Power Control for S-parameters and Large Signal Characterization at (sub)-mmWave frequencies

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Abstract — In this contribution we present a frequency scalable approach to achieve an accurate power control for levelled s-parameters and large signal characterization of devices working at millimeter and sub-millimeter waves. The method is based on a software-aided control loop that mimics the behavior of an automatic level control system, allowing to dynamically adjust the power delivered to the DUT at every frequency. The proposed hardware configuration employs only the VNA mm-wave extender modules, bypassing the need of expensive add-on test-sets.

Measurement results are provided in WR-10, WR-05 and WR-03 waveguide bands to show the applicability of the method at different frequencies and different hardware setups (i.e., VNA extender modules from different vendors). The power control at the system ports and the capabilities of the proposed setup for power controlled S-parameters and large signal measurements are reported.

Index Terms — mm-wave characterization, vector network analyzer (VNA), S-parameters, large signal characterization.

I. Introduction

SiGe bipolar technology is continuously increasing the device maximum operating frequencies, in terms of f_T and f_{MAX}, currently approaching 0.5 THz [1]. In this framework, large emphasis is placed on demonstrating the capabilities of SiGe in real life application, aiming at large volume markets. In order to foster the technology improvements, there is an increased need for accurate small and large signal characterization test-benches which could support device model validation together with technology optimization.

When considering measurements at mm-wave and submm-wave, one of the limitations is the measurement dynamic range reduction. As frequency increases the power available decreases while the noise floor, which is set by the measurement instruments, remains ideally constant, bringing to a reduction of the dynamic range. In standard VNA configurations, the maximization of the dynamic range (for a given power level) is achieved by means of the automatic level control (ALC). The ALC dynamically adjusts the power available from the source by sampling the test channel in a feedback loop, resulting in an output of the source transmitter essentially constant, thus maximizing the measurement dynamic range. When measuring at frequencies higher than 75 GHz, mm-wave extenders are employed, excluding the ALC from the measurement loop and disallowing power level control. As shown in Fig 1, available power at the extender ports can present large fluctuations in standard setups, which would cause a (potential) loss of dynamic range as high as 10 dB, when the power is backed off from maximum drive. Furthermore, when the source power is not controllable, ensuring a small signal stimulus to a DUT (active device) during s-parameters measurement becomes problematic.

In this paper we present a hardware and calibration procedure to achieve a frequency scalable method for absolute power control and measurement in small signal and large signal measurements. The presented method, based on a software based loop, allows refined control of the power presented at the DUT in the entire frequency band covered by the VNA extender.

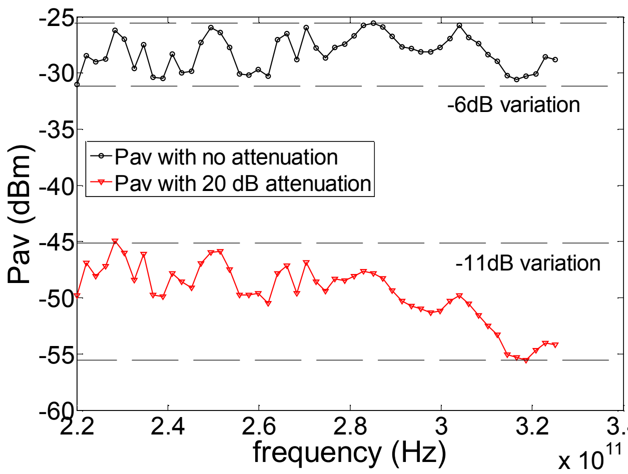

Fig. 1. Output power versus frequency of a mm-wave extender module in the WR-03 range, at different value of external attenuation.

The control of the available power enables the possibility for power controlled s-parameter measurements as well as large signal characterization of devices at every frequency covered by the VNA extenders. In this work, measurement data are presented in the WR-10, WR-05 and WR-03 waveguide bands.

II. System Architecture

Fig 2 shows the schematic representation of the proposed test-bench. In this setup, the test-set is equipped with two VNA extender modules, allowing full two-port calibrated s-parameters. Currently, modules for different waveguide bandwidths are commercially available, covering an overall frequency range from 50 GHz to 1.1 THz [2], and the designed setup is suitable for all the possible waveguide bandwidths. The generation of the RF and LO signals providing the feed to the mm-wave extenders is performed using the internal sources of the VNA, when using a two-source analyzer.

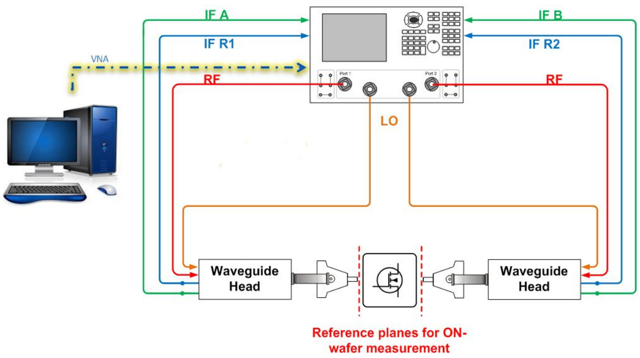

Fig. 2. Simplified schematic for the proposed measurement setup.

The acquisition of the coupled waves is performed using the VNA receivers. The values of the scattered waves are then sampled and sent to an external controlling PC, where all the computation is performed. In addition to the previous components, not shown in the schematic, a power meter is needed to perform the absolute power calibration, as it will be discussed in following sections. In this setup a calorimeter based power meter has been used, allowing power measurement from 75 GHz to 1.1 THz [2]. Finally, for on-wafer DUT measurements, wafer probes need to be used.

III. The Proposed Method

In order to properly control the power, the knowledge of the absolute power at the reference port, together with the chain gain/losses of the mm-wave extender modules are required. Once these parameters are known, the software aided-solution could mimic the behavior of a closed-loop control system.

The proposed calibration procedure that allows the refined power control at the input of the DUT requires four steps. First, a conventional off-wafer two-port calibration (i.e., TRL [3] or LRM [4]) is performed at the mm-wave modules waveguide sections. Then a power calibration, as described in [5], is performed at the waveguide port in order to have a complete knowledge of the absolute power at the output of the module. The power calibration is performed by connecting the power meter at the port 1 calibration reference plane, as set from the off-wafer calibration. After the power measurement is performed, a link between absolute power and the waves measured at the VNA receiver is created by means of an additional error term [5].

Once the power at the waveguide reference planes can be correctly measured, a last OFF-wafer step must be performed in order to characterize the relation between the RF source power, set in the VNA, and the power available at waveguide Port-1 and Port-2. This step is the so-called "power leveling". During power leveling, a large number of frequency sweeps is performed, varying the VNA RF source power level while measuring the related output power at the waveguide port and the reflection coefficient Γ at both Port-1 and Port-2, which are connected to a 50Ohm termination. Hence, the power available at the same reference planes, at each frequency, can be computed as:

$$P_{av_{Port=1,Port=2}}|_f = \frac{P_{in_{Port=1,Port=2}}}{\left(1-\left|\Gamma_{Port=1,Port=2}\right|^2\right)} \quad (1)$$

The result, as depicted in Fig. 3, is a look-up table, showing the power available at the specified port as a function of both the source power provided by the VNA, P_{RF}, and the frequency. Once the power leveling is performed, the system is able to compute the source power level that must be set in the PNA in order to have the desired power available at Port-1 and Port-2, for all the frequencies of interest.

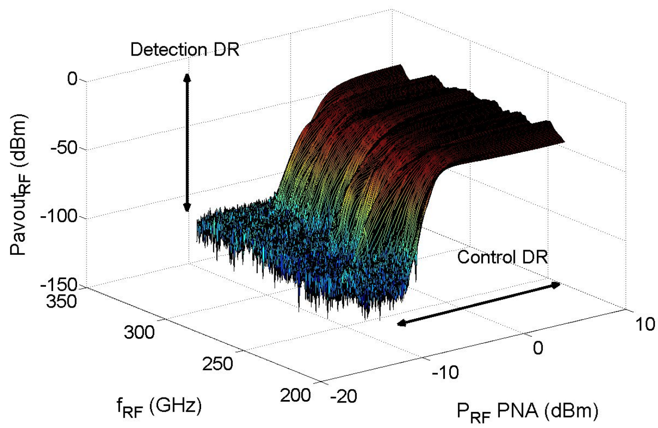

Fig. 3. Power leveling results for Port1 of the proposed setup, in the WR-3 waveguide band. The plot depicts the value of the output power at the port of the extender module as a function of the source power provided by the VNA and the frequency.

In order to move the calibration reference plane to the probe tips, a further calibration step is needed, consisting in the de-embedding of the wafer probes. This de-embedding procedure can be performed on alumina based impedance standard substrate (ISS) or on a calibration kit manufactured on fused-silica substrate as described in [6], using standard two-port de-embedding procedures.

IV. Experimental Results

A. Power Control

After the setup is properly calibrated and the power leveling is performed, it is possible to accurately control the power at the output of the extenders, or at the probe tips if an on-wafer configuration is selected.

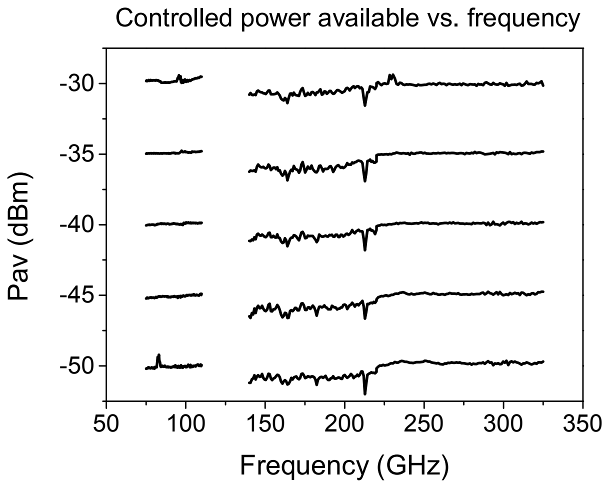

Fig. 4. Power available at Port1 of the proposed setup versus frequency in the WR-10, WR-5 and WR-3 waveguide bands, after power leveling. The plot shows the measured output power for different values of power set from the user, versus frequency.

In Fig. 4 values of power available at the waveguide ports of the mm-wave extenders are shown for the three considered frequency ranges after the power leveling is applied. The accuracy in power control depends on the frequency range and on the hardware implementation of the up-conversion chain, which depends on the manufacturer. For the considered configuration, the largest spread in control level is obtained in the WR-5 frequency range, where the power control can only be set with a ±0.75dB error. Note, that the read out in the absolute power provides an accurate value independent of the uncertainty in the set power.

B. Stability

In order to showcase the performance of the proposed setup in terms of measurement stability, repeated measurements have been performed in a limited time period over the different waveguide bands, and the results have been used to extract the stability of the measurements in terms of standard deviation, versus frequency.

First, 100 consecutive measurements have been performed in the entire frequency range. Then, another measurement has been performed after 10 minutes, in which the system has been turned off. In Fig. 5 the variation of the mean value of the available power, normalized to the available power at thermal regime, is shown versus time. For all the considered waveguide bands, the result highlights an RC time constant behavior, which can be associated to a thermal transient. The average available power thus vary from an initial value, measured when the system is in a "cold state", to a regime value when the thermal transient is completed. When the RF and LO signals are switched off for a sufficiently long time period, the system returns to its initial state.

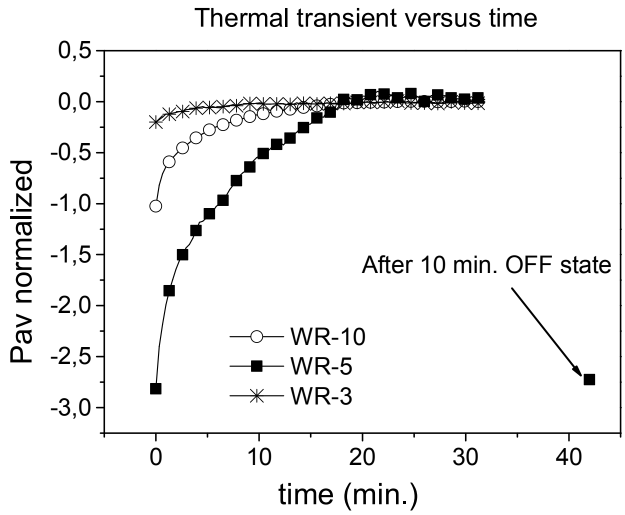

Fig. 5. Average available power, normalized to the regime value, measured at port-1 of the designed setup, for WR-10, WR5 and WR-3 waveguide bands, for the same power set from the user equal to -30 dBm, over 100 consecutive measurements.

As shown in Fig. 5, the characteristics of the thermal transient, in terms of time constant and power variation, are strongly dependent on the considered module, being frequency and manufacturer dependent.

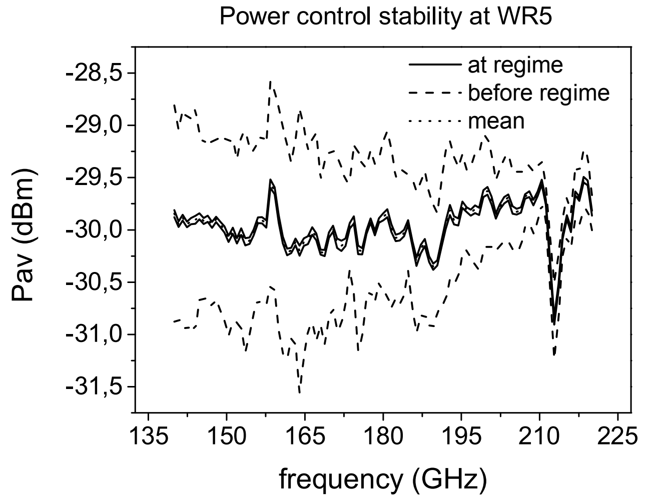

Fig. 6. Stability of the power control in the WR-5 waveguide band. The dashed lines represent the stability boundaries defined using the standard deviation extracted from the 100 measurements considered in Fig.5. The solid lines define the stability boundaries using the standard deviation extracted from measurements when thermal stability is reached.

This thermal transient has to be taken into account when defining the stability of the measurement setup. In fact, the measurement repeatability strongly depends on the region of the transient in which the specific measurement is performed. In order to define the impact of the thermal drift on the stability performances, first the standard deviation versus frequency has been extracted from the 100 repeated measurements shown in Fig. 5. Then the same procedure has been performed only considering measurements obtained at the thermal regime. The results are showcased in Fig. 6, where the stability boundaries defined using the two different standard deviations are sketched for the WR-5 waveguide band. This plot shows a drastic improvement in terms of stability when performing measurements at thermal regime, with the average value of standard deviation varying from 2 dB to 0.03 dB.

C. Large signal capabilities

The procedure described in section III allows the refined control of the available power at both ports of the measurement setup. When the power measurement and control capabilities are enabled, large signal measurements can be also performed.

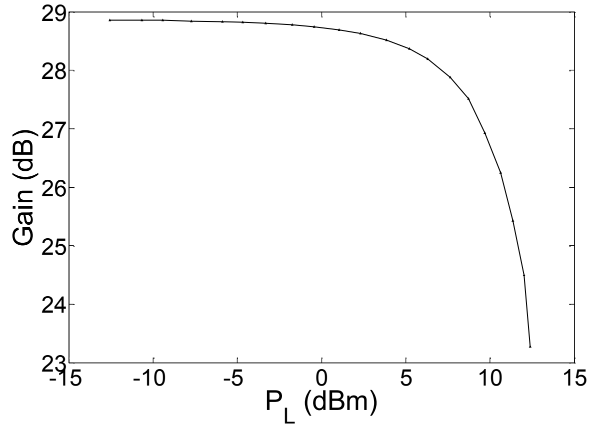

Fig. 7. Gain vs. power delivered to the load measured for a Norden Millimeter N09-2412 amplifier at 90 GHz

In order to showcase the capabilities of the system for large signal measurements, a Norden Millimeter N09-2412 amplifier has been measured in the frequency range from 75 to 110 GHz, for an input power range from -40 to -10 dBm. Fig. 7 shows the results in terms of power gain versus power delivered to the load obtained at 90 GHz.

V. CONCLUSIONS

In this work a novel method to achieve power control for s-parameters and large signal characterization for mm-wave and sub-mm-wave devices has been presented. The method aims to maximize the measurement dynamic range in setups in which mm-wave extender modules are used, allowing a refined control of the power available at the DUT. The system architecture has been described, together with all the calibration steps required for achieving the power level control.

Measurement results have been shown highlighting the power level control capabilities at the mm-wave extender ports in the WR-10, WR-5 and WR-3 waveguide bandwidths. A study has also been performed in order to showcase the stability performances of the proposed setup and their dependence on the system thermal state. Finally the capability of the designed setup for large signal measurements in the WR-10 frequency range has been demonstrated.

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