INVITED PAPER

Millimeter Wave and Sub-THz Power Sweep and Active Load-Pull Measurements

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The advancement of semiconductor technologies is driving the emergence of new and expanded applications within the mmWave and sub-THz frequency spectrums. These applications include 5G, 6G and upcoming evolutions of wireless communications, radar in automotive and security markets, imaging and sensing, radio astronomy, satellite communications, military applications like electronic warfare and scientific research. Whether a particular semiconductor technology is ultimately successful in one or more of these applications is determined, in part, by its performance in certain critical areas, including output power, gain and efficiency. Designers can determine and optimize these performance parameters through device characterization and, more specifically, by performing power sweep and load-pull measurements.

AN INTRODUCTION TO LOAD-PULL MEASUREMENTS

Load-pull refers to the technique of altering the load impedance presented to a device under test (DUT), typically a transistor. This is done to assess the performance characteristics of the device across different large signal conditions. Systematic adjustments are made to impedances while concurrently measuring or calculating parameters like output power, gain and efficiency. Contours are generated to reflect fixed performance values, such as an output power of X dBm or efficiency of Y percent. These contours aid in visualizing the optimum performance point, understanding how performance changes and evaluating the trade-offs between different parameters.

To understand the load-pull technique, consider a DUT as a two-port network, as shown in ***Figure 1***. The magnitude of reflection, Γ_L, is calculated as shown in Equation 1:

$$\Gamma_L = \frac{a_2}{b_2} \quad (1)$$

Load-pull changes the magnitude of reflection presented to the load of the DUT by manipulating the reflected signal, a_2, and this manipulation has a similar effect on the phase of the reflection signal. Any load impedance can be expressed as the relationship shown in Equation 2.

$$Z = Z_0\left(\frac{1+\Gamma_L}{1-\Gamma_L}\right) \quad (2)$$

This relationship can be applied to the DUT as long as achieving the desired a_2 signal is feasible.

There are two common methodologies to vary the impedance presented

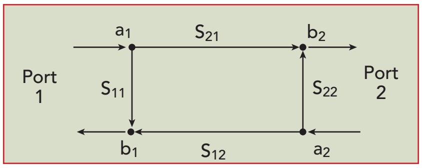

Fig. 1 Two-port network representation of DUT.

to a DUT: passive load-pull and active load-pull. Passive load-pull employs mechanical impedance tuners to modify both the magnitude and phase of a_2, which alters the impedance encountered by the DUT. Instead of using a mechanical tuner, active load-pull artificially creates, controls and injects the a_2 wave into the output port of the DUT to synthesize the desired Γ_L condition. In the specific case of open loop active load-pull, an external signal source that is phase-coherent with the a_1 wave and equipped with magnitude and phase control is used to generate a_2.

OPEN LOOP ACTIVE LOAD-PULL AT MMWAVE AND SUB-THZ FREQUENCIES

Armed with these basic concepts, the block diagram of a typical mmWave and sub-THz active load-pull system is shown in ***Figure 2***. The system works by generating an RF signal using the first signal source embedded in the vector network analyzer (VNA). The RF signal is routed into the vector modulator unit (VMU) where it is split into an RF1 and an RF2 signal that can be independently manipulated in magnitude and phase using embedded IQ modulators. The RF1 signal is routed into the VNA frequency extender module at the input of the DUT and the RF2 signal is routed into the VNA extender on the output side of the DUT. The VNA extender modules provide frequency up-conversion for the RF signals with an extender-specific frequency multiplication factor that takes the signals to the mmWave or sub-THz frequency of interest. The up-converted RF1 signal, which is equivalent to the a_1 wave shown in Figure 1, is injected into the input of the DUT to drive it at a specific power level. The up-converted RF2 signal, which is equivalent to the a_2 wave shown in Figure 1, is injected into the output of the DUT. By using the VNA extender modules to measure the b_2 wave, it is possible to iteratively adjust the injected a_1 wave to obtain the desired load condition. The drive power for the DUT is dependent on the power output of the VNA extender module, minus any losses between the module and DUT. An example of these losses would be losses caused by the wafer probe. It is important to note that the RF1 and RF2 signals, and therefore the a_1 and a_2 waves, are phase-coherent since they have been generated from the same signal source within the VNA. Additionally, the b_2 wave will be phase-coherent with the a_1 wave and with the a_2 wave. This allows the a_2 wave to be properly adjusted with respect to the b_2 wave to obtain the desired Γ_L response.

The formula that governs the relationship between the transistor, the system impedance, the injection power and the tuning range is presented in Equation 3:

$$Z_L = \frac{Z_{Sys} + K\,Z_{DUT} - \sqrt{\left(Z_{Sys} + KZ_{DUT}\right)^2 - \left(1-K\right)\left(Z_{Sys}{}^2 - KZ_{DUT}{}^2\right)}}{1-K} \quad (3)$$

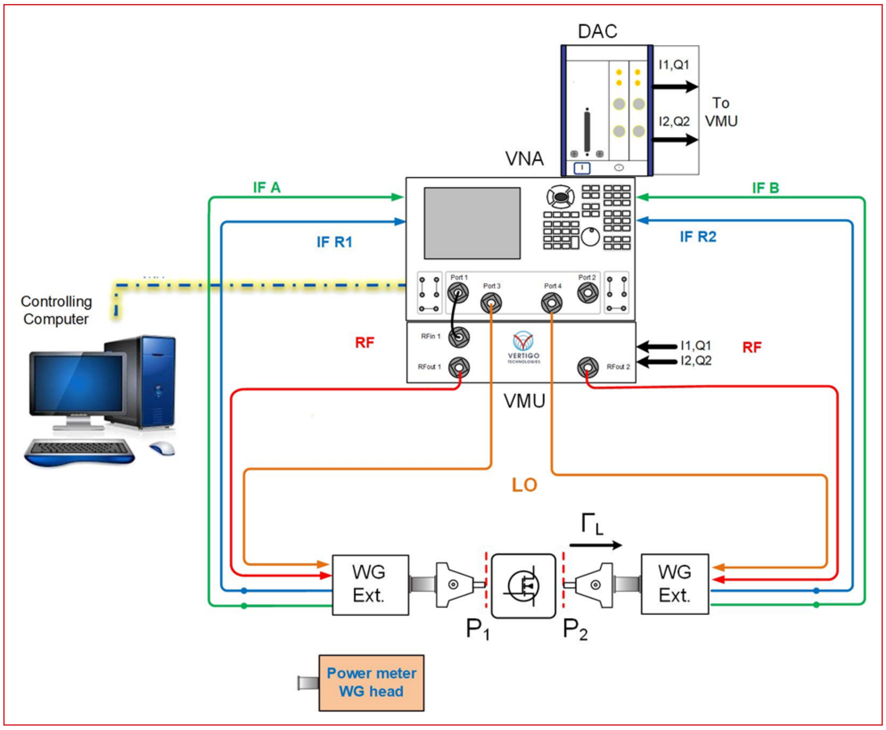

Fig. 2 mmWave and sub-THz active load-pull system block diagram.

Where:
Z_L is the impedance presented to the DUT
Z_{Sys} is the system impedance
Z_{DUT} is the DUT's output impedance
The factor K is defined in Equation 4:

$$K = \frac{P_{a2}}{P_{b2}} \cdot \frac{1-\left|\Gamma_{Sys}\right|^2}{1-\left|\Gamma_{DUT}\right|^2} \frac{\left|Z_{Sys} + Z_0\right|^2}{\left|Z_{DUT} + Z_0\right|^2} \quad (4)$$

Where:
P_{a2} is the active tuning power injected into the output of the DUT at the DUT reference plane
P_{b2} is the DUT's output power
$Z_0 = 50\ \Omega$

The net magnitude of reflection achievable at the DUT reference plane can be calculated using the equation shown in Equation 5:

$$\Gamma_L = \frac{Z-50}{Z+50} \quad (5)$$

From Equation 5, a higher available output power, P_{a2}, allows for a higher achievable Γ_L or Smith chart coverage. In a mmWave and sub-THz active load-pull system, the available power is determined by the VNA extender module used to up-convert the signal to mmWave or sub-THz frequencies.

VNA EXTENDER MODULES

VNA extender modules are used to extend the VNA measurement capabilities to higher frequency bands. These modules typically contain components that use rectangular waveguide connectors for signal transmission. This means that each system operates only across a particular rectangular waveguide frequency band.

A functional block diagram of a typical VNA extender module is shown in ***Figure 3***. The test signal from the VNA is coupled to an amplifier-multiplier chain to increase the frequency to the desired band with an overall multiplication factor of NRF as shown in the diagram. This signal then passes through a series of components before being transmitted out the test port. These components often include a variable attenuator, an isolator and most importantly, a pair of directional couplers. The local oscillator signal, coming from a second synthesizer within the VNA, is also amplified and multiplied by a factor of N_{LO} and then coupled to two down-conversion mixers through a splitter. The reference mixer, located in the "Ref." path, receives a small portion of the outgoing signal. This signal is converted to a lower frequency that can be detected and analyzed by the receivers in the VNA. This path essentially defines the magnitude and phase of the outgoing wave for the VNA. The second mixer performs the same function for any signal that is coupled in through the test port. Examples of this are signal power reflected from the input match of the DUT back to the extender mod-

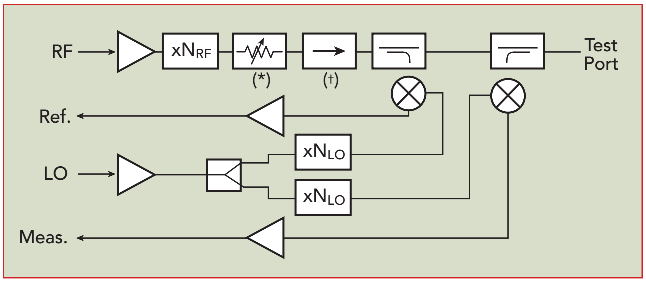

Fig. 3 Functional block diagram of a typical VNA extender module.

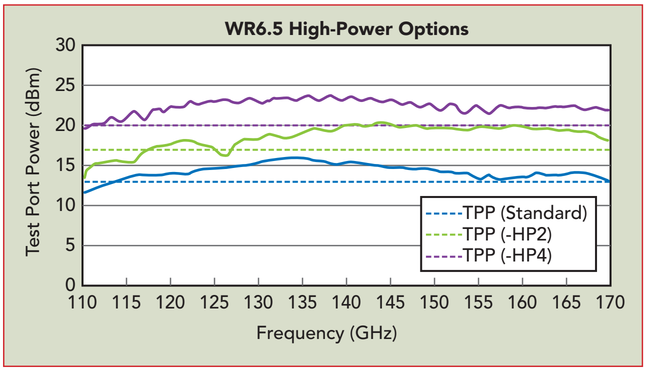

Fig. 4 Measured test port power for three VDI WR6.5 extenders.

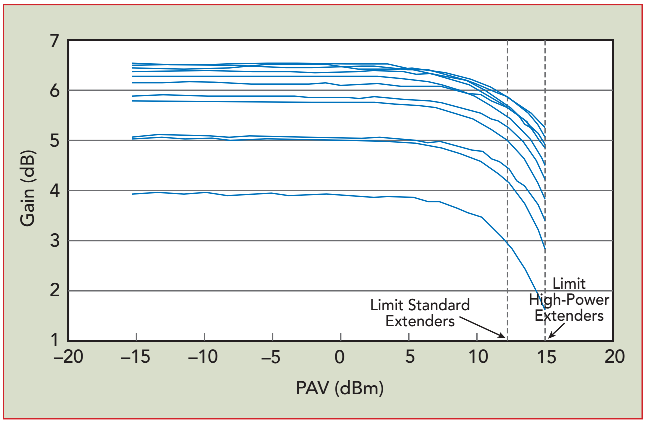

Fig. 5 Gain compression power sweep measurements at 140 GHz.

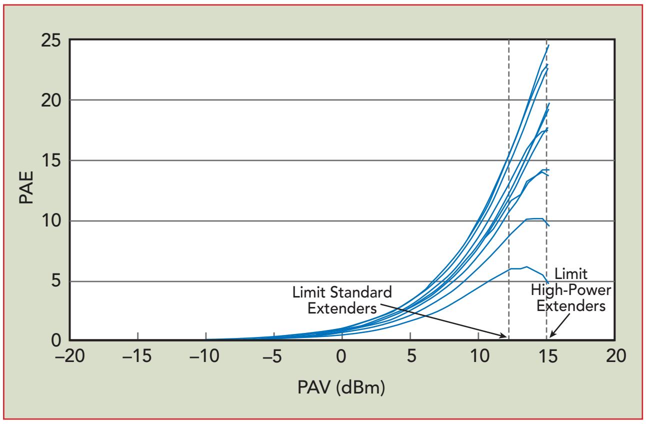

Fig. 6 PAE power sweep measurements at 140 GHz.

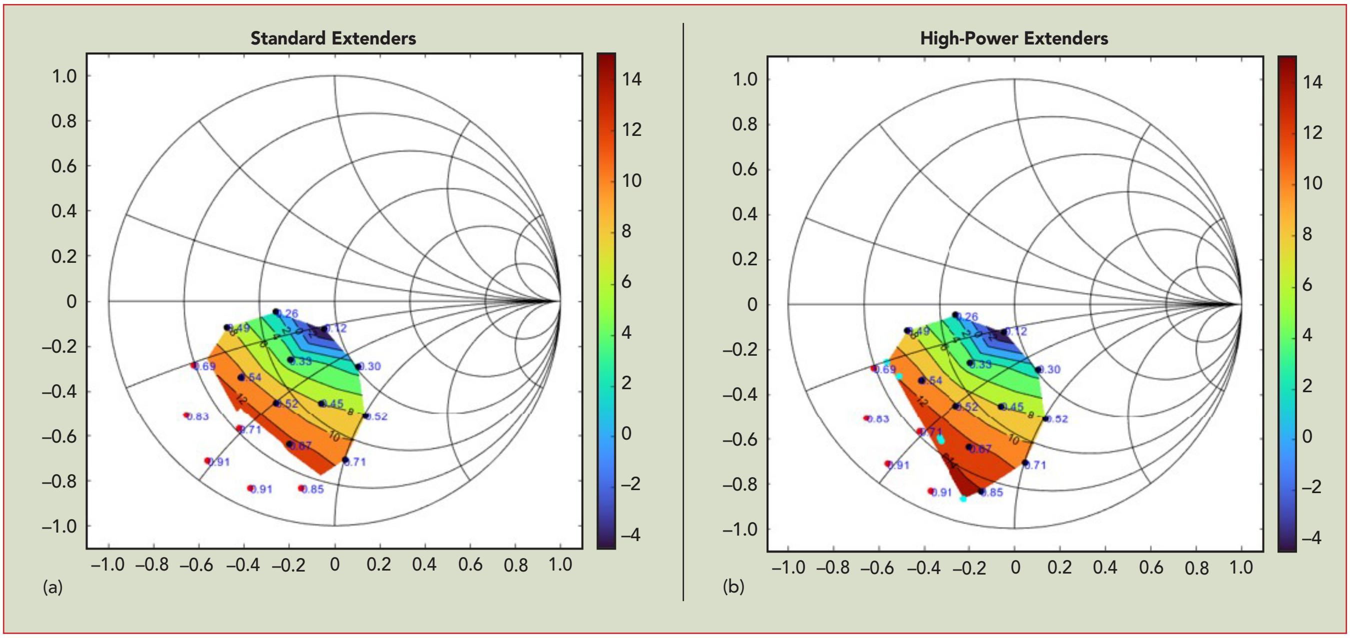

Fig. 7 **(a) Load-pull iso-contours for output power using standard extender modules at 140 GHz. (b) Load-pull iso-contours for output power using -HP2 high-power extender modules at 140 GHz.**

ule or signal power from another extender module that has passed through the DUT. Using two identical modules, it is possible to measure all four S-parameters of a two-port DUT.

For measurements of passive components, the S-parameters do not depend on signal power. This means that only a modest signal power is required. However, for active load-pull, power levels commensurate with the maximum power available from the DUT are desired to enable measurements that cover greater regions of the Smith chart.

New high-power VNA extender modules have been developed with higher-power multipliers and amplifiers. However, other system components must also be modified to ensure appropriate function and reliability at these higher power levels. Also, the system must be modified so that the mixers cannot be saturated under the full range of expected operating conditions. Other aspects of the module design, including thermal considerations and the module size, must also be reconsidered. The increased test port power levels for a WR6.5 extender module are shown in ***Figure 4***.

It is important to note that the measurements presented in this article used the standard and -HP2 high-power versions of the VDI extender modules. Additional power sweep saturation and load-pull contours could be achieved by using the -HP4 extender module.

GAIN COMPRESSION AND PAE POWER SWEEP MEASUREMENTS

Gain compression and power-added efficiency (PAE) power

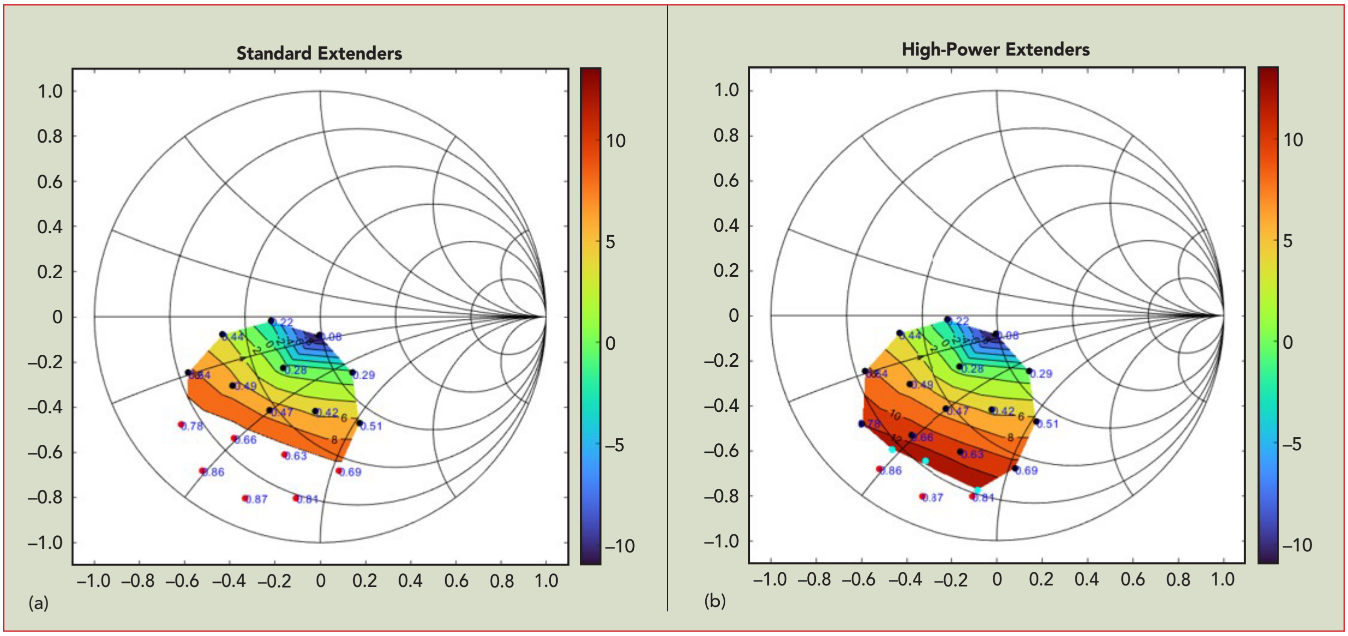

Fig. 8 (a) Load-pull iso-contours for output power using standard extender modules at 170 GHz. (b) Load-pull iso-contours for output power using -HP2 high-power extender modules at 170 GHz.

Fig. 9 Active load-pull system with characterization software.

sweep measurements were performed on a four-finger InP HBT from the ETH Zurich Millimeter Wave Electronics Group. The measurements were performed at 140 GHz using both the standard and the -HP2 high-power extender modules. While the standard extender was able to drive the DUT into compression, it did not have sufficient power to meet the P1dB threshold or achieve maximum PAE. Switching to the high-power extender resulted in approximately 2.5 dB of additional transmit power, surpassing the P1dB threshold and allowing determination of the maximum PAE. Gain compression power sweep measurements are shown in ***Figure 5*** and PAE power sweep measurements are shown in ***Figure 6***. Each curve represents a gain compression power sweep measurement at a unique load impedance using the same impedance pattern that will be shown in the next section of this article.

ACTIVE LOAD-PULL MEASUREMENTS

Active load-pull measurements were performed on the same four-finger InP HBT at 140 GHz and 170 GHz using the standard and -HP2 high-power extender modules. As expected, the high-power extender modules were able to achieve a higher magnitude of reflection, Γ_L, or Smith chart coverage as compared with the standard extender modules. The load-pull iso-contours for output power at 140 GHz are shown for the standard extender modules in ***Figure 7a*** and the iso-contours for output power using the high-power extender modules are shown in ***Figure 7b***. The iso-contours for output power using the standard extender module results at 170 GHz are shown in ***Figure 8a***. ***Figure 8b*** shows the iso-contours for output power using the high-power extender modules at 170 GHz.

CONCLUSION

Active load-pull is an elegant and practical method of characterizing semiconductor technologies at mmWave and sub-THz frequencies. The maximum power available to drive the DUT into compression and to perform active tuning is often limited by the output power of the VNA extender module. However, high-power models using higher-order combining techniques enable the complete characterization of larger devices as well as allowing higher magnitudes of reflection and more Smith chart coverage for load-pull measurements up to 1.1 THz. ***Figure 9*** shows an active load-pull setup that enables all the measurements and characterizations that have been discussed in this article. This setup will operate to 1.1 THz with the appropriate VNA extender modules. ■