Large Signal Characterization of Microwave Power Devices

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ABSTRACT — **This paper presents an overview of nonlinear measurement techniques of microwave power devices and amplifiers. Several useful measurement techniques of nonlinear components available in Europe are described. Trends, especially in the area of high power and time domain measurements, are discussed. Finally, a summary of the TARGET measurement related tasks is proposed, in order to show how TARGET can improve the European capabilities in terms of nonlinear measurements.**

I. Introduction

Today there exists an abundance of different measurement methods to characterize the nonlinear behavior of RF power semiconductor devices (transistors or solid state power amplifiers (SSPA)): DC or pulsed I(V), small-signal multi-bias S-parameters, large signal measurements, time domain slopes, load and source pulling techniques, single tone and multi-tone measures, intercept points, IM3 and IM5 inter-modulation. Why so many measurement methods are available and employed ? the answer is not simple, several kinds of explanations can be proposed :

1) many physical phenomena take place in active devices, and a good understanding and management of each phenomenon behavior require to separate each effect,
2) more and more frequently, RF power amplifier designers have to deal with the trade-off of power added efficiency and linearity,
3) new modulation techniques, like CDMA, induce variable envelope signals, the final bit rate error is affected by thermal effects and trapping effects, these effects, the so-called memory effects, usually neglected in the past but which are now to be considered more carefully,
4) the growth of telecommunication RFICs market reduces the commercial life of products, it can now be approximated to one year, so the first pass success of a design is a key factor for the manufacturer.

It clearly appears that the constraints applied to the RF designers are difficult to manage, and their rescue can come from accurate and relevant measurements (and thus reliable models !) of the employed transistors.

I. Classification Of Measurement Techniques

We can classify the nonlinear measurements versus the measurement stimuli, versus the acquisition method, or versus the environment of the device under test (DUT).

Basically, the signal used to drive the DUT can be :

- I(V)
- CW RF small signal
- CW RF large signal
- Dual-tone RF signal
- Multi-tone or modulated RF signal
- Each of these stimuli can be pulsed or not.

Several acquisition methods are employed :

- Voltmeter, Ammeter, thermometer
- Oscilloscope
- Power meter, detector
- RF couplers and mixers
- RF couplers and samplers
- RF High Z probes.

DUTs can be connected in many systems or set-ups :

- RF on-wafer probing system
- Test fixtures, device bounded on alumina
- 50 Ohms or variable source and load impedance
- Thermo-chuck or no temperature control.

If we perform a world tour of laboratories, may we can find all the combinations of these 3 (non-exhaustive) lists. It nearly means each lab makes its “own” measurements ; there exist no common standards beyond good practice. But we can exhibit some major tendencies or choices.

II. Major Measurement Techniques of Nonlinear Devices

Pulsed I(V) and pulsed small-signal S-parameters have proven their efficiency to obtain good equivalent-scheme large signal models of transistors, including nonlinear capacitances [1]. The I(V) acquisition is usually based on an oscilloscope. Pulsed I(V) set-ups offer a very convenient way to avoid or to manage the device temperature and self-heating, moreover if a thermo-chuck is employed. The trapping effects are easy to detect and to characterize with pulsed I(V). In other words, pulsing the signal at the device terminals is a good way to exhibit low frequency memory effects and frequency dispersion of nonlinear functions. These pulsed set-ups are now very popular, a commercial solution is available in Europe for pulsed I(V). In order to acquire multi-bias pulsed S-parameters and to characterize nonlinear capacitances and non quasi-static effects, a vector network analyzer (VNA) with a receiver mode (including an IF synthesizer) is required, because the IF source cannot be easily synchronized by a pulsed RF signal.

Load-pull and source-pull systems are very popular too. But many very different set-ups can be found : early systems are based on mechanical tuners and power meters or detectors. Some more sophisticated benches take benefits of active loops in order to achieve very high reflection coefficients. Moreover, one can use several tuners or multi-stage tuners or several active loops to adapt the device at harmonic frequencies. Finally, the data acquisition performed with power meters can be replaced by a VNA, or by a VNA with receiver capabilities in order to perform measurements at harmonic frequencies [2]. A better and more recent solution is to use a Large Signal Network Analyzer (LSNA) or a Microwave Transition Analyzer, in order to achieve time domain waveforms, i.e. the load cycle of the DUT [3]. In other words, several basic acquisition techniques are used here : power meters, mixers (recent VNAs are based on mixers), samplers (MTA, LSNA are based on samplers).

Some very easy to use motorized tuners with multi-harmonic tuning capabilities are now commercially available, and a complete passive load-pull + LSNA integrated system is also commercially available. A European company proposes to quickly improve power-meter based old motorized load-pull systems to a VNA-based system with dedicated software.

The load-pull set-ups family has been extended in many more or less exotic directions. We can notice some benches with low-frequency impedances taken into account [4]; some benches handle pulsed signal [5]; some benches allow some modulation of the signal around the carrier; last but not least one can study in a load-pull environment the effect of a large signal pumping a small signal [6] or the response to multi-tone stimulus.

The great interest of the load-pull techniques is to provide a realistic and tunable impedance environment for the DUT. For that reason, all the improvements added to these set-ups go in two directions : on one hand, get more information on what appends at the DUT terminals. This is the evolution from the power meters to VNAs and now to LSNAs (or MTAs with switches). On the other hand, the test signal can be improved to provide more information on the DUT or to handle higher power levels : from CW to modulated or pulsed signals. The super-imposition of 2 tones with a large signal pumping a small signal is maybe an ultimate step, it can allow to detect instable modes in active devices. Another use of a two-tones signal within a load-pull system is to measure the intermode levels IM3 and IM5, in order to get a figure of merit of the device linearity.

S-parameters have shown their limits with load-pull systems, AM to AM and AM to PM characteristics have also shown their interest but their limitations too. The new theory of “Hot S-Parameters” goes beyond S-parameters, offering a way to represent in frequency domain the nonlinear behavior of devices [7]. But the time-domain techniques with I(V) slopes are usually the most suitable way to represent accurately what is going on at the terminals of a nonlinear device. One can notice that the calibration of these improved load-pull time domain systems is very complicated, using classical standards (TRL, LRM, SOLT…) in combination with an absolute amplitude standard and a phase standard [8]. Moreover, for on-wafer measurements, reciprocity properties are useful because some standards are not available at the probes terminals. The software effort required to build an automated test solution is large, but this is a key point.

The load-pull measurements were initially and are still used to tune the optimal impedances of devices, but they are now often used to verify the nonlinear models of transistors. Moreover, when a LSNA is available in conjunction with a modulated signal, the data provided are easy to integrate in order to build a Volterra or behavioral frequency domain model [9].

New modulation techniques (CDMA, X-QAM) strongly depend on the linearity of the power amplifier. Thus, some benches have been developed to address some new criteria or figure of merit at the circuit or system level : the Noise Power Ratio (NPR) [10] and the Adjacent Channel Power Ratio (ACPR) for example. One of the key equipment of such modern set-ups is an Arbitrary Wave Generator (AWG) in combination with a RF modulator (I-Q) or a RF synthesizer with extended modulation capabilities (direct modulation from a data flow provided by a PC). Thus some specific RF signals can be easily generated, like multi-sine signals with a notch for NPR, or many kinds of modulated signals with arbitrary properties and peak-to-average ratio or statistics. The measurement system of such benches can be either based on sampler technology, or be performed by an oscilloscope after a demodulator (I-Q) stage[11].

High impedance RF probes are another way to investigate deeply inside a circuit, for example a power amplifier. This is very useful for debugging purposes : look for an unstable behavior, see the inter-stage signal, verify the cycle of all transistors of a distributed amplifier…[12] Classically, a fast sampling oscilloscope is employed, but its calibration procedure is not accurate enough. Another approach consists of using the LSNA as a receiver. All samples are rigorously taken simultaneously and a complete calibration procedure is available, so with 2 probes on the same line one can plot I(V) time domain slopes everywhere in the circuit under test [13]

The temperature strongly affects the semiconductor devices. Moreover, the temperature of amplifiers can be modulated by the varying signal envelope, in particular in the case of large peak-to-average ratios or pulsed signals. Due to the fact that the amplifier output depends on the temperature, the amplifier linearity is affected by the statistics of the signal envelope. So, there is a request for the known of the “inner” temperature distribution of the transistors under operating conditions. Simulations can show the flows and time constants of the temperature inside a device when the signal envelope varies, with differences between the external and middle fingers temperature of transistors. Measurement techniques of these parameters are still very complicated and expensive (they can be based on optical analysis of Raman spectroscopy), they are available with a time resolution close to 1 ns and a space resolution of 1 µm [14].

Other nonlinear measurement techniques can be mentioned here, like the problem of non-reciprocical frequency converter devices measurement. Some special benches are built so address the special needs, like a 6-port LSNA dedicated to mixer characterization [15].

Finally, integrate the transistor measurements into the simulation now begin to be possible [16] : the types of signals used in the applications can drive characterizations. A simulation CAD tool could apply a computed signal to a real DUT with a dedicated set-up, and get back the measurement results in order to continue the simulation.

III. Trends in Measurements of Nonlinear Devices

Obviously, we can say that better, faster, cheaper is the tendency. More seriously, we can notice a large increase of interest for nonlinear measurement techniques in the microwave community. A few years ago, an experienced RF designer with the S-parameters measurements of his transistors and some "rules of thumb" was able to design good amplifiers. This time as gone, the mass market requests, the increased complexity of devices, the new modulations, the specifications to fulfill now imply a full nonlinear approach. The tendency is to dispose of more and more information and details about the active DUT, in order to address all the problems (power efficiency, gain, linearity, stability, reliability, thermal range, load mismatch handling capabilities (antenna) …).

The key point we can notice is : fast sampling techniques are the foundation for the characterization of the nonlinear behavior of high frequency active components. Unfortunately, analogue to digital converters do not exist yet today to make single shot measurements of microwave electrical signals. Sampling technology is the key to compress the frequency content before digitizing the signals. Sampling is crucial to maintain signal coherence in contrast to mixing. Sampling a periodical signal allows to get all the information on this signal, it operates like a stroboscope. The problem now is the availability of fast RF samplers, only a very few product are on the shelf. Moreover, these products are more dedicated to oscilloscopes, because the triggering circuitry, based on a nonlinear line, is usually embedded with each sampler. So it is difficult to have a network measure with 4 samplers simultaneously activated. The LSNA calibration theory requires all the samplers are accurately simultaneously activated (precision close to a few ps [10]).

The increasing request for high performance, reliability, short time development and growing circuit/subsystem complexity pushes the needs for different characterization/modeling approaches providing the right compromise between complexity and accuracy.

The microwave power devices community is more and more convinced of the need of many nonlinear meaningful characterizations. The measurement system companies now understand there are still methods lacking or in their infancy in their product list for measuring nonlinear parameters. But, most of them still think "the market is not here". We can imagine that some of them (and maybe the largest ones), focused on multi-port fast S-parameters measurements, will miss the train of nonlinear characterizations.

IV. Status of Nonlinear Measurements in Europe, the TARGET Opportunity

European researchers have made important contributions to the development of novel measurement methods in the area of nonlinear devices. A deep discrepancy exists between the expertise of Europe and the USA concerning the characterization of the nonlinear or large signal behavior of power devices. Most of the leading laboratories in the domain of nonlinear measurements (especially time domain measurements based on LSNA or MTA), are located in Europe (ESAT-TELEMIC Leuven, Cardiff University, IAF Freiburg, ELEC/VUB Brussels, Stuttgart University, IRCOM University of Limoges, MIDRA University of Firenze, TUW-EMST Wienna, NMDG Tech. …).

Most measurement equipment and almost all measurement software are produced in the U.S. The deplorable lack of European measurement hardware is the challenge for the TARGET CLASSIC B task force that strives at establishing a technology development plan for a microwave front-end sampler.

In many European microwave labs, highly specialized characterization resources exist for the measurement of the nonlinear behavior of microwave components, devices, circuits, and systems. The TARGET LAB work package aim at the creation of a common virtual lab infrastructure. The setup of TARGET LAB will provide the partners with highly specialized measurement systems adapted for shared use. This approach includes the definition of common "standards" for measurements and for the documentation of the results. The publication of sets of reference measurement data via TARGET INTRANET will enable network partners to compare their own results with the "standards".

TARGET LAB is one of the key elements for the building of an efficient and lasting network of excellence. It is the appropriate answer to the objective of the European Commission to strengthen scientific and technological excellence by integrating at European level the critical mass of resources and expertise. TARGET LAB has the potential to become a source of income for the network thus contributing to the durable integration of research capacities of the network partners. Already now strong industrial interest exists – even from associate TARGET members – for measurement services.

VI. Conclusion

Nonlinear comprehensive characterization of RF power devices is a key point for optimized and efficient designs. Many measurement techniques are available in many places, but the tendency is to go to large signal time domain waveforms with the tuning of impedances, because this approach provides the most realistic information.

Since many years, European research labs have a leading position worldwide in terms of nonlinear measurement and modeling. But all the measurement equipments and parts we can buy to build our innovative measurement systems come from the USA. So, a co-ordinate European effort would ensure a world lead in nonlinear and time domain measurement area, both technically and commercially.

The TARGET Network Of Excellence improves the communication between European researchers and laboratories, many very good contacts have already been taken between research teams within TARGET opportunities.

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