Novel Hardware and Software Solutions for a Complete Linear and Nonlinear Microwave Device Characterization

Andrea Ferrero, *Member, IEEE*, Ferdinando Sanpietro, Umberto Pisani, and Claudio Beccari

***Abstract*—While S-parameter test sets are well suited for linear active device characterization, many problems are still unsolved for a complete large-signal characterization. In this paper a test set, which performs measurements of S-parameter and load-pull characteristics at the fundamental and harmonic frequencies, is used to produce a set of data (constant gain, constant output power, efficiency, and so on), which completely describes the linear and nonlinear transistor behavior. The goal is reached by means of a special design of the test set which quickly makes the measurements with a particular tracking algorithm for load-pull contours. The high speed and the accuracy that can be achieved make the test set particularly useful for production testing of microwave active devices and for power amplifier design.**

I. Introduction

FAST and extensive RF characterizations are mandatory for active device development and manufacturing. While S-parameter test sets are well established in linear characterization, no user-friendly, fast, and reliable test set is available for nonlinear characterization. In this field load-pull approaches used to be employed mainly for power amplifier design under defined operating conditions. Both the heavy experimental procedures and the inaccurate data made these techniques unable to complete an overall device characterization. In order to improve the measurement speed, [1] proposed an automatic test set based on motorized passive tuners and on an automatic curve-tracking algorithm, based on a previously characterized load model.

Passive tuning structures are unsuitable, especially for on-wafer device measurements, where the loss introduced between the tuning sections and the device prevents setting high reflection coefficients. Furthermore, if the load is not measured, but is set according to a model, the system accuracy can decrease with respect to a real-time measurement of the load. These problems can be avoided by using active load techniques, first introduced in [3], and recently implemented in automatic test-sets [4]–[6] based on the HP8510 network analyzer and a voltage-controlled active load. The lastest evolution of these test sets, which integrate both the S-parameter and the load-pull measurements, is presented here. The system hardware and software are optimized in order to reach very fast acquisition of the data, so that it can be effectively used for an overall device characterization.

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This paper describes all the details and the mathematical tools used to improve the test-set performances. Besides the S-parameters, the system monitors the large-signal device performances useful for power device development and circuit design, including output power levels at harmonic frequencies, input power, frequency, and bias conditions as functions of the load. For example, if the performance of interest is the device power gain, the system software can automatically draw constant gain contours versus load.

A complete characterization of one device performance can be accomplished in a few minutes thanks to the special attention devoted to speed up the data acquisition and the contour-tracking process. Harmonic power levels are measured in real time and harmonic loads [7]–[9] can be added to the test set by an external connection, so that the system capabilities can be extended to the harmonic load-pull characterization.

In Section II we describe the system hardware; then in Section III we discuss the algorithm for automatic curve tracking; in Section IV we present a procedure describing each transistor performance by means of a 3-dimensional function which fits the experimental data; finally, in Section V we report some experimental results.

II. Hardware Description

The block diagram of the test set is represented in Fig. 1. It is mounted on a 6-in rack module and is connected with the HP8510/HP8511 ANA, which measures S-parameters, power levels, gains, and harmonic frequencies up to 26 GHz.

The module, included in the dashed box shown in Fig. 1, has RF switches for the S-parameters or the load-pull system configuration. When S-parameters are measured, the "port 1-2" switch connects the RF source to port 1 or port 2, respectively. An active load controlled by two voltages is included in the test set, and it is automatically connected when load-pull measurements have to be carried out. An external amplifier can be added at port 1 to increase the input power level with respect to the one provided by the HP8340 synthesizer. When higher power levels are required, a boost amplifier can be used so as to substitute the jumper in the active load loop in order to reach high reflection coefficients. The test set also includes an electronically controlled input attenuator, the bias tees, and all the control circuits.

To avoid cable losses, which reduce the equivalent reflectometer directivity, the dual input and output directional couplers are left out of the box in order to be put as close

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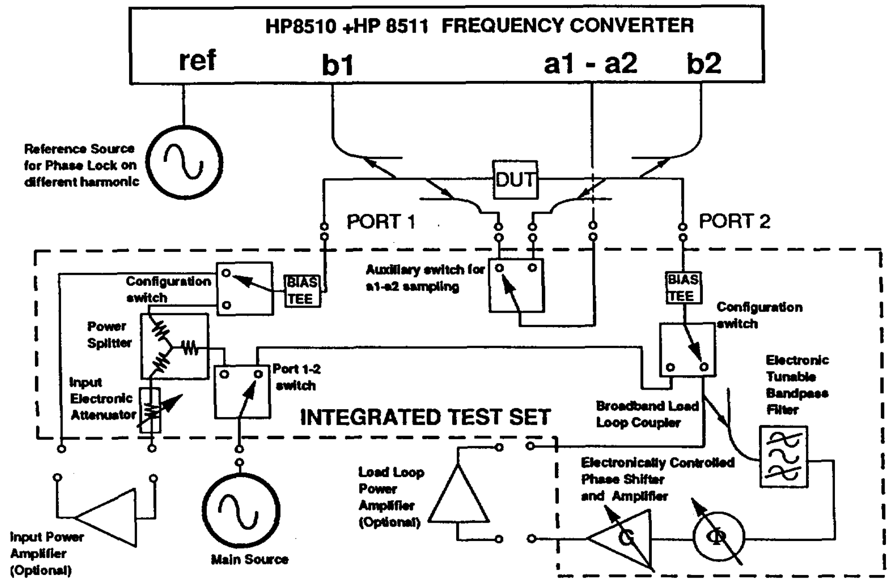

Fig. 1. Test-set block diagram.

as possible to the DUT. An HP8511 frequency converter is used to sample the coupled waves and to link the test set to the HP8510. The network analyzer samplers are used both for vector ratio measurements and for frequency-selective power measurements. With an extra synthesizer, aimed to lock the HP8511 to the harmonic frequencies [7], the test-set capabilities are extended to harmonic measurements.

The new main features of the test-set are the following:

1) The system integrates an active load, which can be electronically controlled and quickly set to reach high speed in load-pull contour tracking. For each load the ANA automatically acquires all the interesting RF parameters at the device ports (i.e., input and load reflection coefficients, gain, power levels, $\cdots$) in real time; dc bias voltages and currents are also acquired.

While keeping constant the available input power level and frequency, over 2000 different loads are set, and the corresponding parameters are acquired in less than 2 min.

2) While keeping constant a selected load, the test set can drive the DUT with fast input power sweeps for gain compression and harmonic measurements. In this working mode, 51 different input power levels are set, and all the device parameters are measured in less than 3 s.

3) A special feedback search algorithm tracks a defined objective function by varying the load, so that the constant function contour is automatically tracked on the Smith chart.

A single broadband calibration is performed for both linear and nonlinear measurements. The technique links a usual LRM [11] or SOLT [10] algorithm (devoted to S-parameters) to the special-purpose power calibration algorithm presented in [12] for load-pull and harmonic power measurements. Besides a usual set of broadband S-parameters for linear characterization, in the load-pull mode the following transistor parameters are measured for each

1) the input reflection coefficient,
2) the load reflection coefficient,
3) the power delivered into the load,
4) the available input power,
5) the net input power,
6) the actual compression level,
7) the transistor bias point.

Furthermore, when harmonic measurements are required, the output power at each interesting harmonic frequency (up to 26 GHz) is acquired with only a small reduction in the overall test-set speed.

III. The Tracking Algorithm

The load-pull characterization of a particular device performance is generally achieved by varying the load so as to obtain the desired target value. This way it is possible to get a set of points on the Smith chart that is the locus of loads which keep constant the desired device performance.

The algorithm described in this section is a tool which automatically tracks load-pull loci by electronically driving the active load. The main purpose of the algorithm is to optimize the tracking procedure in order to reduce the number of measures in each contour, together with the global time needed for the overall device characterization.

The starting point is to consider the target device parameter (i.e., output power, or gain or efficiency and so on) as a real function W of the complex variable Γ_L. The load-pull loci are the contours of the function $W(\Gamma_L)$ in the Γ_L plane. The solutions proposed by other authors [13] is to get many random measures in the whole Smith chart and then to fit the acquired points by a proper function. The drawback of this technique is the large number of experimental points required, while the

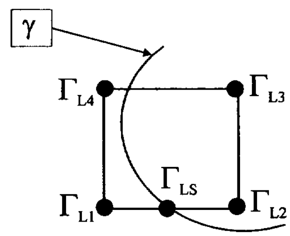

Fig. 2. Building process of the first cell.

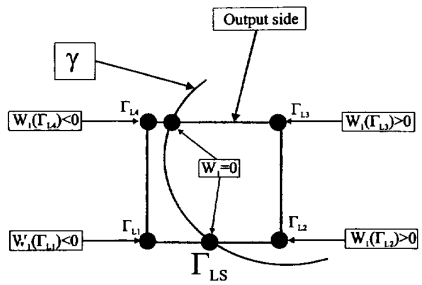

Fig. 3. Process for obtaining the exit side.

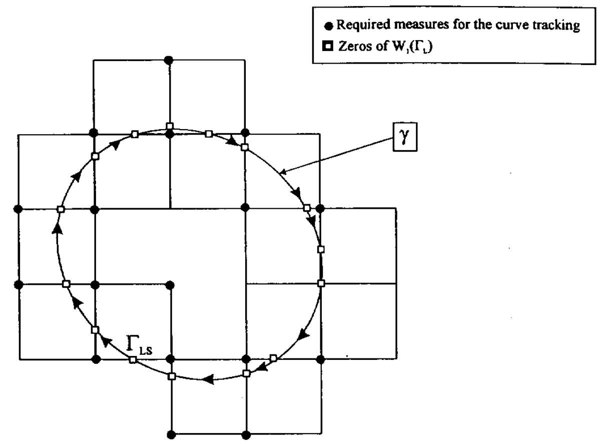

Fig. 4. Actual tracking; the cells that have been sequentially built are explicitly shown.

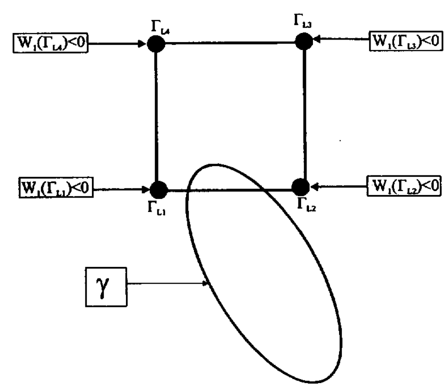

Fig. 5. Sign distribution.

tracking algorithm reduces it with a proper choice of the Γ_L points.

In order to identify all the points of the specific contour W_0 of $W(\Gamma_L)$ which represents a particular device performance (i.e., $W(\Gamma_L)$ can represent the relationship P_{out} versus Γ_L and $W_0 = 24$ dBm), we define the contour as

$$\gamma = \{\Gamma_L \in \boldsymbol{D} : W(\Gamma_L) - W_0 = 0\} \tag{1}$$

where $\boldsymbol{D}$ is the set of all Γ_L values $|\Gamma_L| \leq 1$.

If we let

$$W_1(\Gamma_L) = W(\Gamma_L) - W_0 \tag{2}$$

the desired contour is the locus where $W_1(\Gamma_L) = 0$. So the solution is based on the determination of the zeros of a two-dimensional function which is unknown since it is device dependent, but it is assumed to be continuous in $\boldsymbol{D}$ and to have only one absolute maximum in this domain [14].

If we suppose to know at least one zero Γ_{Ls} of W_1, we can build a pseudosquare cell where Γ_{Ls} is located on one side, as shown in Fig. 2. This is easily accomplished by stepping both the driving voltages of the active load. The continuity property of W_1 in the domain guarantees that, if the curve γ enters the cell, it will necessarily leave it. The curve γ divides $\boldsymbol{D}$ into two parts: the first one is characterized by a positive value of the function W_1, while the second one by a negative value. In these conditions, the exit side is easily identified by looking at the sign of the unknown function measured in the cell vertices: the exit is found on the side where W_1 has another zero, as shown in Fig. 3.

In the next step a new cell on this exit side is to be built. At this point, finding the new exit side could require only one new measurement, since 2 of the 4 vertices are already known from the previous step. The procedure continues by building new cells until the curve is completely determined (see Fig. 4).

The tracking of the curve stops when a defined number of points is acquired for each contour, or when the difference between the last point and the first one is less than a fixed tolerance.

The length of the cells is changed during the tracking in two different cases: the first one is when one or more square vertices go outside the Smith chart, and the second one is when the curve goes out from the same side it entered. It is possible to determine this case by examining the sign distributions as illustrated in Fig. 5. In both cases it is sufficient to reduce the cell side (by decreasing the controlling voltage steps) in order to continue the curve tracking.

In order to evaluate the zero of W_1 along the side of the cell, it is possible to apply a numerical algorithm to search for the zeros of a function in one variable. In fact the exit side of a single cell, identified by its vertices Γ_L^- and Γ_L^+, satisfies the following parametric equation:

$$\Gamma_L = \Gamma_L^- + \eta(\Gamma_L^+ - \Gamma_L^-) \tag{3}$$

with $0 \leq \eta \leq 1$.

The solution corresponds to the η value which annihilates the single-variable function:

$$g(\eta) = W_1[\Gamma_L^- + \eta(\Gamma_L^+ - \Gamma_L^-)].$$

This solution can be numerically evaluated by the classical secant method on the basis of the measured W_1.

To complete the description of this procedure, it remains to evaluate the tracking starting point. To find Γ_{Ls}, it is necessary to know two points, one inside and the other outside the region bounded by the curve γ.

Such points define a segment in the Γ_L plane which is crossed by the target curve γ, so that the starting point can be evaluated by applying the secant technique between them. The initial segment can be identified as follows.

Let's start from a point Γ_{L0} such that

$$W(\Gamma_{L0}) < W_0$$

where W_0 specifies the contour to be followed. A classical numerical optimization technique is used to find a point Γ_{Lx} such that

$$W(\Gamma_{Lx}) \geq W_0.$$

The starting point Γ_{Ls} can be found by applying the iterative secant process to the segment that joins Γ_{L0} and Γ_{Lx}.

The optimization algorithm explores W around Γ_{L0} in order to identify the direction in which the function increases. This is done by exploring two different directions, defined by

$$\vec{d}_1 = \pm\delta\vec{x} \tag{4}$$
$$\vec{d}_2 = \pm\delta\vec{y} \tag{5}$$

where δ is a real constant, and by measuring W corresponding to the loads

$$\Gamma_{L1} = \Gamma_{L0} \pm \delta\vec{x} \tag{6}$$
$$\Gamma_{L2} = \Gamma_{L1} \pm \delta\vec{y}. \tag{7}$$

If we suppose that

$$\begin{aligned} W(\Gamma_{L1}) &> W(\Gamma_{L0}) \\ W(\Gamma_{L2}) &> W(\Gamma_{L1}) \end{aligned} \tag{8}$$

the new directions can be found by

$$\vec{d}_{1,\text{new}} = \frac{\Gamma_{L2} - \Gamma_{L0}}{|\Gamma_{L2} - \Gamma_{L0}|}. \tag{9}$$

If $W(\Gamma_{L1}) - W(\Gamma_{L0}) \geq W(\Gamma_{L2}) - W(\Gamma_{L1})$ then

$$\vec{d}_{2,\text{new}} = \frac{\Gamma_{L1} - \Gamma_{L0}}{|\Gamma_{L1} - \Gamma_{L0}|} \tag{10}$$

else

$$\vec{d}_{2,\text{new}} = \frac{\Gamma_{L2} - \Gamma_{L1}}{|\Gamma_{L2} - \Gamma_{L1}|}. \tag{11}$$

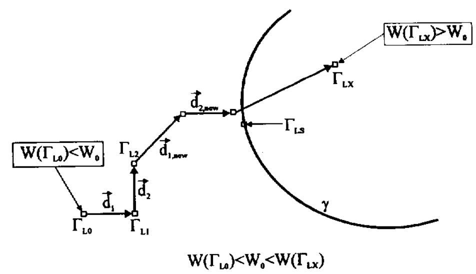

Fig. 6. Starting-point search: Γ_{Ls} is found by the secant method applied between Γ_{Lx} and Γ_{L0}.

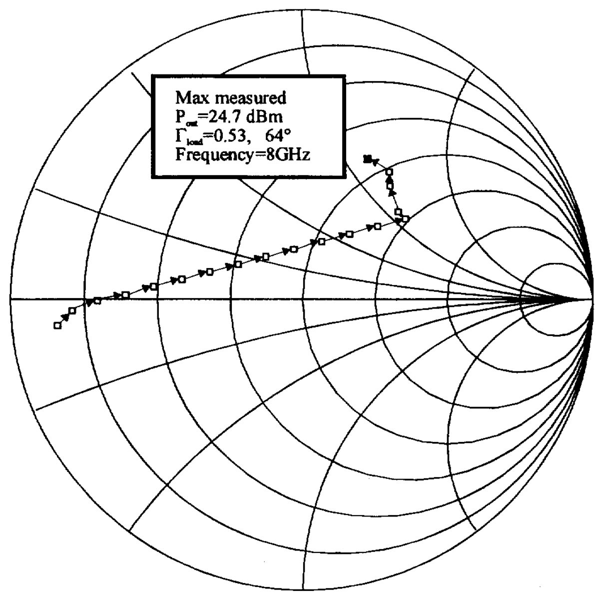

Fig. 7. Search for the output power maximum of a 600-μm MESFET: Example of a path in the Γ_L plane.

This process can be repeated for the point Γ_{L2} with the new computed directions, until finding the Γ_{Lx} load

$$W(\Gamma_{L0}) < W_0 \leq W(\Gamma_{Lx}). \tag{12}$$

Fig. 6 shows how this process works. If one or both of the explorations fail, it is possible to repeat the procedure with a smaller δ; in this case the initial directions are reset.

If for the initial load we have $W(\Gamma_{L0}) > W_0$, the method can be applied as described by changing the function sign. This algorithm can be effectively used to search for the absolute maximum of the performance $W(\Gamma_L)$ of the device under test.

Fig. 7 shows an example of the load path followed by the algorithm to search for the maximum of a particular transistor performance. It can be noted that the described algorithm does not require any load precharacterization or any load model, because both methods for finding the maximum and for

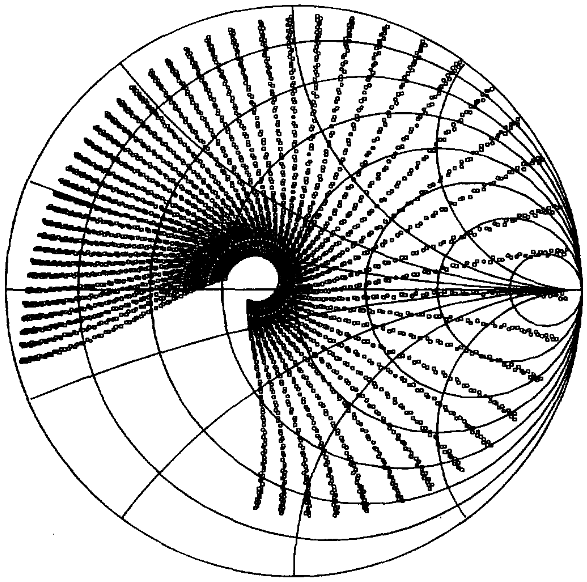

Fig. 8. 3500-point random load mapping; measuring time 210 s.

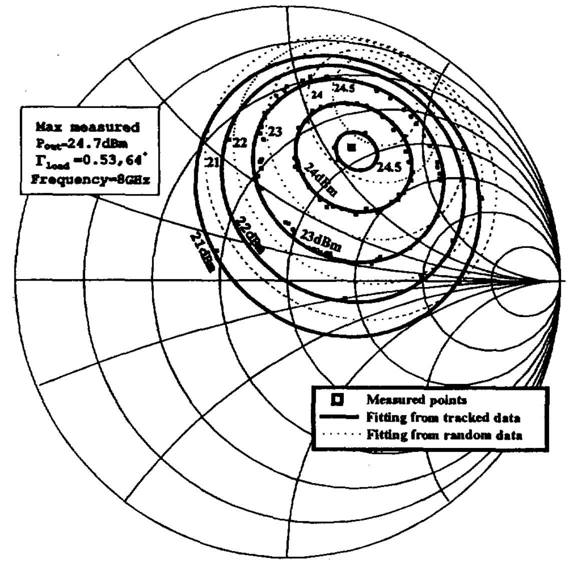

Fig. 9. Comparison between fitted output power contours obtained by tracking 23 and 24 dBm curves and contours obtained by fitting random data points.

tracking the general contour are independent from the variables and their domain of definition.

In practice the active load is controlled by two voltages V_1 and V_2, and it can be seen as a black box characterized by such two driving voltages. Each load is obtained by setting that two voltages and measuring the load presented at the DUT reference planes in real time. The algorithm acts on the V_1 and V_2 plane, and the relationship between these voltages and the corresponding loads can be general and unknown.

IV. 3-Dimensional Fitting Algorithm

A 3-dimensional fitting procedure can also be applied to the data obtained with the tracking algorithm previously described. This fitting procedure has been proved to give very accurate prediction of the device performance by using a few well-suited data points obtained from the contours previously tracked.

The chosen fitting function is suitable for the description of several typical device characteristics as they vary with Γ_L and can be identified with a small number of experimental data points. On the contrary a large number of points are required by the fitting techniques based on random points.

In order to fit the whole set of curves, we use a 3-dimensional surface satisfying an equation of the form:

$$\begin{aligned} W =& \alpha_1(W)x^2 + \alpha_2(W)y^2 + \alpha_3(W)xy \\ &+ \alpha_4(W)x + \alpha_5(W)y + \alpha_6 \end{aligned} \tag{13}$$

where the coefficients α_i are functions of the device performance W and $\Gamma_L = x + jy$.

If the coefficients α_i are linear functions of W it is possible to invert (13) and compute the performance W directly as a function of the load. With the linear assumption, (13) becomes

$$\begin{aligned} W =& h(x, y, W) \\ =& (a_1W + a_2)x^2 + (a_3W + a_4)y^2 + (a_5W + a_6)xy \\ &+ (a_7W + a_8)x + (a_9W + a_{10})y + a_{11} \end{aligned} \tag{14}$$

or

$$W = \frac{a_2x^2 + a_4y^2 + a_6xy + a_8x + a_{10}y + a_{11}}{1 - a_1x^2 - a_3y^2 - a_5xy - a_7x - a_9y}. \tag{15}$$

The main property of such surface is that the constant performance contours are conic sections, that is, hyperbolas, ellipses, and parabolas, depending on the coefficients a_i and on the performance W, and are suitable for fitting several nonlinear device performances, i.e., gain, intermodulation, output power, and so on.

The a_i coefficients are determined by applying the classical least squares method (LSM) to a proper set of experimental data points. Since the shape of some load-pull contours (i.e., output power curves) may be critical, especially close to the boundary region of the Smith chart, the use of random data may cause inconsistent solutions, as is shown in the next section. On the contrary, if the data to be fitted are taken from two or three complete contours obtained by the tracking procedure, the LSM gives good results even if few experimental data points are used. The designed software integrates the tracking and 3D-fitting algorithm, selects the proper set of measures, and defines the final load-pull paraboloid or the whole set of contours on the Smith chart.

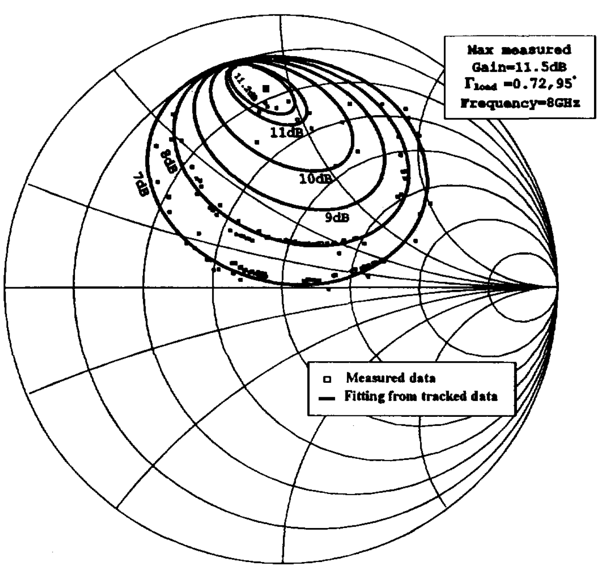

Fig. 10. Fitted power-gain contours obtained by tracking the curves at 7 and 8 dB.

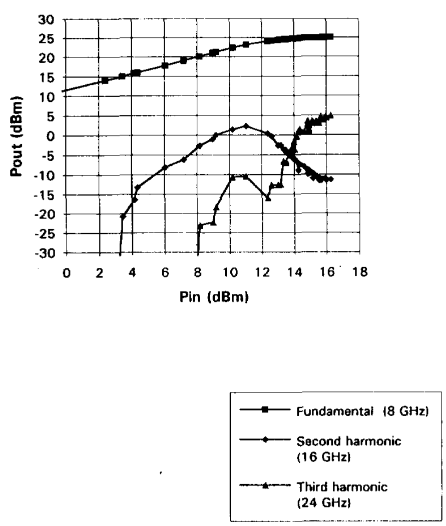

Fig. 11. Output power levels at the fundamental and harmonic frequencies versus input power while the load is kept at the optimum value.

V. Experimental Results

The system capabilities have been evaluated by a complete small- and large-signal (load-pull and harmonics) characterization of a 600-μm MESFET produced by ALCATEL/TELETTRA. Fig. 8 illustrates about 3500 random loads set at the DUT. The available input power was fixed and all the device performance data were acquired at each load in a total time of 210 s.

Fig. 9 shows two different sets of fitted equal-level out-put power load-pull contours. The dashed curves have been drawn by fitting the data corresponding to the random loads of Fig. 8, while the other contours (i.e., continuous lines) represent the loci that fit just two curves obtained by tracking the measured output power (total time for the tracking process: 60 s). It shall be noted that, unlike the dashed ones, the continuous curves also fit well some experimental data outside the tracked ones. Furthermore, the prediction of the maximum output power from the random data is far away from the measured one, which on the opposite is very close to the one that can be predicted with the tracked data.

In Fig. 10 we use the same device to illustrate the contours obtained by tracking the measured power gain. Only two tracked curves are used for the whole fitting procedure. Finally a set of measurements is carried out while keeping constant the load corresponding to the maximum output power, and the output levels at the fundamental, the second, and the third harmonic frequencies are measured by sweeping the input power (total measurement time: 150 s). In this measurement the device was loaded with 50 Ω at the harmonic frequencies. Fig. 11 shows these results.

VI. Conclusion

A new system for fast linear and nonlinear device characterization has been presented. The system offers a good alternative with respect to the usual ones based on multiple test sets (i.e., one for S-parameters, one for load-pull and harmonics).

The high speed and the integration with powerful algorithms for load-pull tracking have been described and illustrated. The modeling of a particular transistor performance by means of a 3-dimensional function, obtained by fitting experimental load-pull results, appears to be a successful approach. The model is obtained in a very short time thanks to the HW/SW design of the test set, and the particular approach of the curve-tracking process. The effectiveness of the test set offers a new alternative to the device manufacturers for describing overall linear and nonlinear device performances, which can be applied in a production environment.

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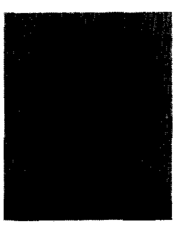

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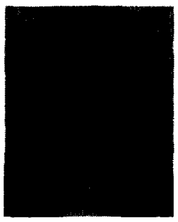

Ferdinando Sanpietro was born in Torino, Italy, in 1961. He received the electronic engineering degree in 1989 from the Politecnico di Torino. Currently, he is a candidate for the Ph.D. degree in electronic engineering at the Politecnico of Torino.

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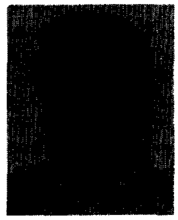
Umberto Pisani was born in Sora, Italy, in 1943. He received the electronic engineering degree from the Politecnico of Torino in 1967.

In 1982 he became Associate Professor and in 1989 Full Professor in Electronics. He has conducted research in the area of active and passive device characterization and modeling, mainly of microwaves. He is presently interested in the MMIC device on-wafer characterization and measurements.



Claudio Beccari was born in Bologna, Italy, in 1940. He received the electronics engineering degree in 1963 and the libera docenza degree in 1971.

He became an Associate Professor at the Politecnico di Torino in 1963 and has been teaching courses in electric circuit theory or synthesis and in microwave circuit design since 1971. He has been a tenured Professor of Electronic Circuit Theory since 1980. His main research fields are in the synthesis of lumped and distributed circuits, optimization algorithms, computer-aided circuit design, broadband matching, and equalization.