Device Modeling with NVNAs and X-parameters*

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***Abstract* — This paper reviews and contrasts two complementary device modeling approaches based on data readily obtainable from a nonlinear vector network analyzer (NVNA) [1]. The first approach extends the application of waveform data to improve the characterization, parameter extraction, and validation methodologies for "compact" transistor models. NVNA data is used to train artificial neural network -based constitutive relations depending on multiple coupled dynamic variables, including temperature and trap states for an advanced compact model suitable for GaAs and GaN transistors. The second approach is based on load-dependent X-parameters* [2], [3], [5], [6], measured using an output tuner working with the NVNA. It is demonstrated that X-parameters measured versus load at the fundamental frequency predict well the independent effects of harmonic load tuning on a 10W GaN packaged transistor without having to independently control harmonic loads during characterization. A comparison of the respective merits of the two approaches is presented.**

***Index Terms* — NVNA, X-parameters, device modeling, compact models, parameter extraction.**

I. Introduction

Good device (e.g. transistor and diode) models are essential to efficient CAD of nonlinear microwave and RF circuits, MMICs, power amplifiers, and nonlinear RF systems. Increasingly complicated demands on the various semiconductor technologies (e.g GaAs pHEMTs, GaN HFETS, InP DHBTs etc.) in terms of power and frequency of operation, and complexity of signal class for the device stimulus and response have placed commensurate requirements on accuracy and generality of the device models used for design.

Most transistor models for circuit simulation are still formulated as nonlinear ordinary differential equations in the time domain[1]. Such models are often constructed in terms of basic electrical circuit elements such as controlled sources, resistors, capacitors, and inductors, arranged in a specific equivalent circuit topology.

These transistor (or diode) models are sometimes known as "compact" models, although, paradoxically, their complexity has grown rapidly over time to the point where several standard compact device models have well over 100 parameters and scores of nonlinear equations [9]. Such models require extensive data for fitting (parameter extraction). Moreover, models with advanced mechanisms, such as both dynamic self-heating and trapping effects, cannot typically be identified from conventional DC and linear (S-parameter) data alone [13].

This paper presents two applications to device modeling using nonlinear data readily obtainable from a modern NVNA. The first uses waveform data with synthetic load-pull together with an advanced artificial neural network infrastructure, to construct constitutive relations of an electro-thermal and trap-dependent compact model for GaAs and GaN FETs. The second method applies load-dependent X-parameters measured with an NVNA to model a packaged 10W GaN HFET, including the prediction of harmonic tuning effects.

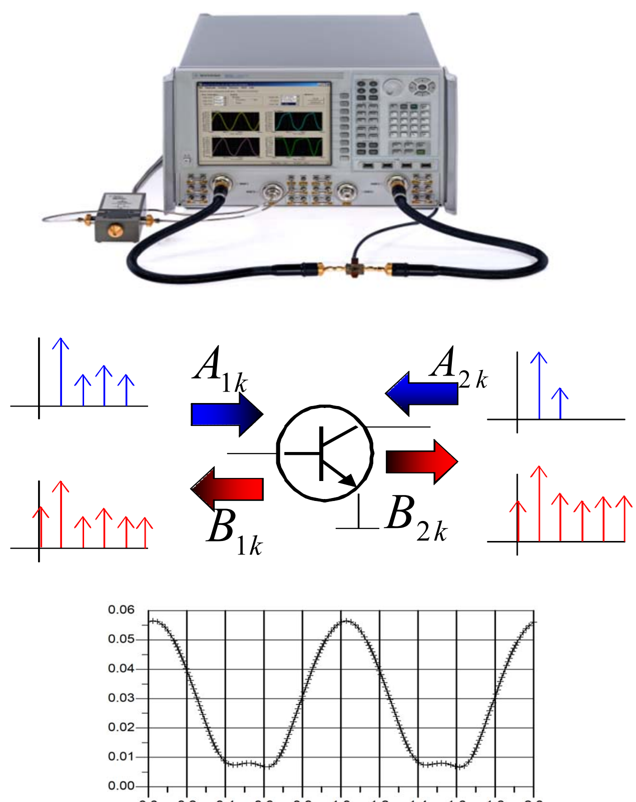

Fig 1. (a) NVNA with phase reference and DUT
(b) Frequency domain representation of simultaneous incident signals with harmonic content at input and output ports and corresponding scattered wave spectra..
(c) Example of output waveform in the time domain obtained by Fourier transform of spectral components.

* "X-parameters" is a registered trademark of Agilent Technologies.

1 For the purposes of this paper, we do not consider "TCAD" device models, typically defined by coupled partial differential equations and solved by physical device simulators.

II. NVNA DATA

The nonlinear vector network analyzer (NVNA) measures the magnitudes and relative phases of incident and scattered spectral components on each DUT port. The device may be stimulated by one or more large- or small-signal sinusoidal inputs at one or both DUT ports simultaneously. An example is shown in Fig. 1. Because the cross-frequency relative phases of the spectral components are measured, it is possible to convert the complex spectra into time-domain waveforms. Thus the NVNA provides fully calibrated waveform measurements at input and output ports of the device.

A. Applications to compact models

Over the past 15 years, there has been significant research applying large-signal measurement systems to the field of nonlinear device modeling. Much of this work has focused on the validation of compact models under realistic large-signal operating conditions, the modifications of parameter extraction methodologies, tuning model parameter values to get better agreement with large-signal performance, and the ability to evaluate the limitations of a particular nonlinear model and suggest improvements [10]. Using NVNA data, one can get the optimal parameter set for a given compact model. Such data enables the modeling engineer to manage tradeoffs between fits to DC and S-parameters on one hand and distortion and large-signal waveforms on the other.

NVNA data extends the range of device characterization beyond that possible under DC or static operating point conditions. This is especially important for high power devices and when operating the device into limiting regions of operation such as breakdown. An example is given in Fig. 2 for the case of a GaAs pHEMT. The measured load-line extends well beyond the range over which DC and S-parameter data can be taken. Simulations are discussed below.

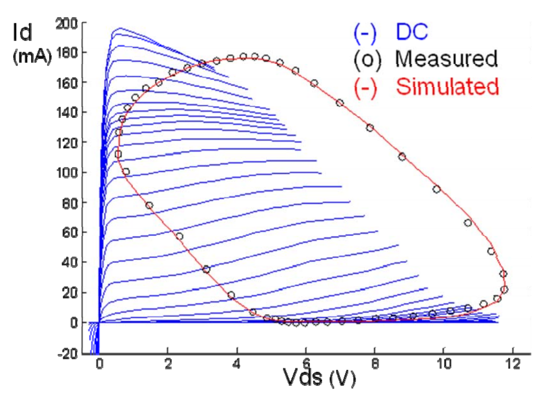

Fig. 2. NVNA-measured (O), and compact model simulated (red curve) dynamic load-lines superimposed on measured DC I-V curves (blue lines) of a GaAs pHEMT.

B. Advanced compact models from NVNA data

The present work goes beyond the preceding considerations by using NVNA data to directly identify the large-signal constitutive relations of an advanced nonlinear dynamical model applicable to GaAs and GaN FETs. The model incorporates dynamic electro-thermal effects and includes trap capture and emission processes similar to [13]. Unlike [13], we allow complete flexibility in terms of the model current and charge functions. More details will be presented in [4].

Phase control of the two-source NVNA enables active load control of the output impedance seen by the GaAs pHEMT device. The NVNA large-signal data covers the complete range of device operation and provides validation data under realistic operating conditions. The problem becomes identifying nonlinear functions of current and charge that depend on five variables, instantaneous terminal voltages, V_1 and V_2, the time-varying dynamic "junction temperature", T_j, and two state variables corresponding to gate-lag and drain-lag trap states, ϕ_1 and ϕ_2, respectively. That is, we seek to identify model functions, $I_D(V_1,V_2,T_j,\phi_1,\phi_2)$ and $Q_D(V_1,V_2,T_j,\phi_1,\phi_2)$, from the NVNA measured contours over various input powers, frequencies, bias, loads, and temperatures. The NVNA waveforms, represented by over 1000 dynamic load-lines such as in Fig. 2, but corresponding to different powers, loads, biases, and temperatures, are used to train artificial neural networks to learn the complicated five-variable constitutive relations for current and charge. Results of NVNA measurements used to validate model simulations are shown in Fig. 3. The model fits well the non-standard gain compression and non-monotonic bias current

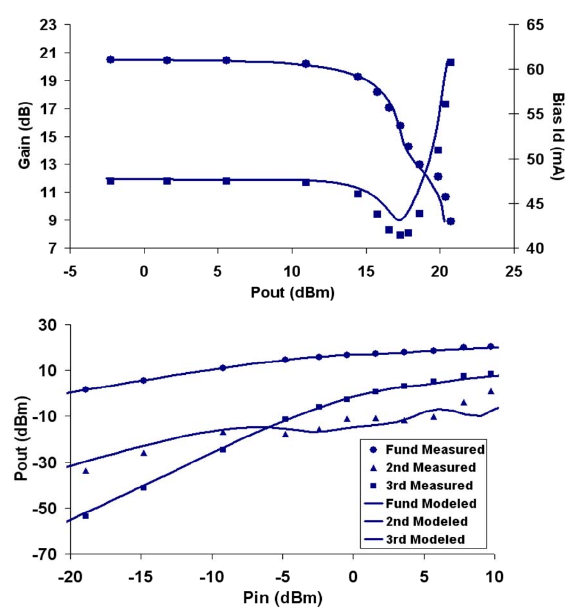

Fig. 3. Model validation, using independent NVNA measurements, of advanced large-signal FET model constructed from NVNA waveform data.

versus power characteristics, as well as levels of harmonic distortion from small-signal to very large-signal conditions.

III. LOAD-DEPENDENT X-PARAMETER DEVICE MODELS

A quite different approach to transistor modeling with NVNA data is provided by the new paradigm of X-parameters. X-parameters are the rigorous supersets of S-parameters and load-pull, applicable to both linear and nonlinear conditions [7]. X-parameters are native frequency/envelope domain models, formulated in the mathematical language native to the simulator algorithm (harmonic balance (HB) or circuit envelope (CE)) that most efficiently solves the design problem. X-parameters are a black-box approach that can be directly measured on transistors manufactured in any technology. X-parameters are especially useful for less mature technologies where there may not be a suitable compact model available [3] or where compact model IP needs to be protected. X-parameters measured by NVNAs are being increasingly used to provide device models with high accuracy [2]. Because a transistor, especially a power transistor, will not usually be used in an environment nearly matched to 50 ohms, load-dependent X-parameters provide the appropriate foundation for general use [3], [6]. In this case, the NVNA is used together with a load-tuner presenting impedances that can be varied across the Smith Chart. Load-dependent X-parameters for this application are given by

$$\begin{aligned} B_{e,f} &= X^{(F)}_{ef}(DC,|A_{11}|,\Gamma_2)P^{f} \\ &+\sum_{g,h} X^{(S)}_{ef,gh}(DC,|A_{11}|,\Gamma_2)P^{f-h}\cdot A_{gh} \\ &+\sum_{g,h} X^{(T)}_{ef,gh}(DC,|A_{11}|,\Gamma_2)\;P^{f+h}\cdot A^{*}_{gh} \end{aligned} \qquad (1)$$

where $P = e^{j\phi(A_{11})}$.

The incident and scattered waves have two indices, the first is the port index (1, 2) and the second is the harmonic index (0,1,2,…) that can range up to the highest harmonic measured within the bandwidth of the NVNA. Each term depends nonlinearly on the available power (proportional to $|A_{11}|^2$), the complex fundamental load at the output port, Γ_2, the DC bias, and the frequency (not shown). Equation (1) is the spectral map between incident and scattered waves, linearized around a large-signal operating point defined by the two large signals at the fundamental frequency incident into ports 1 and 2, respectively. That is, the wave at the fundamental frequency reflected by the tuner into DUT port 2 is assumed to be large, and its full nonlinear effect on the operating point is accounted for. The sum is over harmonic indices 2 and 3, at each port, which means that this X-parameter model is assumed to be spectrally linear in the complex amplitudes of second and third harmonics incident at both the input and output ports of the DUT. The assumption is validated below.

In this example, the load-dependent X-parameters were measured on a 26GHz Agilent NVNA with load-dependent X-parameter option enabled, in conjunction with a Maury load tuner and Maury ATS software. Measurements were made at 900 MHz. The DUT is a 10W GaN packaged transistor (CGH40010) manufactured by Cree [11]. The model is validated by first augmenting the measurement setup to a harmonic load-pull system by adding two additional tuners at the output port to control the second and third harmonic impedances, independently from one another and from the load at the fundamental. Validation data from nine sets of independent fundamental and harmonic terminations are measured with the augmented system. The harmonic loads that were used for the validation measurements were presented to the fundamental-only load-dependent X-parameter model using (1), and simulations of waveforms, PAE and other figures of merit compared to the validation measurements.

The results are shown in Fig. 4 for one of the 729 sets of impedances measured (nine each for fundamental, second, and third). Similar results are obtained at each of the independently set harmonic output port impedances. More complete results and experimental details will be presented in [12]. It must be emphasized that the X-parameter model was obtained without independently controlling the harmonic loads. Only the load at the fundamental frequency was controlled by the tuner during the X-parameter characterization, and small signals were injected separately at each harmonic. The dependence on the uncontrolled harmonic loads of the tuner was calibrated out in the process of extracting X-parameters. The fact that such a model can predict with such accuracy for any set of harmonic loads is a direct validation of the formulation in (1), the approximation known as the "principle of harmonic superposition," first proposed in [14] and recently validated for the second harmonic in [5]. The benefit is that a full two-port functional block nonlinear model can be created without the need for a full harmonic load-pull system, dramatically reducing the

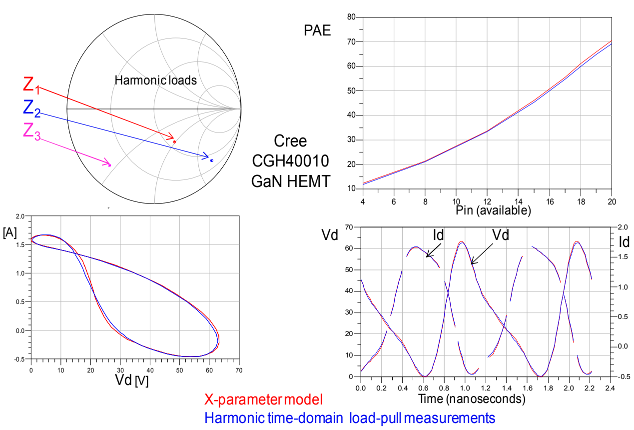

Fig. 4: PAE , Id and Vd waveforms, and load-lines from load-dependent X-parameter model simulations (red) and measured time-domain harmonic load-pull validation measurements (blue) at the harmonic impedances, Z_n, specified in upper left plot.

measurement time, data, and hardware cost. Moreover, there is no need for source tuning other than for good power transfer [12]. With just input power swept, the X-parameter model gives the correct response for whatever source impedance is encountered when placed in a circuit design. It should be noted that there is no requirement to use the simplification of the general nonlinear spectral map given by (1); multi-harmonic load-dependent X-parameters can always be measured using a full harmonic load-pull system should that be desired.

IV. Discussion and Comparison

Compact models work in all simulation modes, e.g. transient analysis (TA), harmonic balance (HB), circuit envelope (CE), S-parameter (SP), AC analysis, etc. Compact models are more scalable with layout, and can extrapolate well to higher frequencies. Compact models can often be used for "what-if" scenarios by modifying parameter values to account for physical or geometrical changes. However, formulating and implementing compact models can take years. Extracting such models can take time and great expertise.

X-parameter models are device and technology independent. They are much easier and faster to extract than compact models. They completely protect the component and model IP. X-parameter models are limited to the range of data used for extraction, but this can sometimes be as wide as the entire operating range during actual use. Over the measurement range, X-parameter models are extremely accurate. X-parameter models are not scalable with geometry, but more can be done in this direction with future research. File size can become large if sweeping all independent variables densely. Memory effects are not yet included (but see [15]). A simplified comparison of the two approaches is summarized and presented in Table 1.

Table 1: Compact and X-parameter device model comparison

Approach	Advantages	Disadvantages
Compact device model	• Works in all simulation modes (TA, HB, CE) • More scalable • Noise models; Temp dep. • What-if scenarios possible	• Development time long • Extraction difficult
X-parameter device model	• Technology independent • Extremely accurate within characterization range • Complete IP protection • Works for packaged parts • Easier and faster to extract	• Limited by NVNA BW • Large file size • Limited memory effects at present

V. Conclusion

Examples using NVNA data for two very different approaches to device models were presented and contrasted. NVNA data was used to identify advanced measurement-based nonlinear compact model constitutive relations depending on terminal voltages, junction temperature, and trap states, that could not be identified from DC and small-signal data alone. This approach is attractive for modeling modern transistors in III-V technologies, such as pHEMTs and GaN HFETs.

Fundamental load-dependent X-parameters predicted, with high accuracy, the detailed nonlinear device characteristics of a packaged GaN transistor, even under tuned harmonic loading conditions, despite not having to independently control harmonic impedances during characterization. This means extremely accurate measurement-based nonlinear two-port functional block device models can be obtained with a significant reduction of data and measurement time compared to conventional harmonic load-pull measurements. This is especially useful for modeling devices in new technologies, such as GaN, for which an accurate compact model may not be available, or where device model IP may need to be protected.

Acknowledgement

The authors thank T. Nielson, F. Sischka, and J. Verspecht for useful discussions, and Agilent management for support.

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