Accurate On Wafer Measurement Of Phase And Amplitude Of The Spectral Components Of Incident And Scattered Voltage Waves At the Signal Ports Of A Nonlinear Microwave Device

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Abstract — **A measurement setup and calibration procedure are described allowing the accurate on wafer measurement of phases and amplitudes of the spectral components of incident and scattered voltage waves at the signal ports of a nonlinear microwave device. A comparison is made between measurements performed with the setup and simulations based on a Root-model.**

I. INTRODUCTION

The design of microwave circuits containing nonlinear devices is cumbersome and expensive. Many designs can only be realized by using powerful commercially available simulators based on the principle of harmonic balance [1]. The accuracy of these simulators is determined by the accuracy of the large-signal nonlinear models used. As a consequence, a lot of research is going on concerning the accurate modelling of all kinds of nonlinear microwave devices. A major problem presently faced by modelers and designers is the lack of commercially available instrumentation to accurately measure or verify the large signal behavior of devices.

In this article a new measurement setup and calibration procedure is described which allows the accurate on wafer measurement of all quantities that completely characterize the large signal behavior of nonlinear microwave two-port devices in the frequency domain, namely the phase and amplitude of all spectral components of both incident and scattered voltage waves. The authors believe that the availability of such instrumentation, which they call "calibrated vectorial nonlinear-network analyzers" (VNNA) will help modelers to build more accurate models and will help circuit designers to check the accuracy of the models they are using. In the past measurement setups with the same goal have already been build (although most of the researchers did not have wafer probing available) [2]-[7]. The new setup is original because of the hardware used, allowing fast data acquisition with a very good dynamic range, and because of the calibration procedure used, allowing traceability to a "nose-to-nose" calibration procedure for sampling oscilloscopes [8].

In order to verify the calibration procedure, a successful consistency check is performed between a harmonic distortion measurement of a MESFET and a simulation based on a Root-model [9], which is believed to be the most accurate model presently available for such a device.

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II. EXPERIMENTAL SETUP

For the measurement set up realized, a microwave synthesizer together with a power splitter and attenuators is used for the signal generation. A wafer probing station together with four couplers is used as test set (to detect incident and scattered waves). The data acquisition has two parts: a broadband downconvertor and an intermediate frequency (IF) digitizer. The broadband downconvertor is based on the use of two synchronized and modified "Transition Analyzers" (HP-70820A modules) [6]. The resulting IF-signals are digitized by fast analog-to-digital convertors (HP-E1430A modules).

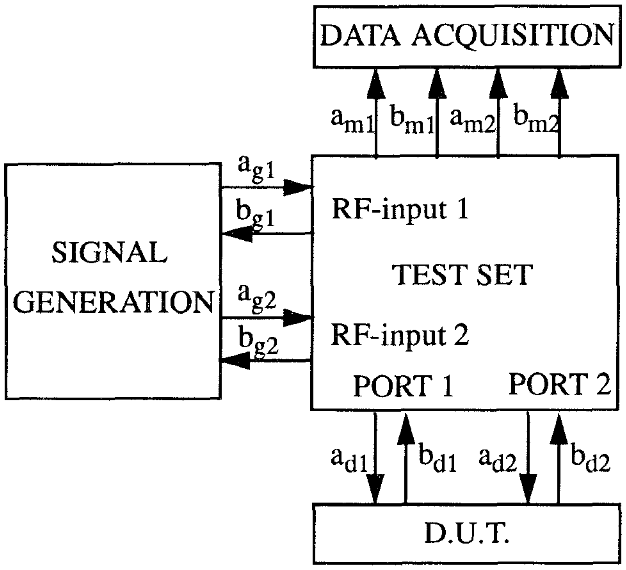
For an accurate calibration additional hardware is used: an on wafer linear calibration substrate (LRM), a 3.5mm linear calibration standard set, a power meter and a reference generator [7]. This reference generator is build with a "step-recovery" diode and standard microwave power amplifiers. The characterization of the reference generator is done by means of a broadband sampling oscilloscope, which on his turn is characterized with the so-called "nose-to-nose" calibration method [8]. All instruments are computer controlled through IEEE-488 or through an MXI-interface.

With this set up a calibrated bandwidth can be achieved from 1 GHz to 18 GHz (limited by the bandwidth of the power sensor and reference generator available) with a dynamic range of about 60 dB (taking into account linearity and noise).

III. CALIBRATION

In order to remove the systematic errors a calibration method was developed and tested. The assumptions used are: the data acquisition part is linear, the crosstalk between the probes is negligible, the errors are repeatable and reciprocity is valid from generator input to the probe tip.

Fig. 1



A general schematic of a two-port VNNA is given in Fig. 1. The number in a wave subscript refers to the corresponding VNNA signal port. Note that all quantities in Fig. 1 may contain several spectral components. The characteristic impedance of the waves is 50 Ohm.

Using the assumptions mentioned above, the following equation represents the error model used. The index i refers to the spectral component with a frequency index i.

$$\begin{bmatrix} a^i_{d1} \\ b^i_{d1} \\ a^i_{d2} \\ b^i_{d2} \end{bmatrix} = K^i \begin{bmatrix} 1 & \beta^i_1 & 0 & 0 \\ \gamma^i_1 & \delta^i_1 & 0 & 0 \\ 0 & 0 & \alpha^i_2 & \beta^i_2 \\ 0 & 0 & \gamma^i_2 & \delta^i_2 \end{bmatrix} \begin{bmatrix} a^i_{m1} \\ b^i_{m1} \\ a^i_{m2} \\ b^i_{m2} \end{bmatrix} \qquad \text{Eq. 1}$$

The goal of the calibration procedure will be the determination, for each frequency, of the 8 a priori unknown complex coefficients $(K^i, \beta^i_1, \gamma^i_1, \delta^i_1, \alpha^i_2, \beta^i_2, \gamma^i_2, \delta^i_2)$, describing the relationship between the measured quantities and the device-under-test (DUT) quantities. As can readily be verified a classical linear calibration technique is sufficient to calculate all coefficients except for the K^i's. We use a line-reflect-match probe calibration procedure (LRM) [10] for the linear calibration.

As explained in [7], an accurate and efficient way to find the K coefficients is the use of a reference generator and a powermeter at the VNNA signal ports. Accurate implementations of these “absolute calibration standards” are only available however in connector technologies, like APC-3.5®, such that they can not be directly connected to the probe tips of our set up. This critical problem is solved by using the principle of reciprocity between the testset RF-input connectors (APC-3.5®) and the probe tips [11]. This is done as follows.

Eq. 2 describes the correlation between the voltage waves at the probe tips and the voltage waves at the RF input 1 port.

$$\begin{bmatrix} a^i_{g1} \\ b^i_{g1} \end{bmatrix} = T^i \begin{bmatrix} 1 & \lambda^i \\ \mu^i & \nu^i \end{bmatrix} \begin{bmatrix} a^i_{m1} \\ b^i_{m1} \end{bmatrix} \qquad \text{Eq. 2}$$

A load-open-short (LOS) calibration is performed for each frequency at RF input port 1. For this purpose the probes are connected to the LRM line and a generator is connected to RF-input 2. This results in the knowledge of the a priori unknown λ^i, μ^i and ν^i. Next the powermeter is connected at RF input port 1 and the power measured by the data acquisition is compared with the power measured by the power meter, resulting in the amplitude of T^i. The phase of T^i is determined by connecting the reference generator to RF input port 1 and by comparing the measured values of the spectral components of the reference generator signal with the values as measured by a sampling oscilloscope calibrated with the “nose-to-nose” calibration procedure.

It can readily be verified (expressing reciprocity) that K^i can be calculated as follows.

$$K^i = \pm T^i \sqrt{\frac{\nu^i - \lambda^i \mu^i}{\delta^i_1 - \beta^i_1 \gamma^i_1}} \qquad \text{Eq. 3}$$

Note that the sign of K^i is not uniquely defined. This ambiguity can be resolved by looking at the measured waveform with the reference generator connected to RF input port 1.

IV. CALIBRATED MEASUREMENTS VERSUS A ROOT MODEL

In order to check the validity of the calibration procedure an harmonic distortion measurement of a MESFET transistor is performed and the results are compared with simulations of the same experiment based on a Root-model [9] of the same device. The device is excited with a fundamental frequency of 3 GHz, with a gate-drain voltage bias of -1 Volt and a source-drain voltage bias of 3 Volt. For the harmonic distortion measurement, the gate of the transistor is connected to port 1 and the source to port 2. Port 1 is excited with a variable input power, ranging from about -18 dBm to 3 dBm with a step of 1 dB. For each excitation value both amplitude and phase are measured of the fundamental and the 2nd and 3rd harmonic, and this for both the reflected as well as for the transmitted voltage wave. All phases are referenced to the incident fundamental wave. The result is shown in Fig. 2. The dots refer to the measured values, the solid lines to the modelled values. Note that the uncertainty of the phase of an harmonic becomes very large at low input powers because the corresponding amplitude becomes very low.

If we compare with previous experiments of the same kind [9] we may conclude that the correspondence between model and measurement is very good, except for the amplitude and phase of the third harmonic of the transmitted wave for low input power. The fact that the correspondence is very good for high powers, but bad for low powers, can only be explained by model errors, since the error correction applied is the same for all experiments.

V. CONCLUSION

A new measurement set up and calibration procedure was presented to accurately measure, on wafer, the phases and amplitudes of the fundamental and harmonic components of incident and scattered waves at the signal ports of a nonlinear device under test.

To check the validity of the calibration procedure a comparison was made between calibrated measurements and simulations of an harmonic distortion analysis of a MESFET. The MESFET was modelled by a Root-model. A good correspondence between measurement and simulation was found for most quantities, thereby proving the validity of the calibration procedure.

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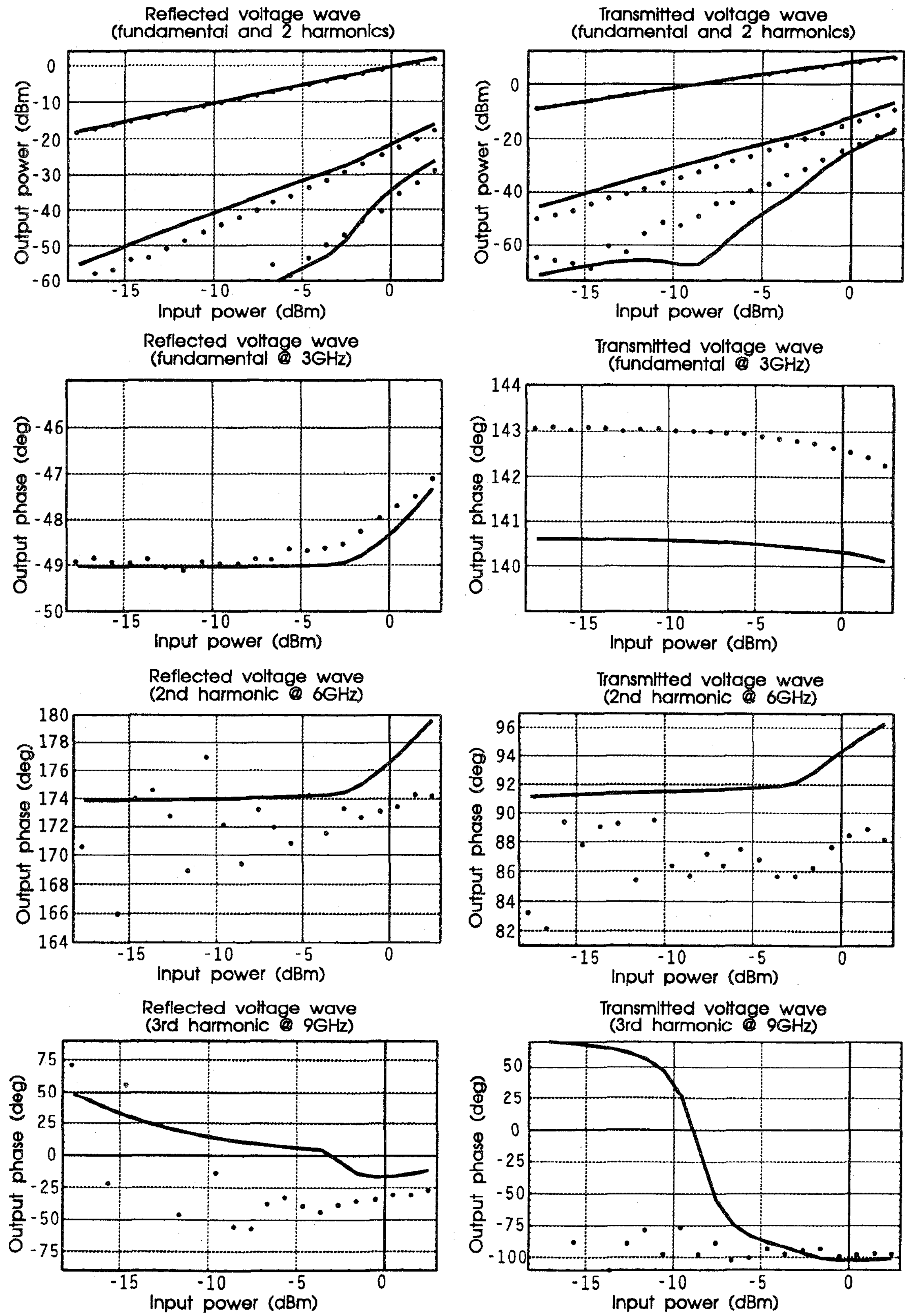
Fig. 2


Reflected voltage wave (fundamental and 2 harmonics)
Output power (dBm)
Input power (dBm)
Transmitted voltage wave (fundamental and 2 harmonics)
Output power (dBm)
Input power (dBm)
Reflected voltage wave (fundamental @ 3GHz)
Output phase (deg)
Input power (dBm)
Transmitted voltage wave (fundamental @ 3GHz)
Output phase (deg)
Input power (dBm)
Reflected voltage wave (2nd harmonic @ 6GHz)
Output phase (deg)
Input power (dBm)
Transmitted voltage wave (2nd harmonic @ 6GHz)
Output phase (deg)
Input power (dBm)
Reflected voltage wave (3rd harmonic @ 9GHz)
Output phase (deg)
Input power (dBm)
Transmitted voltage wave (3rd harmonic @ 9GHz)
Output phase (deg)
Input power (dBm)