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Automated Microwave Device Characterization Set-Up Based on a Technology-Independent Generalized Bias System

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Abstract *– In this paper an automated laboratory set-up for the characterization of micro- and millimeter-wave electron devices under DC, small- and large-signal operation is described, which is based on a generalized, technology-independent bias system. The biasing parameters adopted, which are a linear combination between currents and voltages at the device ports, allow for a complete characterization of the desired empirical data (e.g. multi-frequency S-matrix) throughout all the regions in which the quiescent operation of the device can be conventionally divided, without any need for the switch between different biasing strategies. The look-up tables of experimental data obtained, which are carried out homogeneously with respect to the same couple of bias parameters, independently of the quiescent regions investigated, are particularly suitable for the characterization of empirical non-linear dynamic models for the electron device.*

I. INTRODUCTION

The computer-aided design of non-linear circuits (power amplifiers, oscillators, mixers, etc.) for modern communication systems can be successfully performed only when accurate non-linear dynamic models are available for the active electron devices involved. In the effort of making the task of circuit designers easier, most of the foundries which carry out the fabrication of micro- and millimeter-wave monolithic circuits also provide electrical models of the non-linear devices available within their technologies. Unfortunately, while these models present satisfactory overall capabilities of predicting the device behavior when their figures of merit are averaged on large sets of general-purpose operating conditions, the performance can strongly decrease in the presence of the need for high accuracy under specific operations and application-oriented regimes.

For these reasons, in the last years circuit design centers have been increasing the demand for highly accurate, reliable models to the research groups active in this field, which can offer laboratory resources for the in-house experimental characterization of microwave devices. In this context, the experimental set-ups and the measurement techniques exploited in order to obtain the empirical data, on which the model parameter extraction procedures are based on, can be quite different from those oriented to a general-purpose characterization of the device, and they vary according to the specific modeling approach followed. Among all, device steady-state and/or pulsed I/V characteristics, multi-frequency bias-varying *S*-parameters, large-signal load-pull maps are the most investigated empirical data (see [1]-[3] for examples of some refined techniques). In most of the cases, empirical information is required within all the possible regions in which the quiescent operation of the device can be classified, and the choice of the most suitable controlling electrical quantities for each region becomes essential for the definition of the bias system and strategy.

Conventional procedures for the biasing of electron devices can be considered satisfactory enough when the experimental results are simply analyzed “region by region”, in order to provide general-purpose information about the specific technology and its potentialities. Unfortunately, the availability of empirical data, which are distributed according to different biasing schemes applied to the same device for different regions, can represent a serious obstacle when the object of the investigation is the characterization/extraction of an electrical model. This is particularly true when a behavioral, “look-up” table-based modeling approach is considered [4]-[7], which can be a valid alternative to classical circuit equivalent-based models due to the increasing complexity of the device structures and the difficulty of identifying lumped-element networks, describing with high accuracy the device behavior under both small- and large-signal operation. In fact, the procedures aimed at the extraction of model parameters exploit the measured data *globally*, without distinctions between biasing regions, and their accuracy/reliability can be compromised by the variable transformations, which are needed in order to make the functional dependence of overall empirical data homogeneous with respect to one single couple of controlling bias parameters.

In this paper, an automated measurement set-up for the characterization of microwave electron devices under DC, small- and large-signal operation will be presented, which is based on a generalized, technology-independent biasing strategy. The bias can be applied to the on-wafer device by globally exploiting the same couple of controlling electrical parameters, with no need for the classification of the quiescent operation into different regions and the switch among different biasing methods. The look-up tables of data obtained are particularly suitable for the extraction of empirical non-linear models of the microwave devices being characterized.

II. GENERALIZED BIAS PARAMETERS

In order to point out the need for a unified biasing approach, when considering the modeling of active electron devices from input/output empirical data, the DC characteristic of a Zener diode is schematically shown in Fig.1. The I/V bijection within the direct current region *A* can be suitably characterized in the $V = F_A(I_D)$ functional form by current-controlling the device and measuring the voltage at its port. This is clearly due to the very low differential resistance, which would lead (besides additional troubles) to an unacceptable uncertainty propagation in the presence of a voltage-controlled bias. Nevertheless, this is not the best biasing strategy when the device is operated either below its threshold, or within the reverse current region (region *B*), where a voltage-control is needed to obtain an accurate characterization in the form $I_D = F_B(V)$. Finally, the current biasing and a $V = F_C(I_D)$ characterization must again be considered below the diode breakdown voltage (region *C*).

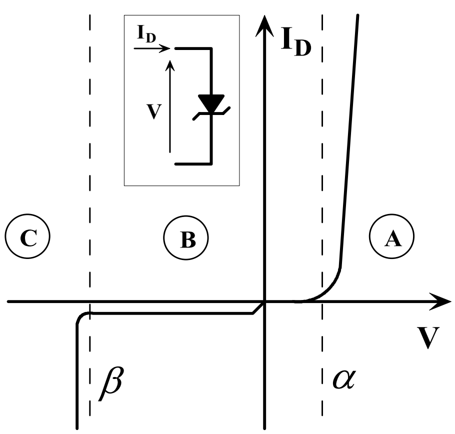

Fig. 1. Classification into different regions of the typical DC I/V characteristic of a Zener diode, according to the biasing procedure needed.

The device overall I/V characteristic is thus split into three different non-homogeneous look-up tables (F_A, F_B, F_C), which need to be variable-transformed in order to obtain one single relationship suitable to be processed by the numerical procedures for the extraction of model parameters. When a two-port device is considered, these transformations can represent a tough task and lead to important discontinuities around the transition planes (lines α and β in Fig. 1). Moreover, the position of these planes is quite arbitrary, as well as the choice of either the current- or the voltage-controlled biasing strategy in correspondence with transition *sub-regions* (e.g. the knees around the threshold and the breakdown of the diode, or between saturation and forward active operation in the output characteristic of a bipolar transistor), where none of above seems to be the optimal one.

In order to identify an unified, technology-independent biasing strategy, capable of providing homogeneous look-up tables of empirical data throughout the global quiescent operation both of field-effect (MESFET, HEMT) and bipolar (BJT, HBT) devices, a *generalized* controlling parameter described as

$$a_i = \frac{1}{2\sqrt{R_i}}(V_i + R_i I_i) \tag{1}$$

can be applied to the *i*th electrical port, which is a *linear combination* between DC current I_i and voltage V_i. This can be easily performed by implementing the *i*th bias source as shown in Fig. 2: it is straightforward to show that the *a*-parameter value can be imposed by controlling the internal voltage U_i. This solution is actually neither a voltage nor a current *ideal* source, but instead represents a *real* voltage source with a well-defined internal resistance R_i. Such an approach presents interesting similarities to the techniques exploited for the experimental characterization of linear network frequency response in the field of micro- and millimeter-waves, in which the investigation on the *scattering* matrix (matrix *S*) is preferred to those on impedance or admittance ones, since, at these frequencies, the direct broad-band measurement of currents and voltages alone is not reliable, as well as the implementation of ideal short and open loads. Instead, excitation sources with an internal reference impedance (50 ohm, typically) are exploited and *S*-parameters (ratios between complex quantities, formally expressed in the frequency domain as in (1), which describe the amplitude and phase of incident and reflected EM waves at the network ports) estimated.

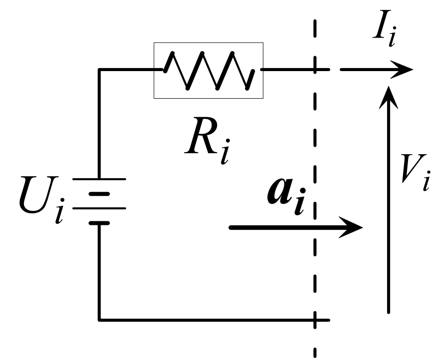

Fig. 2. Implementation of the generalized bias source.

Thus, the proposed strategy can be interpreted as a generalization of the classical biasing procedures, which does not introduce the need for "switching" between the current- and voltage-controls, but allows for an automated characterization of the desired data (I/V characteristics, *S*-parameters, power harmonics on loads under large-signal single- or multi-tone excitation, etc.) independently of the quiescent region of the device being investigated.

III. THE MICROWAVE DEVICE CHARACTERIZATION SET-UP

The main functional blocks which describe the implementation of the measurement set-up for the characterization of micro- and millimeter-wave electron devices in the framework of non-linear modeling are shown in Fig. 3.

A. Bias Source Implementation

The generalized bias system exploits a HP4142B DC source with monitoring capabilities. The outputs of this ideal source (operated as a (U_1, U_2) voltage generator) are cascaded with resistors R_1 and R_2, respectively, in order to implement the two *a*-kind sources (a_1, a_2) as described in Fig. 2. In particular, very high stability, low noise metal film precision resistors (in both cylindrical and planar ceramic former versions) have been considered, since this technology is characterized by very low temperature coefficients (< 10 ppm/^{o}C) and guarantees the needed stability of the resistance parameter over a wide range of power rating. The resistors have been assembled inside shielded aluminum boxes, as shown in Fig. 4, in order to reduce the effect of environment disturbances. Each box is provided with BNC connectors, which allow to insert the component along the coaxial path from the DC source to the microwave bias tees. Resistors can be easily replaced, both in series and parallel configurations, in order to obtain different values of the generalized bias source internal resistances.

B. Criteria to the choice of resistance values

In order to accurately characterize the generalized bias sources (a_1, a_2), it is essential to correctly estimate the resistance parameter pertaining to the *overall* resistive path, between voltage generator U_i and the *i*th port of the on-wafer device. In Fig. 5 details are given concerning the set-up components, which contribute to the internal resistance of the *i*th bias source. The voltage U_i is applied to the electrical port, at which both the biasing and sensing terminals of the HP4142B DC source are connected, through a tri-axial cable. In addition to the shielded box containing the precision resistor, several distributed components must be taken into account along the resistive path, up to the microwave coplanar probe. During the bias source characterization procedure, the latter is contacted to an on-wafer "short" calibration standard, which is usually exploited for network analyzer SOLT calibration. The standard is placed in correspondence with the EM plane, which will result into the *i*th device port during the subsequent measurement steps aimed at its characterization. This is the actual port at which the a_i bias parameter is forced. Thus, the accurate estimate $\hat{R}_i$ of the overall resistance of the biasing path (i.e. the internal resistance of the *i*th generalized *a*-kind bias source) can be carried out, by means of the direct estimation of couple (U_i, I_i) for different power ratings.

As far as the nominal values of the precision resistors are concerned, some criteria should be followed in order to identify the most suitable choice for each given device to be characterized. More precisely, since the biasing system does

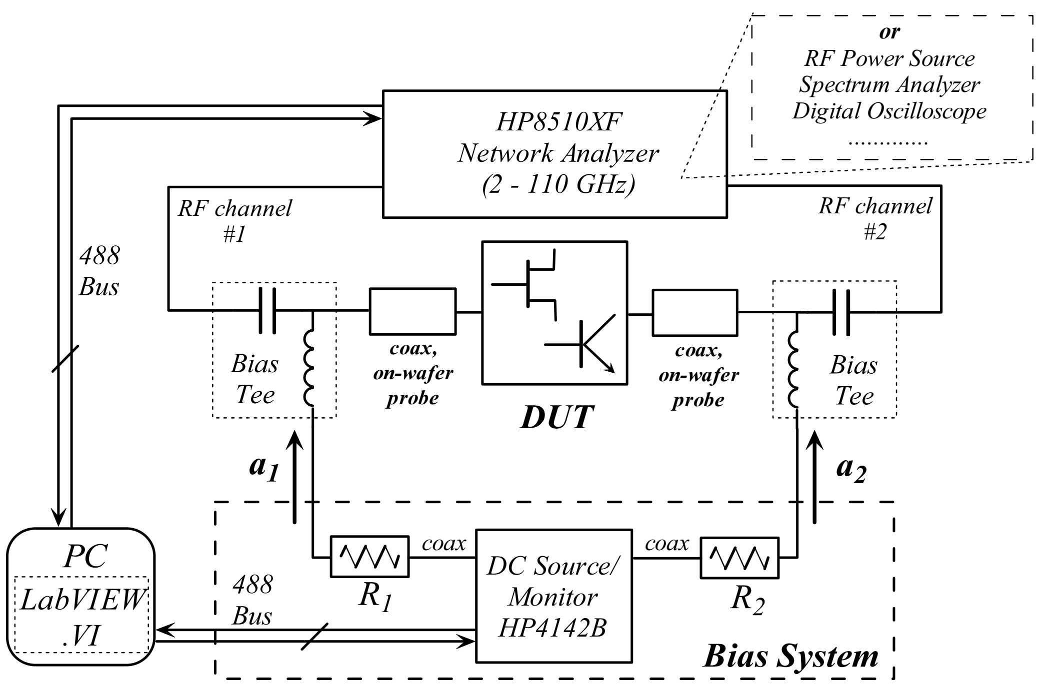

Fig. 3. Functional description of the microwave device characterization set-up with generalized bias system.

not change its configuration throughout the entire measurement, while moving between different quiescent operation regions of the device, the two generalized bias sources implemented should satisfy the best trade-off between the *ideal* current source representation (i.e. virtually infinite resistance value, suitable for high differential conductance regions, e.g. saturation in bipolar devices) and the *ideal* voltage source representation (i.e. null resistance values, this would be the best choice for low conductance regions, e.g. forward active region). Actually, since the HP4142 DC source is practically operated as a voltage generator, the influence of resistor values within low conductance regions (where the current is slowly varying with the bias) is quite negligible. Thus, very high nominal values for the precision resistors should be adopted in order to allow for the best performance of the bias system in correspondence with high conductance device quiescent operation.

Nevertheless, it is quite intuitive that the biasing resistors introduce a partial "out of focus" in the observation of the device: the more the resistor values increase, the more the accuracy in the prediction of device behavior at its ports is reduced. In fact, by considering for example the input port of a bipolar transistor being investigated under common-emitter configuration, the combined standard uncertainty of the estimate $\hat{V}_{BE}$ for the quiescent base-emitter voltage can be evaluated from the standard uncertainties of the estimates $\hat{U}_1$, $\hat{I}_B$ and $\hat{R}_1$ for bias source #1 internal voltage, quiescent base current and bias resistance #1, respectively, according to the following expression:

$$u_c^2(\hat{V}_{BE}) = u^2(\hat{U}_1) + \hat{I}_B^2 u^2(\hat{R}_1) + \hat{R}_1^2 u^2(\hat{I}_B) \qquad (2)$$

$\hat{U}_1$, $\hat{I}_B$ being directly monitored by the HP4142 and $\hat{R}_1$ characterized before the measurement, as described above. A simple manipulation expresses the quantity in terms of normalized values:

$$u_c^2(\hat{V}_{BE}) = u^2(\hat{U}_1) + \hat{R}_1^2 \hat{I}_B^2 \cdot \left(u^2(\hat{R}_1)/\hat{R}_1^2 + u^2(\hat{I}_B)/\hat{I}_B^2 \right) \qquad (3)$$

In (3), the terms $u^2(\hat{U}_1)$ and $u^2(\hat{I}_B)/\hat{I}_B^2$ are independent of the choice for the resistor (although higher values for R_1 lead to the need for a wider sweep of the applied voltage U_1 in order to explore a given range of base current values, thus to higher values of $u(\hat{U}_1)$), the latter being approximately constant as the bias point varies. Also $u^2(\hat{R}_1)/\hat{R}_1^2$ can be considered practically constant for a wide range of resistance values according to the specifications of the technologies taken into account. Thus, for a given point on the input characteristic (V_{BE}, I_B) of the bipolar transistor, while the estimate of the base current is directly performed by the DC source (i.e. independently of the biasing strategy adopted) the uncertainty of the estimate for the base-emitter voltage increases with the resistance value according to a practically linear law. This simple example shows that whatever the measured parameters may be (e.g. S-matrix), the accuracy in associating them to the correct quiescent operation point of the device decreases with the values of the bias resistors, up to an unacceptable "blurring" of the device quiescent behavior.

It should be noticed that, since the experimental look-up tables of data obtained by means of the set-up proposed are oriented to the accurate extraction of the parameters pertaining to empirical non-linear models for the microwave device, the "de-embedding" of bias resistors effects exemplified above from data (which must characterize the behavior of the device "at its ports") is a procedure which is explicitly or implicitly performed, either during the model parameter computation or the implementation of the model within the final circuit design CAD tools. For this reason, suitable constraints on the maximum values for the bias resistors for a given device must be identified and applied. This can be performed by simple algorithms, which take into account the trade-off between the desired performance of the generalized bias system in terms of "biasing resolution" within the high-conductance device regions, which improves with resistor values, and the need for accuracy in the reconstruction of the correct quiescent operation point at the ports of the electron device.

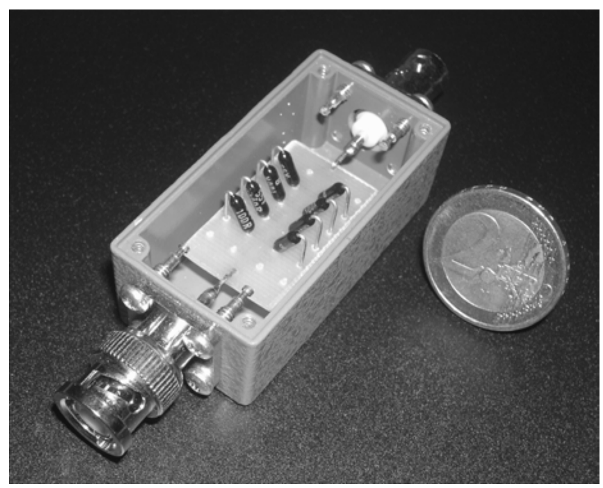

Fig. 4. BNC-connector shielded aluminum box and precision resistors for the implementation of generalized bias source internal resistances.

C. The operation of the microwave measurement system

The bias tees in Fig. 3 gather both the generalized bias and the RF excitations and the access network to the on-wafer device is implemented by coaxial lines and micro-probes. A Cascade Microtech microwave probe-station with thermal control capabilities provides the mechanical support within the DUT probing system.

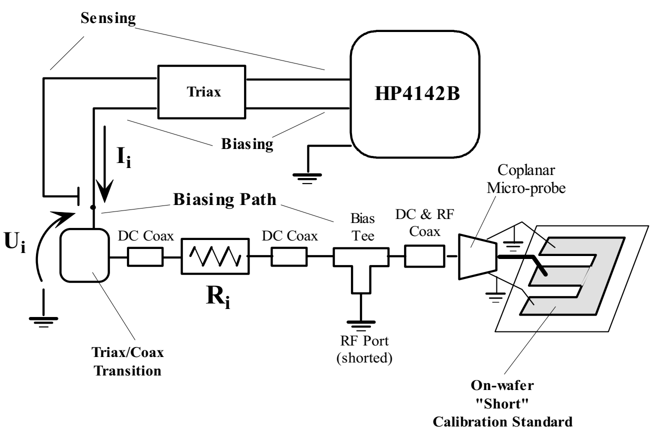

Fig.5. DC & RF distributed components which contribute to the *i*th bias source overall internal resistance and set-up for its characterization.

The RF ports of the set-up can be connected to different microwave instruments in order to collect the measurement data (under both small- and large-signal operating conditions) needed by the device model parameter extraction procedures and model validation tests. In the example of Fig. 3, the HP8510XF network analyzer is considered: under this configuration, the system is capable of providing accurate bias-varying *S*-parameter device characterization up to 110 GHz.

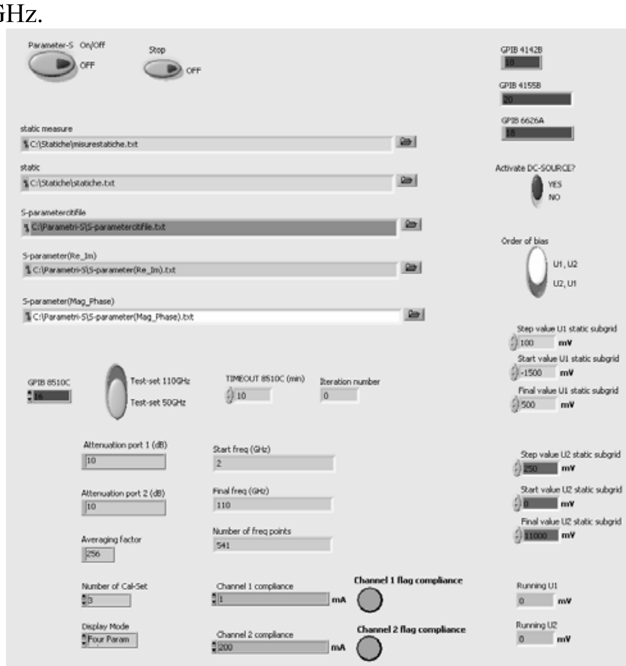

Fig. 6. NI LabVIEW control panel for the configuration of bias-varying, multi-frequency S-parameter characterization of a microwave device by means of the set-up described.

A NI LabVIEW Virtual Instrument controls the set-up under its different possible configurations. In particular, the generalized bias is applied automatically (according to user-defined *a*-grids) throughout all the quiescent operation regions of the device. Both field-effect and bipolar technologies can be investigated, and look-up tables of experimental data obtained, which are characterized by a *global* dependence with respect to the couple (a_1, a_2). Fig. 6 shows one of the several control panels exploited for the set-up configuration and automated operation: in the example, a complete S-parameter characterization of the device can be performed, by configuring the two-dimensional grid of bias, the frequency sweep (up to 110 GHz) and additional constraints aimed at device correct operation within power and current compliances. The overall microwave set-up is shown in Fig. 7 (up), while details can be appreciated (down) about the interfacing among DC source, shielded boxes with precision resistors and microwave bias tees.

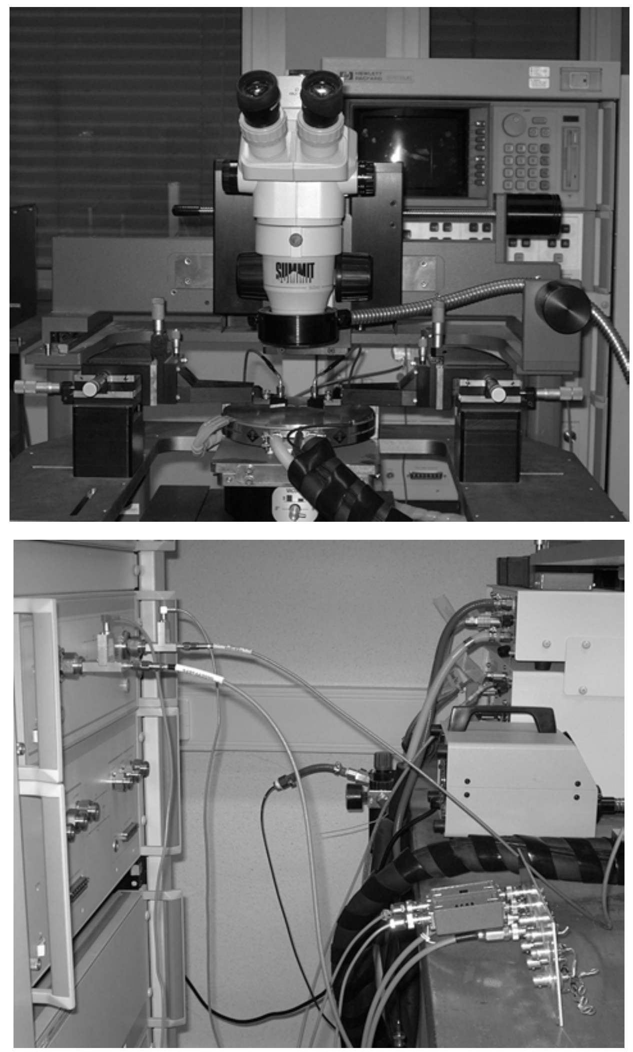

Fig. 7. (Up) Overview of the microwave device characterization set-up and (Down) details of the interconnections among HP4142B DC source, shielded boxes with precision resistors and microwave bias tees.

Figure 8 shows typical I/V characteristics for a microwave heterojunction bipolar transistor (HBT) obtained by exploiting the set-up described, with a single *equally-spaced* global grid of bias *a*-parameters. The output and input characteristic graphs are here traced with respect to the reconstructed V_{ce} and V_{be} values, respectively, in order to

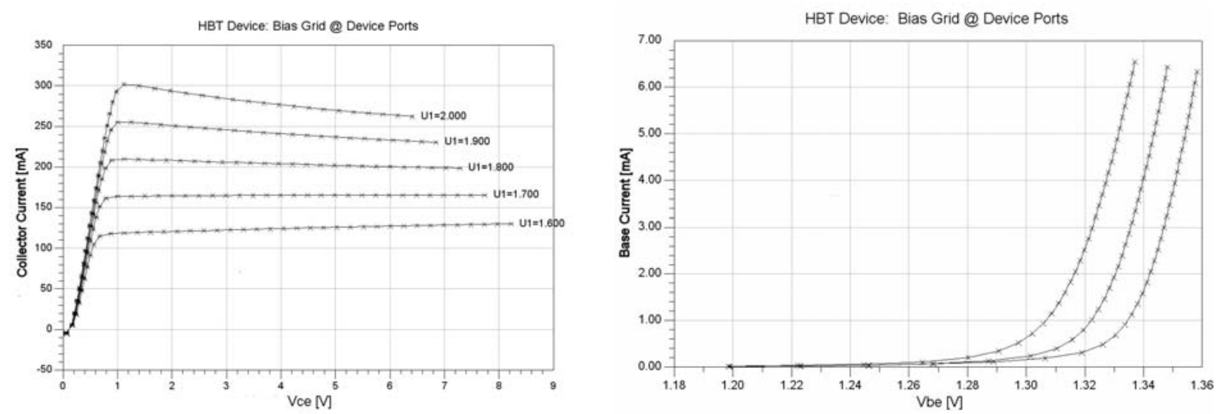

Fig. 8. Output (*left*) and input (*right*) DC I/V characteristics of a heterojunction bipolar microwave transistor (HBT), obtained by means of the set-up described with an equally-spaced grid of *a*-parameters.

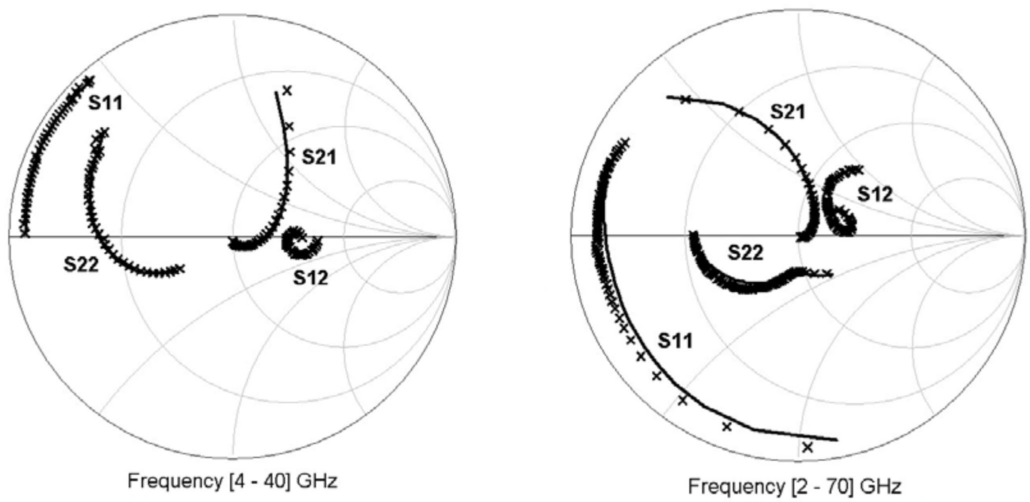

Fig. 9. Multi-frequency *S*-parameter chart for an HBT (I_B = 1.89 mA, V_{CE} = 8.45 V) (*left*) and an HEMT transistor (V_{GS} = -0.55 V, V_{DS} = 6.50 V) (*right*): measurement data from the set-up described (crosses) and NDC model [6][7] predictions (lines).

show how the investigation resolution is automatically modulated by the current variations, as the steady-state point moves from high (large step) to low (small step) differential resistance regions. In Fig. 9, *S*-parameter charts are shown, for a HBT and a HEMT (field-effect technology) transistor. The measured data, obtained over a global grid of generalized biasing *a*-parameters and shown here with respect to the frequency sweep for a single quiescent point, are compared with the predictions provided by an empirical look-up table-based non-linear dynamic model (namely, the Non-linear Discrete-time Convolution (NDC) model [6][7]) extracted for the two devices. The NDC model extraction procedure and accuracy, which is intrinsic to its analytical formulation, fully exploit the benefits deriving from the generalized biasing strategy adopted by the set-up described.

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