Jan Verspecht bvba

Gertrudeveld 15
1840 Steenhuffel
Belgium

email: contact@janverspecht.com
web: http://www.janverspecht.com

Broad-Band, Multi-Harmonic Frequency Domain Behavioral Models from Automated Large-Signal Vectorial Network Measurements

Jan Verspecht, David Root, John Wood and Alex Cognata

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Jan Verspecht, *Member, IEEE*; David E.Root*, *Fellow, IEEE*, John Wood*, *Senior Member, IEEE*, and Alex Cognata*

"Jan Verspecht, bvba", Belgium (www.janverspecht.com)
*Microwave Technology Center, Agilent Technologies, Inc., Santa Rosa, CA 95403 USA

Abstract — **This paper presents an extended nonlinear black-box behavioral model in the frequency domain, automated experimental identification of the model from large-signal vector network measurements, and extensive experimental validation of its application to real microwave ICs. The model is a broad-band extension of the multi-harmonic "linearized scattering function" theory. The characterization is based on large-signal vector network measurements where harmonic perturbations are applied, in phase and in quadrature, to a component excited at the input by a large amplitude tone. The experiment design and model generation are simple and highly automated. The derived model is shown to be valid for both small and large amplitude drive signals, correctly predict even and odd harmonics, and simulate, accurately, load-pull behavior far from 50 ohms. The model is implemented in *Agilent ADS*.**

***Index Terms* — Modeling, microwave measurements, nonlinear systems, nonlinear circuits, design automation, frequency domain analysis.**

I. Introduction

The design of broadband microwave systems and modules for modern instrumentation applications presents a significant challenge. A typical microwave system will contain several active IC components as well as passive elements, both of which may be distributed in nature. Such a system is often too complex to permit complete simulation of the non-linear behavior at the transistor level of description. A complete system simulation can become practical, however, provided the design is done at a higher level of abstraction, using behavioral models of the nonlinear blocks or ICs. The behavioral models must describe both the frequency-dependent nonlinear behavior of the ICs and describe properly the propagation of harmonic and intermodulation distortions through the system, to enable the designer to meet rigid specifications, while being simple enough to allow rapid simulation.

In this paper, we describe an extended nonlinear frequency domain behavioral model and a systematic methodology for generating it from automated large-signal vector network measurements. These are 'black-box' behavioral models requiring no *a priori* knowledge of the device physics or circuit configuration of the nonlinear component.

II. Model Formulation

The behavioral model presented here is a broad-band generalization of the work first presented in [1]-[3].The model theory derives from a multi-harmonic linearization around a periodic steady-state determined by a large-amplitude single input tone. The assumption is that the system, under large-signal drive, responds linearly to additional tones at the harmonic frequencies considered as "small" perturbations around the time-varying system state. These models give accurate responses even when the harmonic terms are relatively large. In applications, these harmonic terms can result from nonlinearities created from previous stages or reflections from nonlinear devices at the next input stage of a multi-stage amplifier, for example. The model presented here has been generalized by extension to an arbitrarily broad frequency range. This is essential for modeling the frequency dependences of the nonlinear responses of such microwave ICs as broad-band traveling wave amplifiers and other components useful in instrument applications.

The model is defined by equations in the frequency domain relating complex transmitted and scattered waves, at each port, p, and harmonic index, k, to a linear combination of terms in the incident waves at each port at each harmonic, and, independently, the complex conjugates of the incident waves and their harmonics. The fact that the complex conjugate terms in the incident waves appear is a necessary consequence of the non-analyticity of the Jacobian, which represents the linearization around the time-varying operating point established by the single large-amplitude tone in the absence of perturbation. The sums are over all port indices q, and harmonic indices, l. (DC is excluded in the cases presented here, so the sum over l starts at the fundamental. In general this method can easily be extended to include the DC term, in which case the sum starts from index 0).

$$B_{pk}(|A_{11}|,f) = \sum_{q}\sum_{l=1,\ldots,M} S_{pq,kl}(|A_{11}|,f)\cdot P^{k-l}\cdot A_{ql} + \sum_{q}\sum_{l=1,\ldots,M} T_{pq,kl}(|A_{11}|,f)\cdot P^{k+l}\cdot A_{ql}^{*} \quad (0.1)$$

In (0.1), $P = \exp(jArg(A_{11}))$ is a pure phase that, along with the magnitude-only dependence on A_{11} of the *S* and *T* functions, is a necessary consequence of the assumed time-invariance of the underlying system and the single, large, input tone excitation. A redundancy, introduced by summing over the fundamental components (*l*=1) in addition to the harmonics in (0.1), requires the imposition of the additional constraints given by (0.2). For the applications demonstrated in this paper, we consider a two-port amplifier model with five harmonics.

$$T_{p1,k1} = 0 \qquad (0.2)$$

III. Excitation Design

The excitation design is based on perturbing the nonlinear component resulting from the large-signal input, by applying, at each port in turn, and separately at each harmonic of the fundamental, a single small-signal tone. This is done for each harmonic up to the maximum number needed for the model or the limitation of the instrument's bandwidth. The structure of the model equations (0.1) and (0.2) is such that, in principle, the *S* and *T* coefficients at each harmonic can be extracted directly from three measurements. These measurements are: the responses at each port and at each harmonic frequency to the large tone without perturbation; and the responses with the small-signal perturbation tone applied with two different relative phases with respect to the fundamental.

The experiments are performed with a 50GHz vector nonlinear network analyzer [4]. The hardware description is presented in Figure 1. Two sources are used: the first source stimulates the amplifier with a large sinusoidal tone, varied from small-signal up to the saturated input power of the amplifier. The second source provides the small amplitude perturbation tones. The switch allows the small tones to be applied at the input and the output ports. For each power level of the large tone, the small perturbation tones are applied one at a time, at each harmonic and at each port.

Because the measurement system cannot control the phase of the perturbation tones relative to the fundamental large-signal tone, the measurements are made with several randomized phases, and the *S* and *T* coefficients are extracted by regression analysis.

IV. Model Implementation

The extended model is implemented in *Agilent Advanced Design System* (ADS) as a sub-circuit using the Frequency Domain Device (FDD) built-in component. The measured and identified *S* and *T* model functions are stored in two-dimensional *Citifile* format. The dimensions correspond to the amplitude and the fundamental frequency of the large-signal input tone, respectively. The equations (0.1) and (0.2) appear in a text file read by the model. A data-access component (DAC) links the tabulated data to the model, and performs two-dimensional interpolation during the simulation.

V. Results

The modeling approach was applied to a wideband microwave IC amplifier, the *Agilent Technologies* HMMC-5200 [5]. This is a DC-20 GHz, 10dB gain amplifier with internal feedback, designed to be used as a cascadable gain block in a variety of microwave circuit applications. It contains eight GaAs HBTs of two different sizes, configured as a compound modified Darlington feedback pair, operating in Class A.

Figures 2-5 show large-signal validation results comparing measurements against the behavioral model simulations. The fundamental frequency for these experiments was chosen to be 3GHz. A load of 27 ohms was used for the experimental validation. This is quite far from the 50 ohm termination that is usually expected, and provides a significant a_2 return signal to test the transportability of the model. The fundamental AM-AM and AM-PM characteristics are compared in Figure 2. Figures 3 and 4 show the second and third harmonic output power and phase, respectively. Figure 5 shows time-domain waveforms of the output currents. Even for the high-degree of

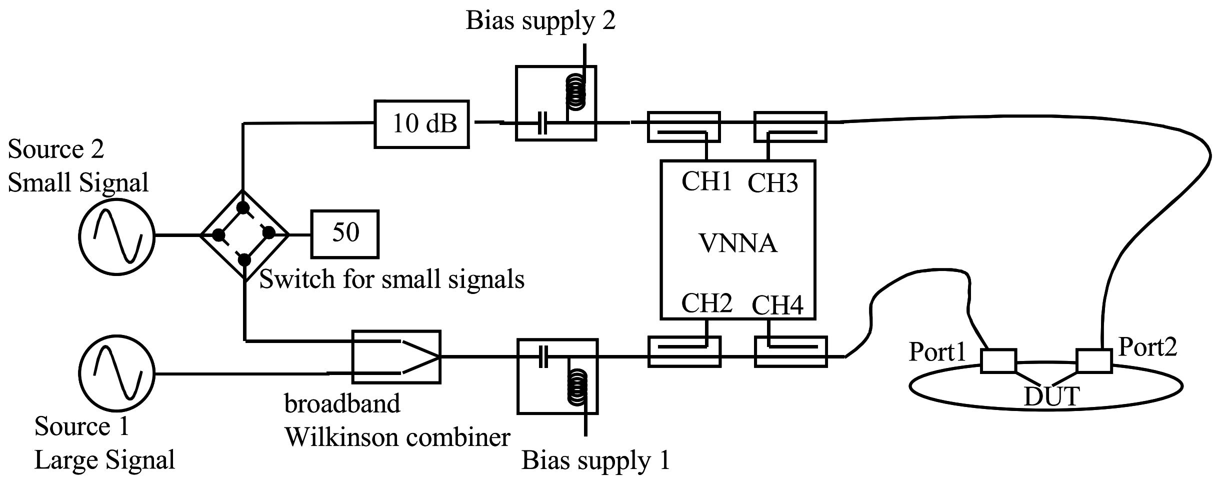

Fig. 1. Schematic connection of the VNNA for the large-signal and small-signal perturbations to the DUT

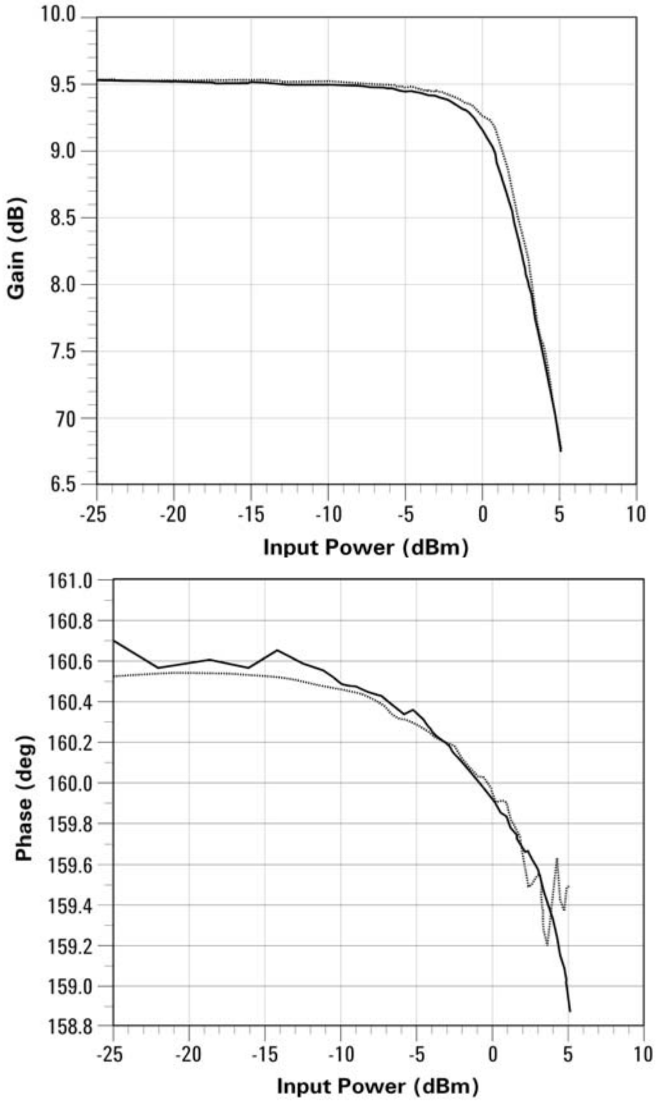

Fig. 2. Fundamental Gain compression (AM-AM) (top) and phase variation (AM-PM) (bottom) as a function of input power. Behavioral Model (dotted) and load-pull validation (solid).

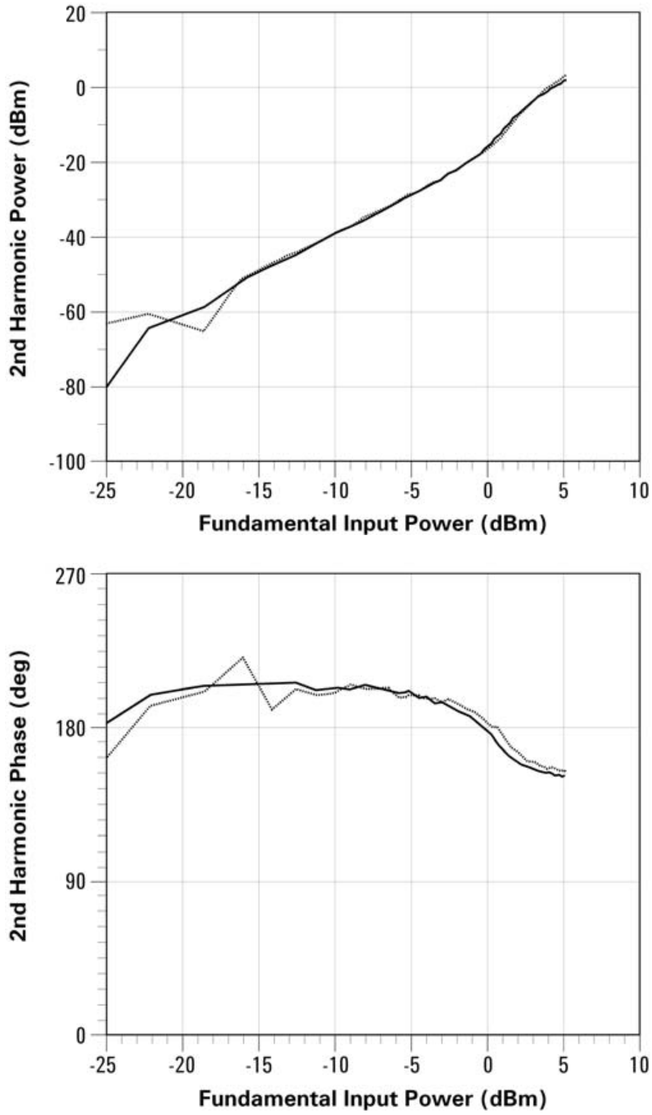

Fig. 3 Second harmonic amplitude (top) and phase (bottom). Behavioral Model (dotted) and load-pull data (solid).

compression shown in the figure, the behavioral model shows remarkably good agreement with the independent nonlinear measurements made with the VNNA in conjunction with the load-pull system. It is important to note that all measurements used in identifying and generating the model were made with only 50 ohm terminations.

VI. Conclusions

We have presented a broadband, multi-harmonic nonlinear behavioral model and validated it with nonlinear measurements for a wideband microwave amplifier IC. The model is identified from automated large-signal measurements using a nonlinear vector network analyzer. The model, implemented in *Agilent* ADS, is very accurate for a wide variety of nonlinear figures of merit, including AM-AM, AM-PM, harmonics, load-pull, and time-domain waveforms, even when used far from the 50 ohm environment in which the measurements for model identification were made. Similar results (to be reported in [6]) have been obtained in the simulation environment starting from a circuit-level model of the IC.

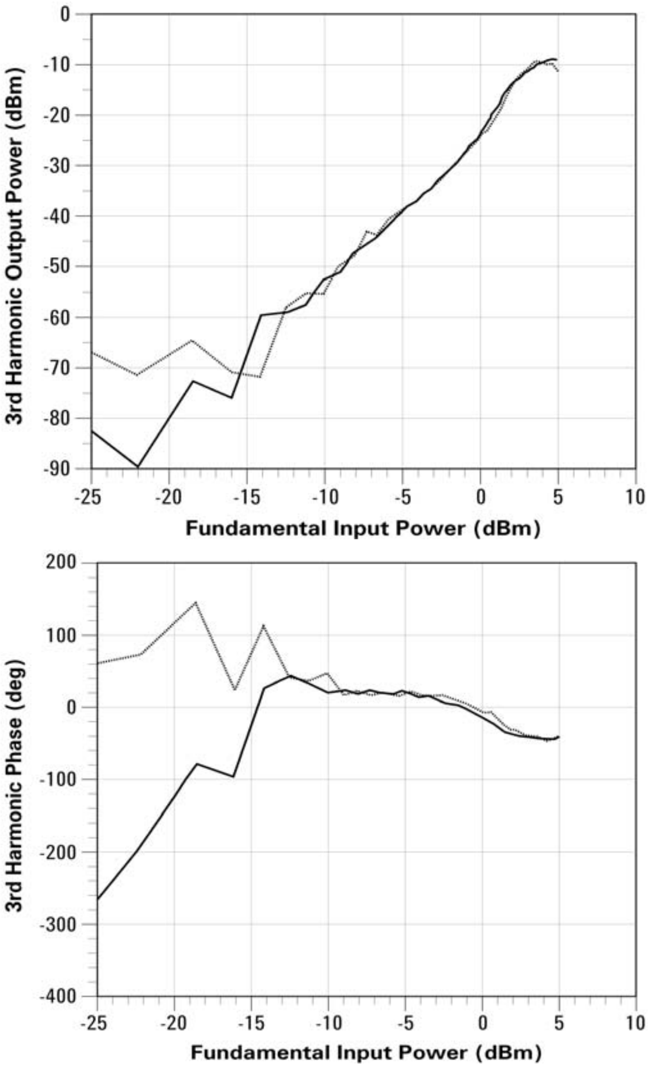

Fig. 4 Third harmonic amplitude (top) and phase (bottom). Behavioral Model (dotted) and load-pull data (solid)

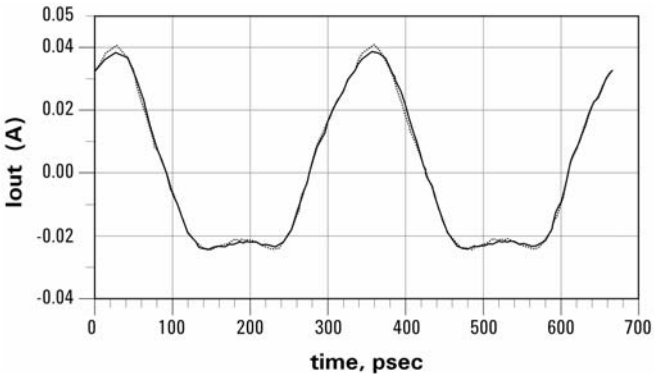

Fig. 5. Time-dependent output waveform validation. Behavioral Model (dotted), Independent large-signal measurements (solid).

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