Power Level Control of mm-Wave Test Benches for Accurate Small and Large-signal DUT Measurements

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***Abstract* — In this contribution we describe the accuracy improvement achievable using a vector corrected, power calibrated test-bench when measuring mm-wave non-linear devices. The absence of automatic level control in commercially available network analyzer frequency extenders can result in AM distortion of the transfer characteristic. Moreover, when large-signal mm-wave test-benches are employed (i.e., using multipliers and power meters) the lack of vector correction causes transfer characteristic errors.**

The usage of power levelled mm-wave VNA test-benches allows to properly measure the true small-signal s-parameter response as well as accurately correct for the impedance mismatch present, providing increased correlation between small and large-signal test-benches response.

The accuracy limitation of classical approaches and the improvement achieved by the levelled mm-wave VNA test-bench are validated on a 140GHz power amplifier.

***Index Terms* — Power control, Power calibration, S-parameters measurements, mm-wave, sub-mm-wave.**

I. Introduction

The increasing interests in millimeter-wave (mm-wave) systems for commercial applications, such as automotive and high data rate communication (falling under the umbrella of 5G), is pushing for higher quality mm-wave measurements and device models. Improving the model predictive capabilities is the path to minimize the redesign attempts, thus making the developing phase of a product commercially feasible.

The mm-wave frequency range is characterized by the extensive use of frequency multiplication stages to generate signals. The testing and instrumentation field also makes use of frequency multiplication in the up- and down-converting extension modules of state-of-the-art VNAs. The frequency multiplier chains used in commercial VNA test-set extenders provide a strongly non-linear power relation between the input and output, nevertheless, as it was shown in [1] accurate power control at the mm-wave port is feasible up to the sub-mm-wave frequency range. Despite this, several contributions in the field still suffer from error arising from a non-accurate power level control during scattering parameter measurements, see Fig. 1 a), and errors arising from the simple scalar corrections of large-signal power-meter based setups, see Fig. 1 b).

In this paper we analyze how these errors can be traced to the absence of amplitude power level control of mm-wave VNA extenders, and we describe how the use of full vector correction, using VNA based large-signal setups, allows to achieve an high correlation between the *small-signal* and *large-signal* test-benches response.

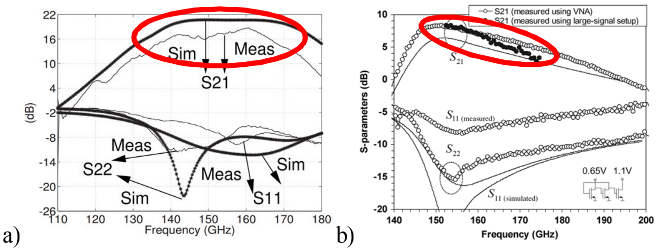

Fig. 1: a), Small-signal model-hardware correlation of the PA from [2], b) measured (circles) and simulated (solid lines) S-parameters of the three-stage 150 GHz amplifier, measured with VNA and large-signal setup, from [3].

The paper is organized as follows, first an analysis of the AM distortion in the transfer characteristics of non-linear device excited by non-levelled drive signal is described, together with the limitation of commonly employed scalar mm-wave large-signal setups. Then, the proposed VNA based power controlled small-signal and large-signal test bench of [1] is briefly described. Finally, a 140GHz power amplifier characterization is used as a test vehicle to reproduce some of the shortcomings that can be encountered in mm-wave test-benches and highlight the high correlation between small-signal and large-signal setups when full vector correction is employed.

II. MM-waves Test-Benches Shortcomings

A. Small-signal

The small-signal characterization of power amplifiers, aims to look at input matching, reverse isolation and the small-signal gain. The latter is often evaluated simply looking at the S_{21} at a sufficient back-off level, i.e., the linear region of Fig. 2. When the amplifier is composed by several stages, which is often the case at mm-wave frequencies due to the limited gain per stage, the compression mechanism of the gain curve can

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be very diverse, from very pronounced to very soft, mostly depending on the area ratios of the stages.

When the absolute power level of the drive signal is unknown and the lower dynamic range, compared to the fundamental VNA operation, advises not to intensively reduce the drive power (i.e., using waveguide attenuators) not to incur in noisy measurement traces, a clear risk of measuring in the weakly non-linear region (Fig. 2) exists. When this occurs the S_{21} parameter is actually modulated by the non-constant drive level (versus frequency) and the non-linear device input-output characteristic. This can result in non-physical fluctuations in the measured S-parameter, as can be observed in Fig. 1 a.

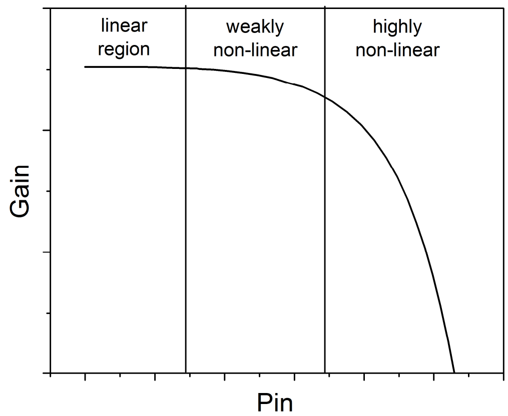

Fig. 2: Gain vs. P_{in} characteristic of a general active device.

B. Large-signal

In order to characterize the key parameters of PAs (i.e., P_{1dB} and PAE), large-signal setup as shown in Fig. 3 are employed. The scalar nature of such setups only allows for a response type of calibration, thus neglecting losses arising from mismatches in the setup.

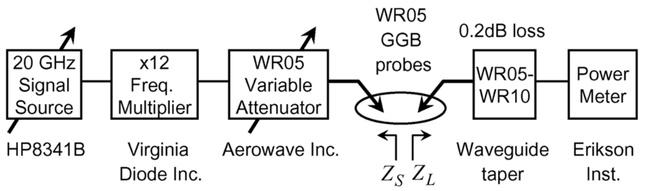

Fig. 3: G-band large-signal measurement setup (153 GHz to 173 GHz), from [3].

It is important to note that all the components shown in Fig. 3 are already part of a VNA with frequency extenders, with the only exception that stand alone frequency multipliers could generate few dBs more of power due to the absence of the directional coupler.

III. SYSTEM ARCHITECTURE AND CALIBRATION PROCEDURE

The block scheme of the VNA based power controlled small- and large-signal setup, using vector correction, presented in [1] is shown in Fig. 4. The system features a calorimeter based power meter, required for power calibration. All the data manipulation, including calibration and power control, are performed using a user friendly GUI interface which runs on an external computing unit.

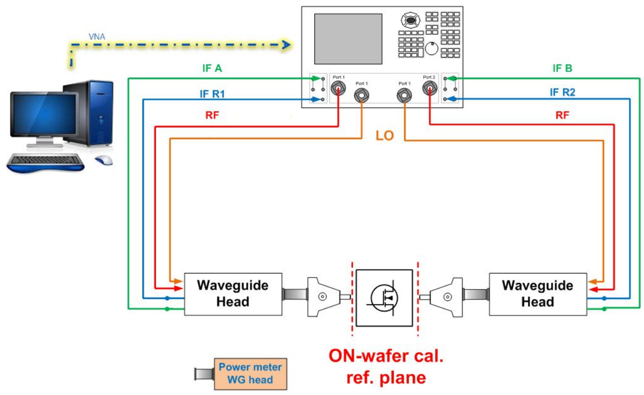

Fig. 4: Simplified scheme block of the employed measurement setup.

The calibration procedure consists of four steps:

1. two-port calibration is performed at the waveguide interface of the extenders (i.e. TRL calibration [4]);
2. power calibration [5] is performed at the input waveguide port, providing knowledge of the absolute power at the mm-wave port of the extender modules;
3. a power leveling procedure is carried out, enabling accurate power control at the waveguide ports;
4. finally, an on-wafer two-ports calibration is performed (i.e. TRL) in order to shift the calibration reference planes from the waveguide ports to the wafer probe tips.

After completing the calibration steps described above, the system is capable to perform power controlled S-parameter measurements as well as large-signal measurement.

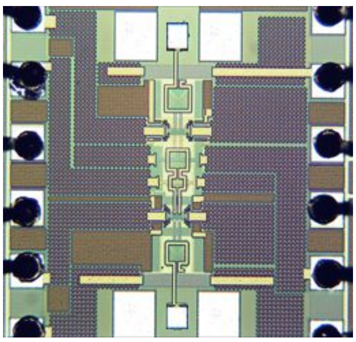

Fig. 5: Chip micrograph of the measured power amplifier.

IV. POWER CONTROLLED VECTOR CORRECTED S-PARAMETER MEASUREMENTS

To demonstrate the capability of the VNA based power controlled setup, measurements of a multi-stage power amplifier, were conducted in the frequency range from 130 to 180 GHz. Two VDI extender modules were employed for the measurements, and a VDI Erickson PM5 power meter, was employed for the power calibration. A micrograph of the measured amplifier is shown in Fig. 5. First, the DUT was measured, for a defined bias level, using the classic mm-wave VNA setup (i.e., without power control). Then, measurements were performed at a fixed, controlled power level of $P_{av,in}$ = -30 dBm. Finally, power sweeps in the range from -43 dBm to -12 dBm, at different frequencies, have been employed to realize large-signal measurement of the device.

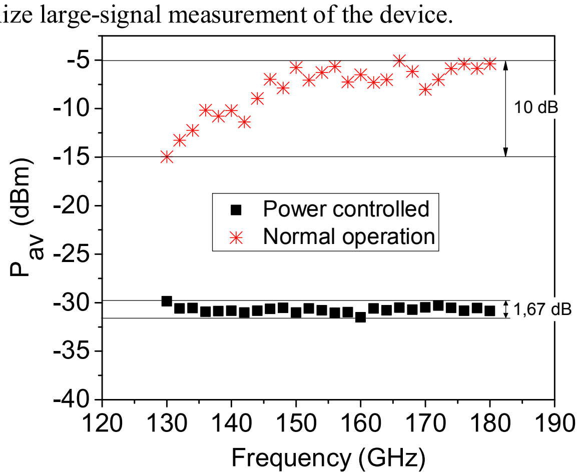

Fig. 6: Power available versus frequency at port 1 of the employed system for normal operation (red asterisks) and using power control (black squares).

A. *Power controlled S-parameters*

Fig. 6 shows the measured available power from port 1 of the WR5 extender in the conventional operation mode, i.e., no power level, (red asterisks) and for power controlled measurements (black filled squares). While the non-controlled available power presents a variation higher than 10 dB across the entire frequency range, the power control guarantees power fluctuations lower than 2 dB in the same frequency range.

Fig. 7 shows the measurement results for the S_{21} of the considered amplifier in the entire frequency range. Measurements highlight a strong discrepancy between the two methods in the frequency range (solid line and dashed line) from 130 to 157 GHz (see, Fig. 7 section A), where the difference in terms of S_{21} reaches 10 dB at 140 GHz. This discrepancy can be better explained when looking at the large-signal measurements. Fig. 8 shows the transducer gain (G_T) of the device under test, versus P_{av}, for 140 GHz (black filled squares) and 170 GHz (red asterisks). At 140 GHz, the power level employed for the S-parameter measurements (circa -10 dBm) is not sufficiently low to operate the DUT in the linear region, see Fig. 2. This means that the S-parameters cannot be correctly measured and a variation in input power would result in a modulation of the measured S-parameter. When the measurement is performed at P_{av} = -30 dBm with the power controlled system, the device is operating in the linear region, so that the S-parameter measurements do not depend upon the input power, as it should be. These results show how the capability to fine control the power level during active device measurement allows to prevent incorrect drive to the device, which could lead to inaccurate measurements.

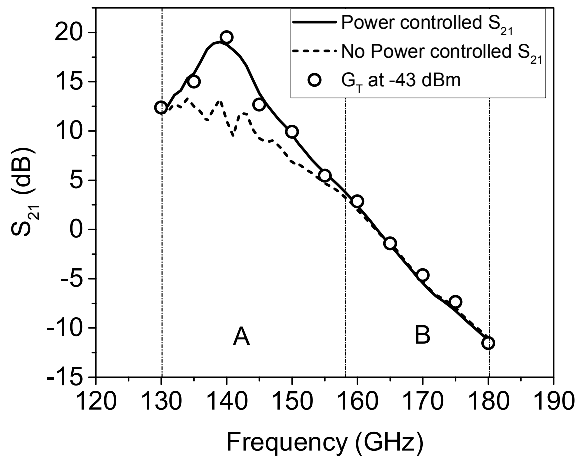

Fig. 7: S_{21} of the considered PA measured in normal system operation (dashed line), with -30 dB controlled P_{av} (solid line) and G_T obtained using the large-signal measurements at -43 dBm.

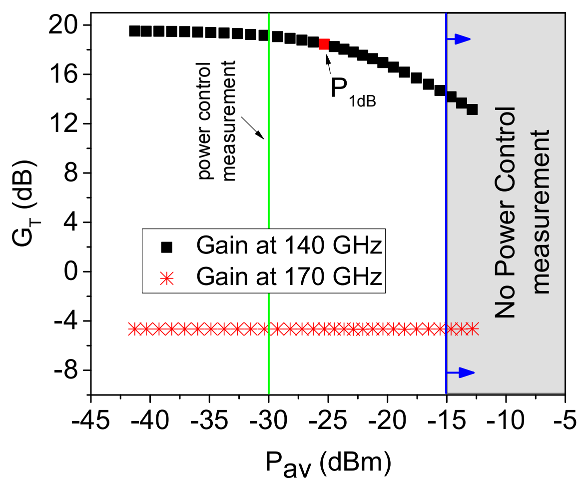

Fig. 8: G_T of the measured PA, obtained using large-signal measurements at 140 GHz (black squares) and 170 GHz (red asterisks). In Gray is shown the range of P_{av} levels where no power control is performed.

B. *Vector corrected large signal measurements*

As explained in Section II, one of the main challenges associated to the use of conventional mm-wave large-signal measurement setups, like the one depicted in Fig. 3, lies in the usage of a simple scalar/response correction, providing different results between small-signal and large-signal test-benches even when the same power level is applied.

The use of a full vector calibration in combination with power measurements, as it is described in section II, allows always having comparable results, both during power controlled S-parameter measurements and large-signal measurements. In order to verify this principle, an experiment was conducted using large-signal measurements of the device. If these measurements are adequately vector corrected, G_T extracted a low power (i.e., in linear regime) should be equal to the S_{21} parameter measured using power controlled frequency sweep.

In Fig. 7 the S_{21} predicted by using G_T measurement at a power P_{av} = -43 dBm is shown (empty circle) as compared to power control S-parameters measurement (solid line). As predicted, the two curves (solid line and the circles) closely track each other, highlighting how the vector correction is correctly applied also to large-signal measurements.

V. Conclusions

In this paper, the advantages of using power control for mm-wave active device characterization is presented. The proposed method allows to properly control the power level during S-parameter measurements. This allows to always guarantee small-signal operation, preventing incorrect measurement results that may occur when large input power fluctuation can drive the device in large-signal regime. Also, the combination of S-parameter and power calibration allows performing vector corrected large-signal characterization at mm-wave, as it was not possible with conventional scalar large-signal mm-wave test-benches.

VI. Acknowledgments

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