifier TCAD simulations.**

***Keywords*— Device variability, microwave amplifiers, X parameters**

I. INTRODUCTION

Based on the Poly-harmonic distortion (PHD) behavioral models, X parameters (X-par) [1], [2], [3], are a modern and very effective approach to model the nonlinear broad-band operation of microwave devices and circuits. X-parameter are especially attractive due to their direct link to measurements, since they can be characterized comparatively easily in the frequency domain exploiting advanced instrumentation as the nonlinear vector network analyzer (NVNA) [4]. Published papers in the last few years confirm that X-parameters, and more in general PHD models, turn out to be a flexible modeling approach with ever growing applications in a variety of device technologies (e.g. GaN HEMT or Si LDMOS [5], [6], [7]) and circuits, especially power amplifiers, also in high efficiency configurations like Doherty Power Amplifiers [8], [7], [9], [10].

In this work we focus on the X-par modeling of the active device *per se*, with the aim of linking it to physical TCAD simulations. We first demonstrate that X-parameters provide an ideal tool to directly insert the results of physics-based large-signal and frequency conversion analysis in circuit simulations, retaining a direct link between the nonlinear model and the device physical parameters, a link that is often lost in other LS compact models. We then extend the X-par capabilities by including the device LS variability effects, i.e. variations of the large signal performances with technological parameters. We demonstrate two possible implementations in ADS: in the first case X-par are extracted from physical simulations as a function of a given technological parameter and loaded into ADS, where a proper additional port is defined in the X-par component allowing for built in interpolation as a function of the parameter itself. Alternatively, for small amplitude variability, we represent the perturbations arising from small technological fluctuations with properly defined impressed generators at the device ports. Since variability characterizations are in practice hard to carry out and it is impossible to single out the effect of each technological parameter from overall device variations, the second approach comes out to be especially important since it allows for an hybrid technique in which experimental (if available) or TCAD generated X-par are complemented by sensitivity physical simulations performed on a calibrated TCAD model.

II. X-PAR AND TCAD SIMULATIONS

The X-par model expresses the reflected waves at at the device ports as function of the incident waves, therefore extending the concept of S-parameters to the non linear large-signal (LS) regime. In the most widely adopted form, only one (or a set of) incident waves are of large amplitude and drive the system into a non linear LS operating condition, while the other incident waves are considered as perturbations of the operating condition and treated through linearization. Hence, for each port p associated to the device at (positive) frequency harmonics k (i.e., at the k-th harmonic of the fundamental angular frequency ω_0), the reflected wave b_{pk} is obtained by adding the LS operating condition to a linear superposition of the incident waves a_{ql} at any other port q and harmonic l, excluding the LS ports. In order to differentiate the contributions from the upper and lower sidebands of each harmonic, the incident wave a_{ql} and its complex conjugate a^*_{ql} are treated independently [3]

$$b_{pk}(|a_{11}|,\omega) = \sum_q \sum_{l=1,\dots N} S_{pq,kl}(|a_{11}|,\omega) P^{k-l} a_{ql}$$

$$+ \sum_q \sum_{l=1,\dots N} T_{pq,kl}(|a_{11}|,\omega) P^{k-l} a^*_{ql} + FB_{pk}(|a_{11}|,\omega)$$

where $T_{p1,k1} = 0$ is assumed, $P = \exp(\mathrm{j}\angle a_{11})$, N denotes the maximum harmonic order and $FB_{pk}(|a_{11}|,\omega)$ are the reflected waves in the device working point. Notice that the DC response is usually treated separately from the harmonics, as e.g. in the Agilent ADS implementation. As discussed e.g. in [1], the FB, S and T parameters are characterized as a function of the input large signal incident wave at the fundamental a_{11} and are used to generate a look up table model to provide the X-par representation of the device (black box model). The characterization is carried out by applying to each port and each harmonic the reference resistance of 50 Ω.

X-par definition is based on a linear perturbation of the reflected waves due to the presence of (small change) incident waves. As a consequence, a one to one relationship exists [11], [12], [13] with the concept of conversion matrix (CM) [15] and, more in general, with the lienarization of the circuit nonlinear equations [14]. The computation of the CM was introduced within the framework of TCAD simulations in [16] and was later extended to device variability and sensitivity analyses [17], [18], [19], [20] and to effective microwave circuit design [23], [24]. For implementation reasons, the CM evaluated into TCAD tools is defined with reference to a bilateral spectrum, so that the harmonic index runs from $-N$ to N. Furthermore, the frequency offset taken into account is positive, so that upper sidebands *only* are actually involved. However, spectral symmetry implies that the *upper* sideband of a negative frequency harmonic $p < 0$ corresponds to the *lower* sideband of harmonic $-p$ for the unilateral spectrum. In other words $(k, l > 0)$

- $S_{pq,kl}$ is obtained transforming into scattering parameter the (k, l) element of the TCAD admittance CM
- $T_{pq,kl}$ is obtained transforming into scattering parameter the $(k, -l)$ element of the TCAD admittance CM

In order to test the X-par derivation from TCAD simulations, we consider a test case of an FET GaAs based power amplifier [24]. The device has 0.25 μm gate length and is biased in deep class AB. TCAD simulations including LS and conversion matrix have been carried first with the device matched on the fundamental optimum load and shorted harmonics (akin to a tuned load) and by varying the active GaAs layer doping. The corresponding LS device working points have been stored in *Citifile* format and imported into Agilent ADS as a reference solution. Then TCAD simulations were repeated with the device in matched conditions (50 Ω at all ports and all harmonics) to extract X-par, using the Y CM as explained above and the large signal working point. X-par are then stored in the ADS format *.xnp* file. Finally, ADS simulations are carried out to test the X-par model capabilities to reproduce the TCAD reference solution, both with a matched output port and with optimum load and shorted harmonics. For this preliminary analysis the input port has been kept on 50 Ω. Results confirm that the X-par extraction procedure is correct. Fig. 1 shows that the reference dynamic load lines (DLLs) on optimum load can be reproduced by the X-par model extracted on 50 Ω for several input powers, up to compression. The model is also capable to correctly reproduce the load variations with respect to the optimum load : Fig. 2 shows how the incident and reflected waves are modified by changing the load condition at the fundamental and the source load at the harmonics. The X-par model still reproduces TCAD simulations accurately. Notice that the simulation time for the TCAD analysis on a 25 input power sweep and 10 harmonics is around 20 hours, while the X-par simulations within ADS allow for the accuracy shown in Fig. 1 in just a few seconds of simulation time. Further amelioration of the accuracy can be obtained by including a non 50 Ohm environment, i. e. load and source-pull, in the X-par analysis (not considered in this work). Hence, we conclude that X-par are a viable tool to accurately insert physical models in circuit analysis.

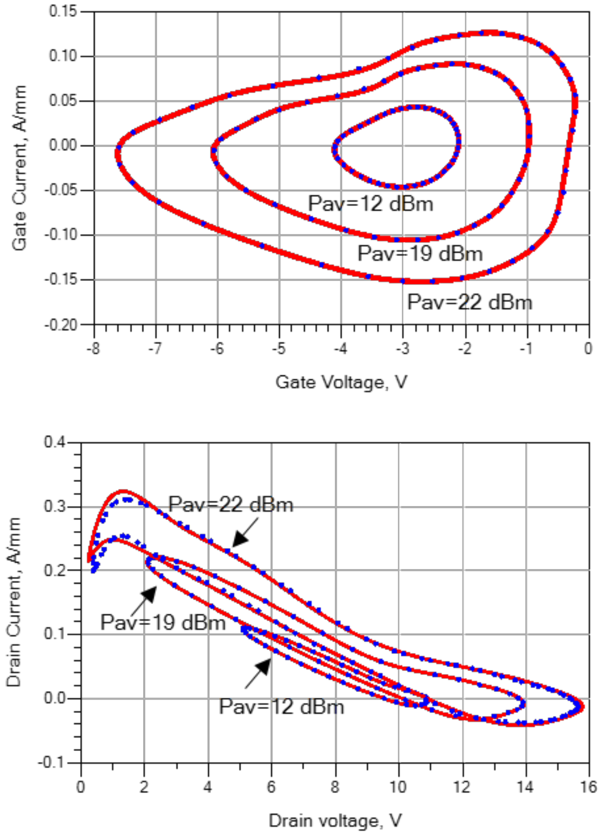

Fig. 1. Dynamic load lines from TCAD physical simulations (blue dots) and ADS results with the X-par model (extracted on matched ports). The device drain port is loaded with the optimum class AB load $Z_{\mathrm{L,opt}} = (46 + j11)\ \Omega$ at the fundamental frequency of 12 GHz and shorted at harmonics. Top: gate current. Bottom: drain current

III. PARAMETRIC LS SENSITIVITY VIA X-PAR

As already mentioned in the introduction, one of the advantages in translating the physical analysis into the X-par model, is that it can retain the direct link with physical process parameters. Such link is of course beneficial to the X-par model, in order to allow for true a otpimization of a circuit performance taking into account possible variations of the active device itself. Despite its relevance, the problem has been addressed so far only in the context of X-par scaling [21], i.e. making device periphery a model parameter, while [22] addresses X-par sensitivity, but only towards embedding circuit variations. In this work, we address the topic in a more general way. To fully exploit the capabilities of TCAD analysis, we address the problem of the parametric sensitivity of LS performances. These can be traced back to the spread of the device characteristics due to technology tolerances, e.g. the variations of the gate workfunction, of the active layer doping or of a fixed charge. As an example, we take doping variations of the active device layer. Independent X-par models can be obtained by repeated TCAD simulations with varying doping and then independently loaded in ADS for circuit analysis, with accuracy similar to the one shown in Fig. 1 for each doping. This solution, though, does not allow for a true doping-dependent model, since the X-par are not interpolated from one doping level to the other. To circumvent

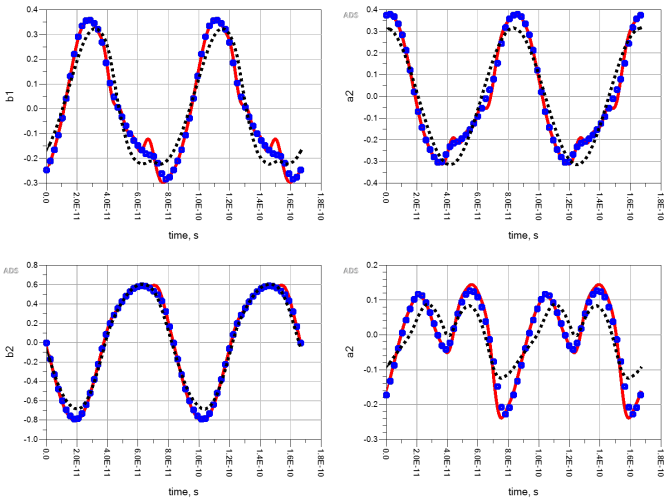

Fig. 2. Waveforms of the device with shorted harmonics (gate and drain) and 10% variation of the imaginary part with respect to fundamental optimum load. Input power is 19 dBm. Solid line: X-par ADS; blu symbols: TCAD simulation; black dotted line: waveform with the loading condition of Fig. 1. Top: b_1 and a_1. Bottom: b_2 and a_2.

this problem, we exploit the features of the *.xnp* file, which allow for interpolation on any set of independent variables. We have therefore inserted an additional, fictitious port in the X-par model: the extra port is isolated from the other ones (X-par are padded with zeros to avoid interfering with the active ports) and its port voltage, linked to the doping value, has the only role to allow for doping interpolation in the X-par file. An example of the implementation is shown in Fig. 3. The X-par file includes values extracted from physical simulations corresponding to three doping conditions: the nominal device with $N_{\mathrm{D}} = 2 \times 10^{17}$ and ±10 % variation. Fig. 4 shows the DLL lines obtained from the X-par analysis sweeping the doping at the extra DOPING port. Besides being accurate at the doping levels used for the X-par extraction, the interpolation performed within ADS allows an excellent accuracy even for doping variations of ±5%, not used for the model extraction, and up to the device compression point.

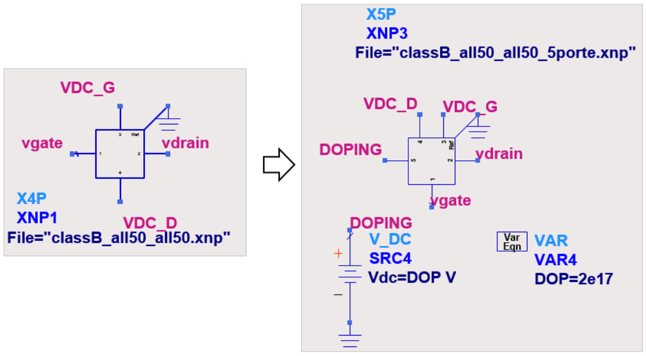

Fig. 3. X-par with extra port DOPING used for doping interpolation in the X-par file. In this example the original 4-port component (two DC and 2 RF ports) becomes a 5-port for doping dependent analysis.

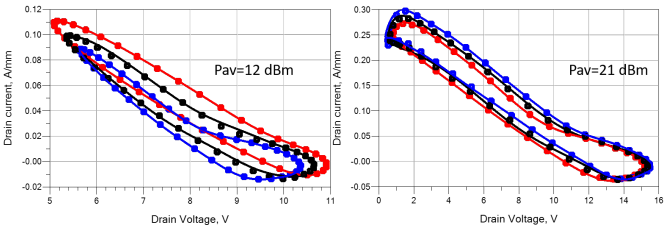

Fig. 4. Dynamic load lines from TCAD (symbols) and ADS simulations with the X-par model extracted on 50 Ω (lines). The device drain port is loaded with the optimum class AB load. Left: doping is $N_{\mathrm{D}} = 2 \times 10^{17}$ cm^{-3} (red lines & symbols); -5% (black lines & symbols); -10% (blue lines & symbols). Right: $N_{\mathrm{D}} = 2 \times 10^{17}$ cm^{-3} (red lines & symbols); +5% (black lines & symbols); +10% (blue lines & symbols).

It is well known that small parameter variations that occur inside the device volume can also be represented, from the circuit standpoint, by means of equivalent short circuit current generators at each harmonic and each device port[24]. These equivalent generators can be calculated within TCAD concurrently with the device Y conversion matrix [25] and greatly reduce the computational cost of TCAD variability analysis, since they must be calculated only once for the device with nominal parameters, hence avoiding repeated simulations. The equivalent generators are extracted from the device linearized around the LS working point, thus being consistent with the X-par model philosophy. Following this approach, the equivalent current generators at the device ports can directly be imported into ADS by means of *citifiles* (see Fig. 5) and connected to the X-par model representing the device with nominal parameter. An example is shown in Fig. 5, where 4 current generators at the DC and RF ports represent ±5 % doping variations for the same device previously considered.

As shown in Fig. 6, the X-par model for the nominal device completed with the variability equivalent port generators yields results in good agreement with the full TCAD analysis with varying doping. The latter example is

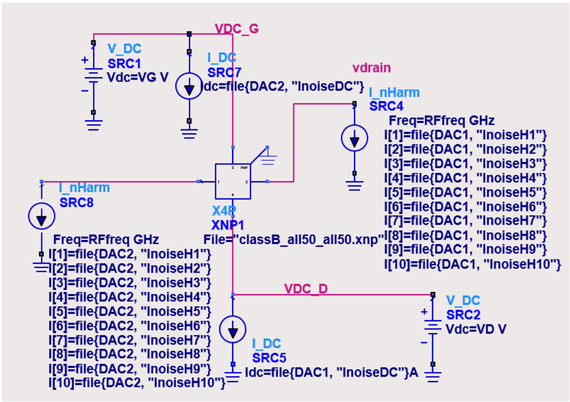

Fig. 5. X-par with extra variability current generators representing doping variations.

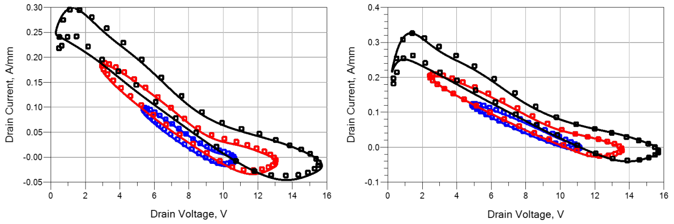

Fig. 6. Dynamic load lines from TCAD (symbols) and ADS simulations with the X-par model extracted on 50 Ω and equivalent variability current generators (lines). The drain port has optimum class AB load. Input power is 12 dBm (blue lines & symbols); 18 dBm (red lines & symbols); 22 dBm (black lines & symbols). Left: -5% doping. Right: +5% doping.

especially important since it provides the way to couple experimental characterization of the X-par on actual devices with the predictions of accurate physical simulations limited to technological variability only.

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