RECENT ADVANCES IN THE MEASUREMENT AND BLACK-BOX MODELLING OF HIGH-FREQUENCY COMPONENTS

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ABSTRACT

This paper gives an overview of recently developed frequency domain measurement and modelling techniques for non-linear microwave components. The system architecture and measurement capabilities of the Hewlett-Packard "Non-linear Network Measurement System" are described. Three modelling techniques, based on the new instrument measurement data, are discussed: empirical models, state-space models and black-box frequency domain models.

INTRODUCTION

Last years significant progress has been made in the measurement and modelling methods for non-linear microwave components. Several research groups build measurement systems in order to characterize the large-signal behaviour of transistors and/or diodes under large-signal excitation [2]-[7]. The data is often used in order to verify or improve large-signal models of the device-under-test (DUT). This paper describes the work performed by the Hewlett-Packard "Network Measurement and Description Group" (NMDG), and the TELEMIC department of the "Katholieke Universiteit Leuven". NMDG developed the "Non-linear Network Measurement System" (NNMS). This system allows to accurately measure voltage and current waveforms under large-signal high-frequency periodic excitation. It is shown how data provided by the NNMS can be used in order to verify and apply optimization to three different kind of non-linear models: a classical empirical model, a state-function model (both approaches developed by the people of TELEMIC) and a black-box frequency domain model (developed by NMDG).

MEASUREMENT TECHNIQUES

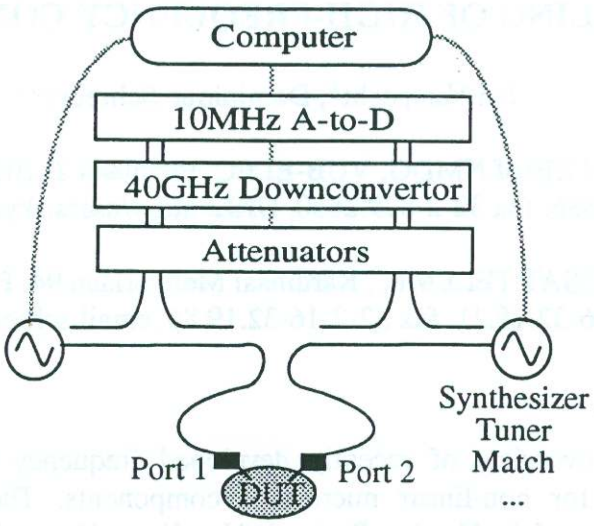
Introduction

From a physical point of view, the behaviour of any electrical component is characterized when one knows the relationship between the voltage and current waveforms at all signal ports. Unfortunately, no commercial instrument exists today which allows the direct measurement of these voltage and current waveforms for non-linear microwave devices. As such, several research groups have build there own system. An accurate and versatile version of such a prototype instrument is the NNMS.

The Non-linear Network Measurement System

A simplified schematic of the instrument is shown in Fig. 1.

Fig. 1 Simplified schematic of the NNMS



The device-under-test (DUT) can be excited at both signal ports by periodic high-frequency signals (frequency range of present NNMS system is 600 MHz to 20 GHz). These signals are generated by adding microwave synthesizers, tuners,... For simplicity, the bias circuitry was omitted from the figure. All spectral components (fundamental as well as the harmonics) of the incident and scattered travelling voltage waves (defined in a characteristic impedance of 50 Ohm) are sensed by 4 couplers. The high-frequency signals are attenuated to an appropriate power level and are send to a broadband downconvertor. At the output one finds a low frequency copy of every spectral component (total intermediate frequency bandwidth is 4 MHz). The downconversion is based on an harmonic sampling principle (sampling rate close to 20 MHz). The resulting low frequency signals are digitized by 4 precision analog-to-digital convertors. A computer takes care of all the data processing and hardware control.

The time domain voltage and current waveforms can easily be calculated once all spectral components of incident and scattered voltage waves are known. Next to simple multiplication and addition in order to convert voltage waves into voltage and current, an inverse Fourier transform is used for conversion to the time domain.

Similar to other microwave measurement techniques, a calibration procedure is needed to get good accuracy. The calibration procedure used is a superset of the typical calibration procedures for classical linear network analysers. Two steps had to be added: correction of the absolute amplitude error and of the phase errors of the harmonic signals relative to the fundamental. The first is done by using a power sensor and by comparing the power meter read out with the amplitude as measured by the NNMS. The phase calibration is done by connecting a so-called reference generator (refgen) to the NNMS, and comparing the measured harmonic phases (relative to the fundamental) with the a priori known phases of the refgen. The harmonic phases of the refgen on their turn are determined by performing a "nose-to-nose" calibrated broadband oscilloscope measurement [12].

Conclusion

The NNMS allows to accurately measure the voltage and current waveforms as they appear at the signal ports of a microwave device under periodic excitation. The frequency range of the present prototype is 600 MHz up to 20 GHz. A special calibration procedure was developed.

MODELLING TECHNIQUES

Introduction

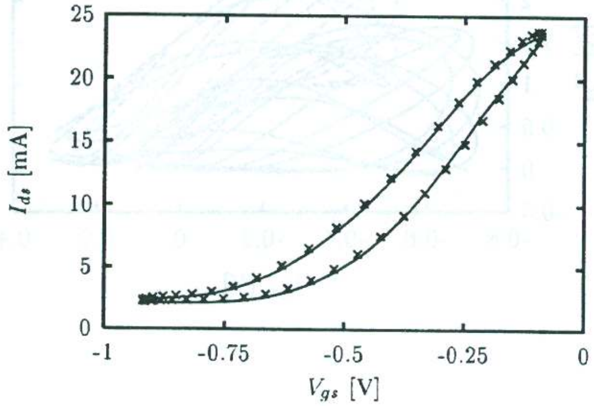
All classic large-signal models for microwave components are indirectly derived from small-signal s-parameter measurements, under swept or pulsed biasing conditions. Once the model is identified, it is used within a simulator to predict the behaviour of the component under high-frequency high-power excitation. It is not uncommon to find significant deviations between the simulation and the final performance of the design [1]. Without accurate high-frequency large-signal voltage and current measurements it is very hard to find out what is exactly wrong with the model. In the following approaches this problem is bypassed by directly deriving models from large-signal measurements. This implies that model verification and identification are happening within a coherent framework, assuring good consistency between modelled and actual component behaviour. In what follows is explained how this approach can be used with three different modelling techniques.

Empirical Models

First will be explained how the approach is applied to the so-called empirical models which are the most commonly used computer models for transistors [9]. They are represented by equivalent electrical circuits, containing non-linear controlled voltage or current sources, together with (linear or non-linear) parasitic resistors, inductors and capacitors. All non-linear elements are represented by empirical functions containing several so-called "model parameters". Dedicated procedures allow to extract the value of these parameters out of direct-current (DC) and small-signal s-parameter measurements.

In the new approach, the parameters are roughly estimated using the classical methods. Next, a set of NNMS experiments (changing bias and power levels) is performed and imported in the "HP Advanced Design System™" harmonic balance simulator. The optimization feature is used in order to tune the parameter values in order to find a minimum discrepancy between modelled and measured high-frequency large-signal data. The method was applied to a so-called "Chalmers model" [8] for an InP HEMT transistor. The final accuracy, after model optimization, is illustrated by Fig. 2. It shows one example of the measured and the modelled drain current versus gate voltage of a 0.2 µm x 100 µm GaAs PHEMT measured under the following conditions: gate-source voltage V_{gsDC}=-0.5V, drain-source voltage V_{dsDC}=1.5V, fundamental frequency f_0= 3.6 GHz, incident power = -3.4 dBm. The correspondence between model and measurement, after optimization is remarkably good.

Fig. 2 Measured (x) and modeled (-) drain current versus gate voltage



State-Function Models

One of the disadvantages of the empirical models is that the equivalent electrical circuit and the mathematical formula differ across different technologies (e.g. MESFET, PHEMT, HBT,...). Each time a novel technology is in development, a lot of work is needed in order to get a new empirical model. By the knowledge of the authors this problem was first solved by the development of the so-called "Root model" [10]. The idea is to use a generic simple deembedding procedure (one resistor and inductance at each port) and to describe the remaining behaviour (this is called the "intrinsic transistor model") by 2 non-linear circuits in parallel: a two-port current source and a two-port charge source which are both controlled by the two intrinsic terminal voltages (gate or base voltage and drain or collector voltage). From a mathematical point-of-view the intrinsic model can be written as:

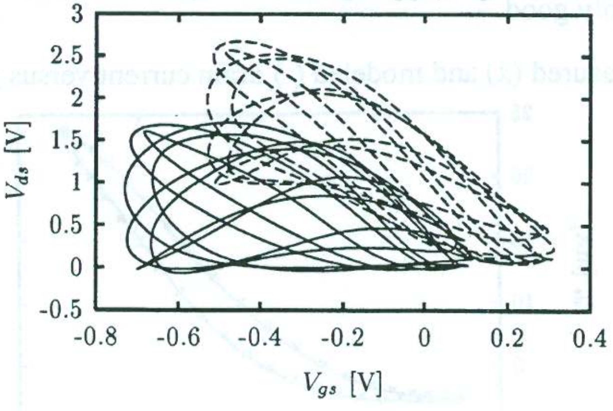
$$I_1 = K_1(V_1, V_2) + \frac{d}{dt}(L_1(V_1, V_2)) \tag{1}$$

$$I_2 = K_2(V_1, V_2) + \frac{d}{dt}(L_2(V_1, V_2)), \tag{2}$$

where V_1 and V_2 denote the intrinsic terminal voltages, and I_1 and I_2 the corresponding currents, K_1 and K_2 are non-linear current functions (unit is Ampere), and L_1 and L_2 are non-linear charge functions (unit is Coulomb). K_1, K_2, L_1 and L_2 are called the "state-functions". In the classical approach these functions are determined by integrating s-parameter measurements performed at a lot of biasing settings. Several problems are encountered with the integration and the fact that one can only measure under small signal excitation. Recently, large signal NNMS data was directly used for determining these state-functions. Artificial neural network technology was used to get a good and smooth fit between the measured and the fitted state-function values. The final accuracy can be compared with the results achieved by the empirical models. Note, however, that the method is completely technology independent.

A disadvantage of the approach is the non trivial experiment design. It is very important to apply a set of signals covering all of the useful (V_1, V_2) space. Good results are achieved by applying two-tone signals. In Fig. 3 two measured (V_1,V_2) traces are depicted. One can clearly see that a significant portion of the space is covered by the two 2-tone signals. For the experiment shown one tone is at 4.2 GHz and another tone at 4.8 GHz (this corresponds to a fundamental frequency of 600 MHz). The DUT is a HEMT transistor.

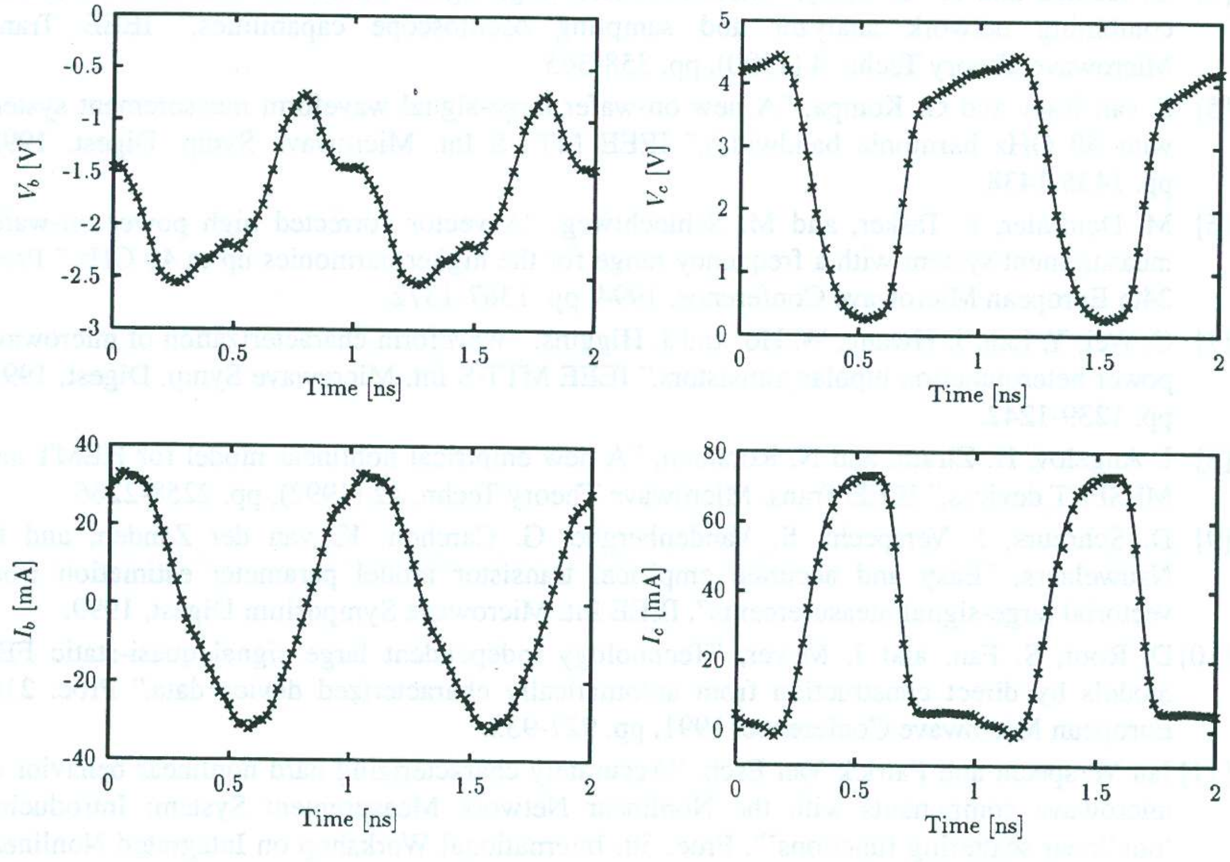
Fig. 3 State space coverage applying a 2-tone



Black-Box Frequency Domain Models

There are applications where the two previously described modelling methods fail. This is e.g. the case when it is difficult to apply an accurate deembedding (so one has not access to the intrinsic data), or when the component under test contains several transistors (e.g. a multi-stage amplifier), or when the component under test can no longer be considered as being lumped. If this is the case one can still apply application specific frequency domain black-box models [11]. Such a model is actually a set of functions which relate spectral input components with the spectral output components (these functions are called "describing functions"). The model is typically characterized at one particular fundamental frequency and is only valid for an excitation at the corresponding frequency. In order to perform the necessary experiment generation, the NNMS test-set is coupled to an harmonic load-pull set-up. The final model can predict the component behaviour under varying power, bias, fundamental and harmonic matching conditions. Effects modelled include harmonic generation, compression, AM-to-PM, non-linear input and output matching. As shown in [11] voltage and current waveforms are accurately predicted, within the valid bias and power range, and for the correct drive frequency.

Fig. 4 Comparison of measured (x) and simulated (-) time domain current and voltage waveforms at both ports of a bipolar RF power transistor



Conclusion

NNMS data is useful for the verification and identification of many large-signal non-linear microwave modelling techniques.

CONCLUSION

Recent advances in microwave large-signal measurement techniques allow to accurately measure the voltage and current waveforms as they occur at the transistor during its actual use. This information is essential for the extraction and verification of large-signal models.

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