Vertigo MT920-Series MMW-STUDIO

Millimeter-Wave and Sub-THz Characterization Software

DATA SHEET / 4T-024

MMW-STUDIO MODELS:

MT920A — MMW-STUDIO, mmW Studio High resolution power control for S-parameters and gain compression power sweep measurements

MT920B — MMW-STUDIO, mmW Studiio Active load pull at millimeter-wave and sub-THz frequencies add-on

MT920C — MMW-STUDIO, mmW Studio Data display

VERTIGO TECHNOLOGIES

Maury Microwave

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Vertigo MT920-Series MMW-STUDIO

MILLIMETER-WAVE AND SUB-THZ CHARACTERIZATION SOFTWARE

Introduction

MT920A MMW-STUDIO is a software suite designed to work with waveguide-banded millimeter-wave VNA systems and add accurate and repeatable high-resolution power control. The software enables the direct measurement of vector corrected power at the DUT reference plane, as well as control over the power delivered to the DUT. Doing so allows engineers to perform gain compression power sweep measurements over the available levels of power, and to perform S-parameter measurements at any arbitrary power level.

MMW-STUDIO enables:

- S-parameters measurements at user-specified power levels
- Fundamental powers (P_{in}, P_{av}, P_{load}), gain and efficiency measurements at 50Ω
- High-resolution power control for accurate and repeatable vector-corrected 50Ω gain compression power sweep measurements
- Calibrated measurements at DUT reference plane
- Support for most commercial waveguide extenders up to 1.1 THz
- Power, frequency and bias sweep

MT920B MMW-STUDIO LP is a software addon, which when used in conjunction with a Vector Modulation Unit (VMU), enables control over the magnitude and phase of the signals delivered to the input and output of the DUT. This enables an engineer to set arbitrary impedances, or perform active load pull measurements, where the magnitude of reflection presented to the DUT is achieved by controlling the reflected a_2 wave and fulfilling $\Gamma=a_2/b_2$.

MMW-STUDIO LP adds:

- Arbitrary impedance control / active load pull
- Measurements of fundamental powers (P_{in}, P_{av}, P_{load}) at arbitrary impedance

The system takes advantage of the frequency multiplication provided by millimeter wave extenders to extend active impedance tuning up to 1.1 THz.

MMW-STUDIO and MMW-STUDIO LP empower conventional waveguide banded millimeter-wave VNA systems to perform power measurements, large signal testing and active load-pull without using power meters[1], passive impedance tuners or additional test-sets, thereby taking advantage of the large dynamic range and high speeds of the VNA's receivers while maintaining a seamless setup configuration and user experience. These capabilities are critical for:

- Small/large signal model extraction of high frequency transistors up to f_T/f_{max}
- Small/large signal model validation of high frequency transistors up to f_T/f_{max}
- Prototype testing and optimization of (sub)THz active circuits
- Research and development, design validation test, and on-wafer production test

[1]A waveguide-flanged power meter is needed during calibration but is not employed for direct power measurement of the DUT.

Power control at millimeter-wave and sub-THz frequencies

Typical millimeter-wave S-parameter measurement systems use banded waveguide extenders to measure at the frequencies of interest, each having a fixed output power determined by the response of the up-conversion chain. Because of the nonlinearity of this response across frequency, the power at the output of the extender will vary as a function of frequency, with a flatness as high as 10 dB over the entire band. Some vendors will offer optional manual attenuators, but these are cumbersome to use and do not offer the high dynamic range required to fully characterize a DUT. In addition, the conventional power-control loop of the VNA is excluded from the measurement path which makes controlling the power complicated.

MMW-STUDIO employs a proprietary calibration procedure and algorithm to control the power delivered to the DUT at every frequency supported by the banded waveguide extender. The system block diagram, typical power flatness of a banded waveguide extender, and power control using MMW-STUDIO are shown in Figure 1.

The procedure is comprised of four steps, and is outlined in Figure 2:

1. S-parameter calibration at waveguide test-port. VNA S-parameter calibration using TRL or LRM methods

2. Power calibration

Using a waveguide-flanged power meter connected to one of the mm-wave extenders, the absolute power is measured across frequency and associated with the measurement of waves using the VNA's receivers. This procedure empowers the system to directly measure power using the VNA instead of a power meter.

3. Power levelling

The nonlinear power responses of the millimeter-wave extenders are characterized by sweeping the frequency at different input power levels (the control dynamic range) in order to cover the entire extender dynamic range (the detection dynamic range). This results in the creation of a look-up-table (LUT) which associates the power set by the VNA to the power available at the waveguide test-port at each frequency. This LUT is used to set any arbitrary power at the test-port, within the extender module's dynamic range.

4. Probe-tips/on-wafer calibration

The effect of wafer probes can be characterized using MMW-STUDIO's calibration GUI, or by using external software (such as WinCal XE). The measurement reference plane is then transferred from the waveguide extender to the probe-tip.

After the system is calibrated, MMW-STUDIO allows, in the entire frequency range of the employed waveguide-banded mm-wave extenders:

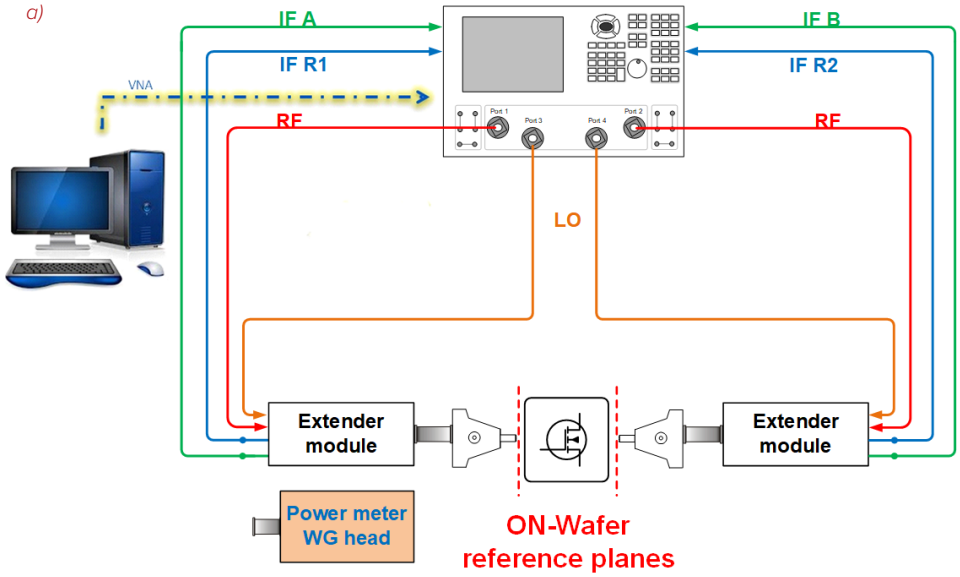
- S-parameters measurements with arbitrary power control at each frequency, defined at the DUT reference plane.
- Gain compression power sweep measurements over large dynamic ranges at the DUT reference plane.
- Measurements of fundamental powers (P_{in}, P_{av}, P_{load}), gain and efficiency at 50Ω

Figure 1:

a) Simplified schematic of a conventional mm-wave VNA setup based on waveguide banded module. When coupled with an external controlling computer and a power meter, MMW-STUDIO can be used to allow power control

b) Power available at the waveguide port of a commercially available WR5 VNA extender, without power control (asterisks) and with fixed -30 dBm power control using MMW-STUDIO (filled square)

a)



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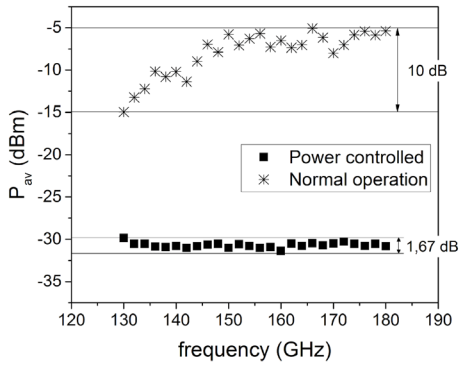
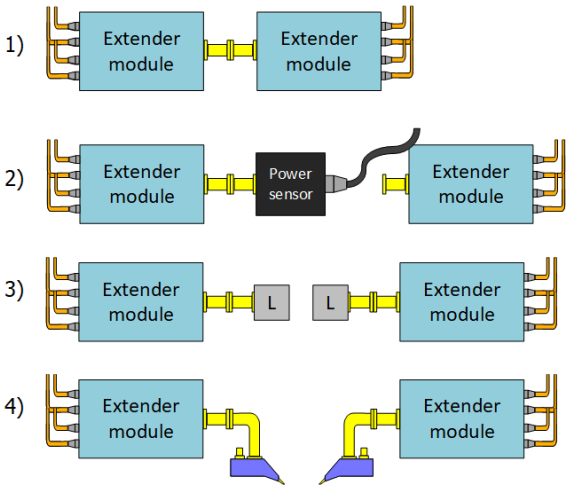


Figure 2:

a) Calibration steps for MMW-STUDIO

b) LUT resulting of a power levelling using commercially available WR3 extender modules

a)



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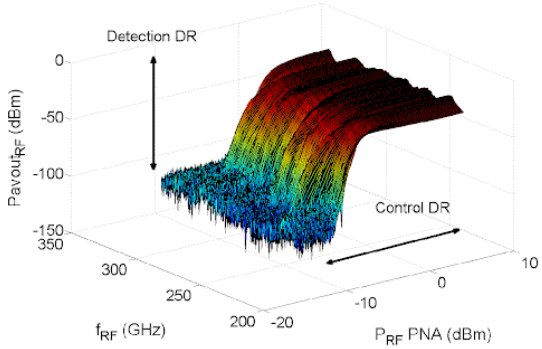


Load pull at millimeter-wave and sub-THz frequencies

An introduction to load pull

Load Pull is the act of presenting a set of controlled impedances to a device under test (DUT) and measuring a set of parameters at each point. By varying the impedance, it is possible to fully characterize the performance of a DUT and use the data to:

- Verify simulation results of a transistor model (model validation).
- Gather characterization data for model extraction (behavioral model extraction).
- Design amplifier matching networks for optimum performance (amplifier design).
- Ensure a microwave circuit's ability to perform after being exposed to high mismatch conditions (ruggedness test).
- Confirm the stability or performance of a microwave circuit or consumer product under non-ideal VSWR conditions (stability/performance/ conformance/antenna test).

Figure 3a—Example of load pull measurements with Output Power (Pout) contours plotted on a Smith Chart.

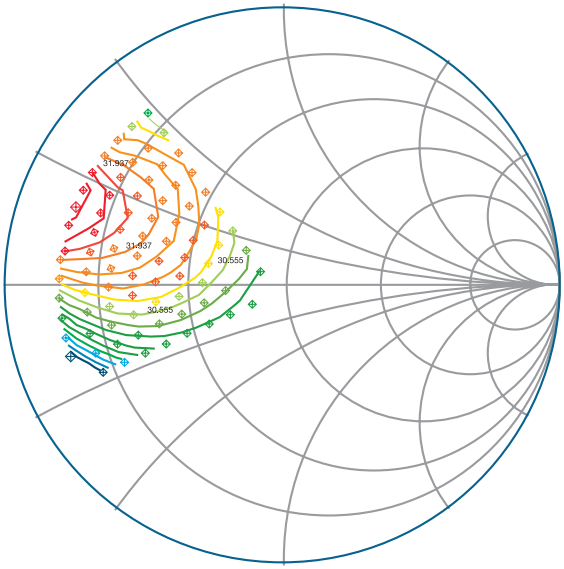


Figure 3b—Iso Pout Contours Measured @ 1.85 GHz

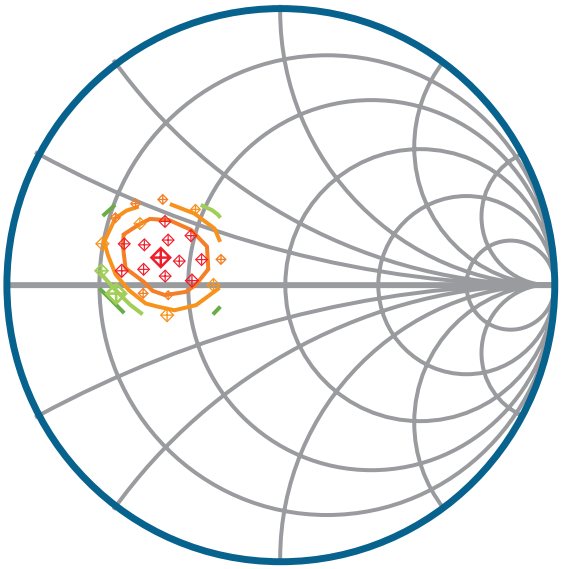
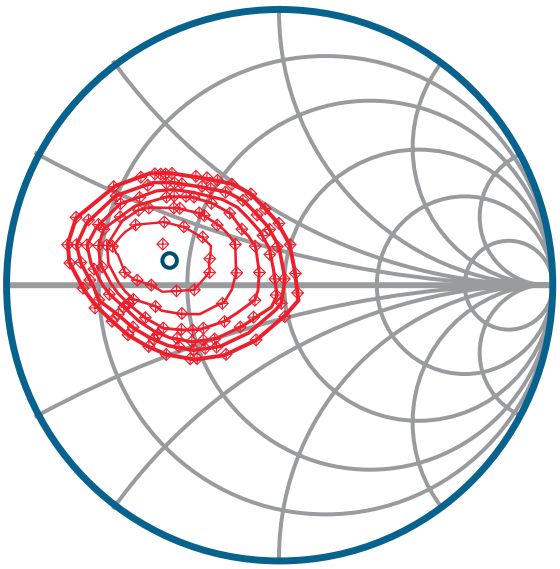


Figure 3c—Iso Pout Contours Simulated @ 1.85 GHz



Active load pull

In order to understand how the impedance presented to a DUT is varied, we must first consider the DUT as a two-port network shown in Figure 4.

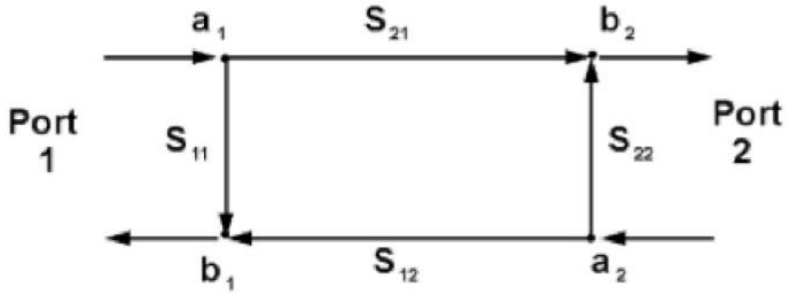


Figure 4: Two-port representation of a DUT

The two-port network consists of four waves, a_1, b_1, b_2 and a_2.

- a_1 is the input signal which is injected into port 1 of the DUT
- b_1 is the input signal which is reflected from the input of the DUT due to the mismatch between the DUT's input impedance and the load impedance of the input network
- b_2 is the signal which emerges from port 2 of the DUT
- a_2 is the output signal which is reflected from the output of the DUT due to the mismatch between the DUT's output impedance and the load impedance of the output network

The magnitude of reflection presented to the DUT is calculated as $\Gamma_L = \frac{a_2}{b_2}$. The magnitude and phase of the reflection presented to the load of the DUT can be varied by changing the magnitude and phase of the signal a_2. In other words, any load impedance $Z_L = \frac{Z_0(1-\Gamma_L)}{1+\Gamma_L}$ can be presented to the DUT as long as the signal a_2 can be achieved.

With regards to active load pull, the signal a_2 is a vector combination of the reflected portion of b_2 due to the mismatch between the DUT's output impedance and the load impedance of the output network, and a new signal created by a signal generator with magnitude and phase variability (referred to as an active tuning loop). An example block diagram of an active tuning loop is shown in Figure 5.

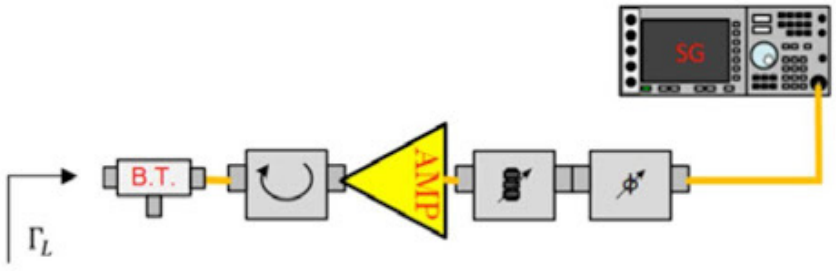


Figure 5: Output network of a simple active load-pull setup

In order to perform active load pull, it is necessary to have a vector-receiver capable of accurately measuring the a- and b-waves, as well as signal generator(s) capable of generating output tuning signals.

Millimeter-wave and sub-THz active load pull

The challenge with active load pull at millimeter-wave and sub-THz frequencies using waveguide extenders is solving how to adjust the magnitude and phase of the a_2 signal in order to obtain the desired Γ_L. MMW-STUDIO LP's methodology is to manipulate the magnitude and phase of the low-frequency signal going into the waveguide extender before the frequency multiplication occurs. This results in a change of the high-frequency signal's magnitude and phase, and when fully characterized, can be used to set an arbitrary a_2 wave and hence perform active load pull. The low-frequency signal is generated using the internal, low-phase-noise, synthesizer of the VNA. The magnitude and phase of the signal is manipulated using a vector modulator unit (VMU), which allows an arbitrary impedance to be set. Like lower frequency active load pull, the high dynamic-range receivers of the VNA are used to measure the a_1, b_1, a_2 and b_2 waves.

A simplified system block diagram of a millimeter-wave and sub-THz load pull system is shown in Figure 6. Compared with the typical 50Ω system shown in Figure 1, the main differences are as follows:

1. The RF signal for both P1 and P2 is obtained from a single shared VNA source
2. VMUs are placed between the VNA and the millimeter-wave extender modules
3. Control signals (CS1 and CS2) are used to tune the output signal of the VMU and are generated using an external digital-to-analog converter (DAC)

During active load pull, a single-tone signal is generated by the internal synthesizer of the VNA, at a frequency $f_{vna} = \frac{f_{meas}}{N}$,

where f_{meas} is the intended millimeter-wave measurement frequency, and N is the multiplication factor of the millimeter-wave extender module. Using CS1 (and the VMU) the power available at P1 is controlled and provided to the DUT. The response, b_2, of the DUT is measured at frequency fmeas using the receiver path of the extender module at P2 and the VNA receivers. The a_2 wave needed to synthesize a desired Γ_L is computed, and achieved using CS2, the VMU and iterative measurements. Finally, the a- and b-waves are measured at the DUT reference plane and used to compute all the quantities of interest (reflection coefficients, fundamental powers, gain and efficiency).

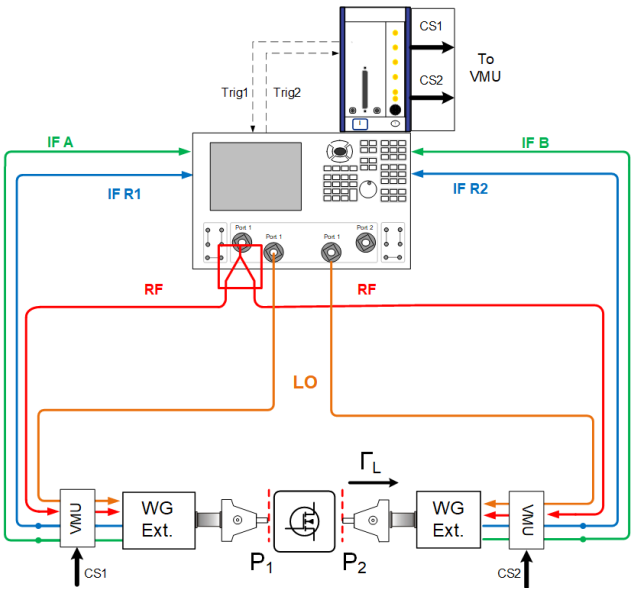


Figure 6: Simplified schematic of a load-pull architecture controllable with MMW-STUDIO LP

MT920A MMW-STUDIO – High resolution power control for S-parameters and gain compression power sweep measurements

MMW-STUDIO is the base module required for high resolution power control for S-parameters and gain compression power sweep measurements. It consists of the following capabilities:

- Instrument control[2] (VNA, power meter, bias control)
- Millimeter-wave VNA configuration (compatible with most commercial mm-wave extenders up to 1.1 THz)
- Full calibration routine
- Frequency, power and bias (up to two bias sources) sweeps
- Small-signal measurements (standard/power-controlled S-parameters)
- Large-signal measurements (P_{out}, P_{in}, P_{avs}, G_t, G_p, E_{ff}, PAE, V_{in}, V_{out}, I_{in}, I_{out}) at 50Ω

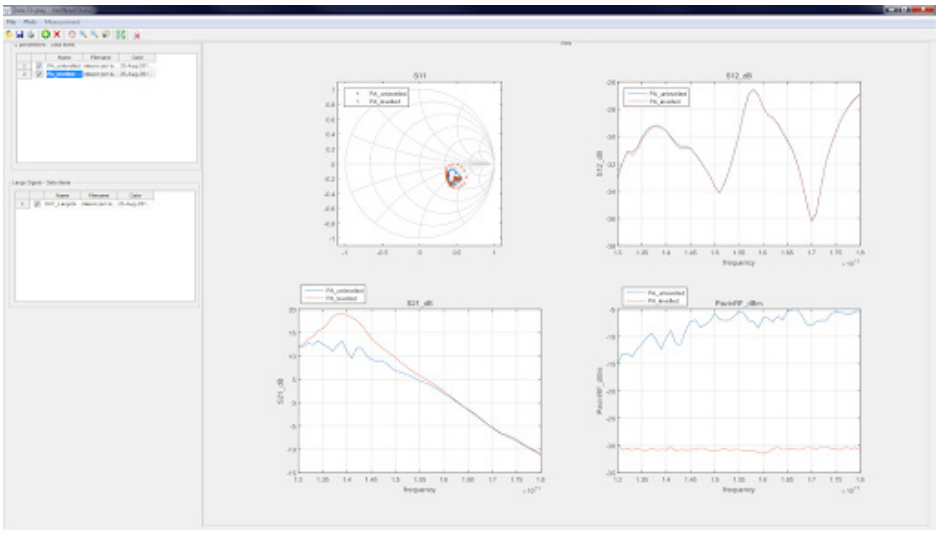


Figure 7: Measurements of S-parameters of a two-stage power amplifier in the frequency range between 130 GHz and 180 GHz, without power levelling (blue) and with power levelling (red).

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[2] Please see list of compatible devices

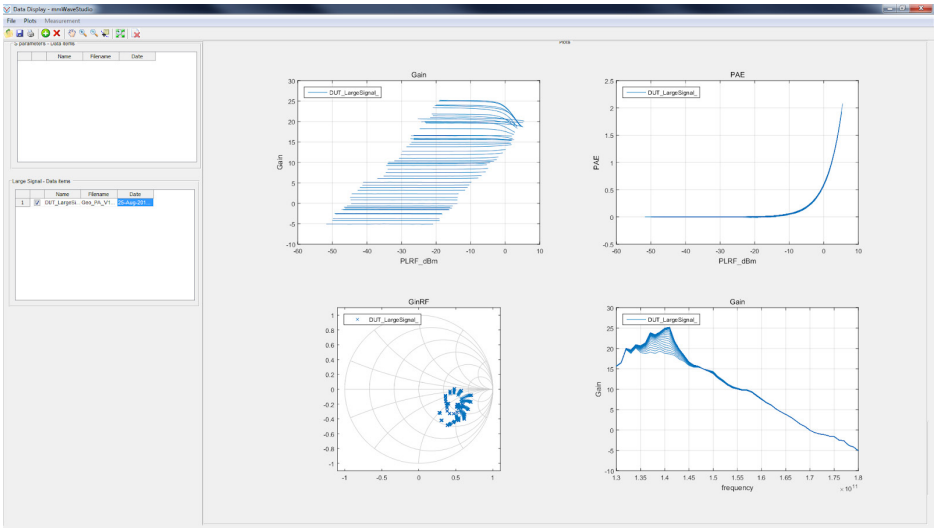

Figure 8: Large signal (power sweep) measurement of a two-stage power amplifier, at multiple frequencies (51 in the range 130 GHz to 180 GHz) for an input power range between -45 and -13 dBm

MT920B MMW-STUDIO LP – Active load pull at millimeter-wave and sub-THz frequencies add-on

MT920B MMW-STUDIO LP is an add-on option to MT920A MMW-STUDIO which enables active load-pull measurements. In addition to the capabilities of the base module MMW-STUDIO, MMW-STUDIO LP provides:

- Additional instrument control (VMU, DACs)
- Fundamental load impedance control
- Large-signal measurements (P_{out}, P_{in}, P_{avs}, G_t, G_p, E_{ff}, PAE, V_{in}, V_{out}, I_{in}, I_{out}) at any controlled load impedance

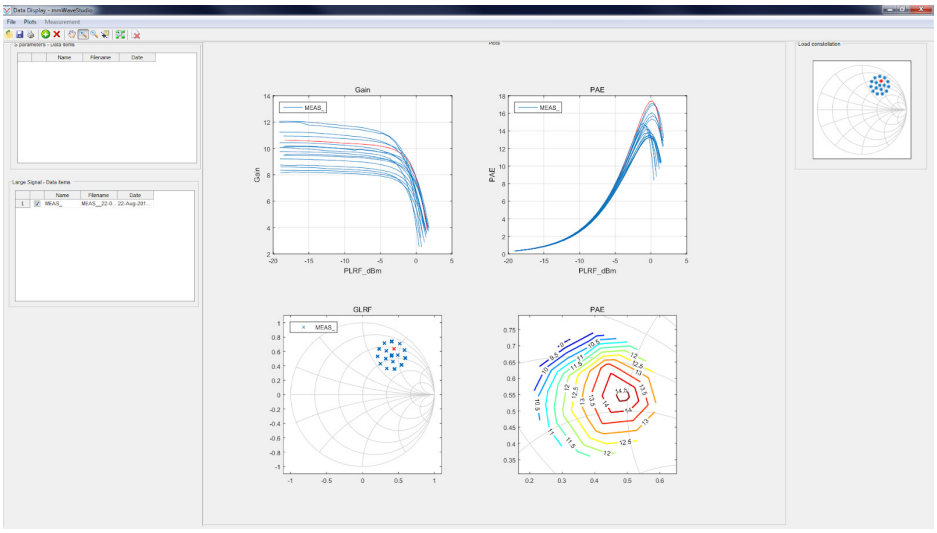

Figure 9: Data Display, showing results an active load-pull measurement of a SiGe 130nm HBT over 15 loading condition, at 75 GHz, for a set input power sweep from -30 to -2 dBm. In the plots: Power gain vs. power delivered to the load, PAE vs available power at the input, measured load impedances, PAE contour at P1dB.

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Note: a VMU is required to perform active load pull using MMW-STUDIO LP

MT920C MMW-STUDIO DD –Data display

MT920C MMW-STUDIO DD is the standalone version of the data display GUI and allows visualization and data analysis of measurements performed with MMW-STUDIO and MMW-STUDIO LP.

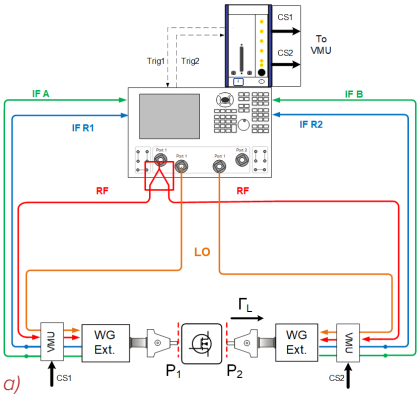
Hardware (VMU) models

A Vector Modulator Unit (VMU) is a required accessory for MMW-STUDIO LP in order to perform millimeter-wave and sub-THz active load pull.

VMU201802

VMU201802 are vector modulator units that are mounted on top of the waveguide extender modules. A single VMU201802 connects to a one waveguide extended module, and hence two VMUs are required per system.

	Min.	Typ.	Max.	Ext.
Pin	4 dBm	8 dBm	13 dBm	-
Pout	-	-	13 dBm	-
Frequency range	-	8 - 18 GHz	-	5 – 20 GHz
Vdc I,Q (abs)	0 V	-	1 V	-



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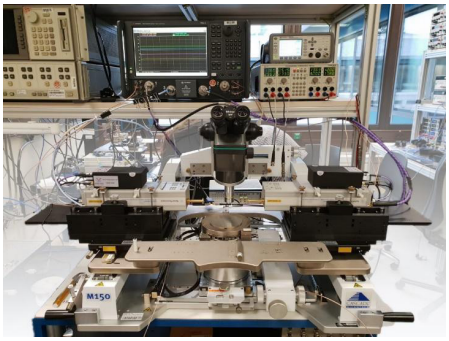


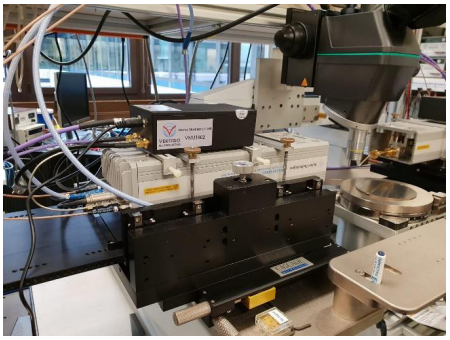
b)

Figure 10:

a) Basic schematic architecture of the MMW-STUDIO LP employing VMU201802.

b) Example of system implementation for load-pull measurements using MMW-STUDIO; 2x VMU201802 are mounted directly on WR10 OMLN5260-60003 extender.

a)



b)

Figure 11:

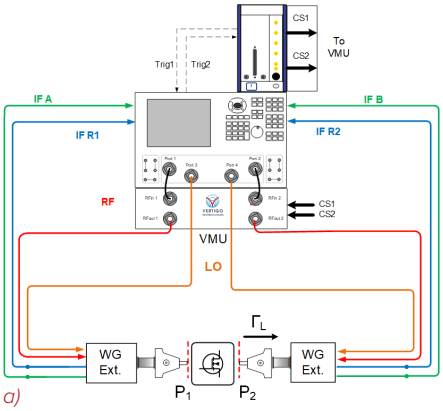
a) Example of VMU201802 casing (please notice, color and dimension may slightly change).

b) Mounting detail of a VMU201802 on an OML N5260-60003 extender.

VMU201901

VMU201901 are vector modulator units that are mounted in a standard 19” rack. A single VMU201901 connects to two waveguide extender modules, and hence only one VMU is required per system.

	Min.	Typ.	Max.	Ext.
Pin	9 dBm	13 dBm	17 dBm	-
Pout	-	-	10 dBm	-
Frequency range	-	8 - 18 GHz	-	5 – 20 GHz
Vdc I,Q (abs)	0 V	-	1 V	-



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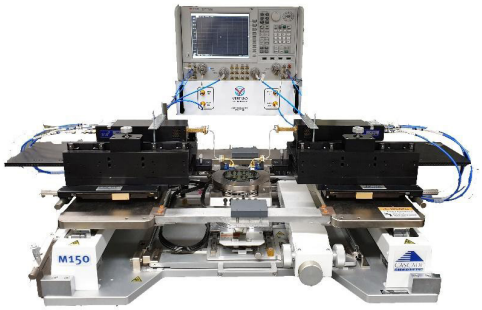

b)

Figure 12:

a) Basic schematic architecture of the MMW-STUDIO LP employing VMU201901.

b) Example of system implementation for load-pull measurements using MMW-STUDIO LP and VMU201901. The VMU is now a single rack-mount box, fixed under the VNA. In this setup, VDI VNAX WR6.5 extenders are used.

Typical system performance

The performance of an millimeter-wave active load pull system (i.e. absolute power control, power handling, dynamic range, stability of power and impedance, etc.) is highly dependent on the specific millimeter-wave VNA system used and is influenced by both the VNA and the waveguide extender modules, and can vary from system to system.

The following table shows typical performance measured on commercially available VNAs and extender modules.

Frequency (GHz)	Stability of Amplitude $\sigma(\lvert\Gamma\rvert)$	Stability of Phase $\sigma(\angle(\Gamma))$ (deg)
96	0.002	0.05
140	0.0035	0.33
180	0.0016	0.17
288	0.001	0.29
500	0.0046	0.57

Reported performances:

- Stability of $|\Gamma_L|$: reports the capability to reproduce a certain loading condition, and the variation on the absolute value, at a specific frequency, over 100 measurements, averaged over four different points on the Smith Chart. This value is reported as an absolute standard deviation (std).
- Stability of $\angle\Gamma_L$: reports the capability of reproduce a certain loading condition, and the variation on the phase (in degrees), at a specific frequency, over 100 measurements, averaged over four different points on the Smith Chart. This value is reported as an absolute standard deviation (std).

Supported instrumentation

VNA

- Keysight N5222A or N5222B (or higher frequency) PNA with option 401
- Keysight N5242A or N5244B (or higher frequency) PNA-X with options 400

Power meters

- Keysight/Agilent/HP E4418/19A/B EPM Series Power meter
- Keysight N1913/14A EPM Series Power meter
- Erickson/VDI PM4 and PM5

DC sources/Parameter Analyzers

- Keysight/Agilent E5270B
- Keysight/Agilent HP4142B
- Keysight/Agilent 66xxA
- Keysight/Agilent 662xA
- Keysight/Agilent E364xA
- Keysight/Agilent E3631A
- Keysight/Agilent E5260
- Keysight/Agilent N57xx

DACs

- NI PXIe-4463
- NI PXI-6733
- NI PXI-5422

Note: supported instrumentation is being continuously updated. Please contact us for a list of the latest instruments, or to request support for an unsupported instrument.

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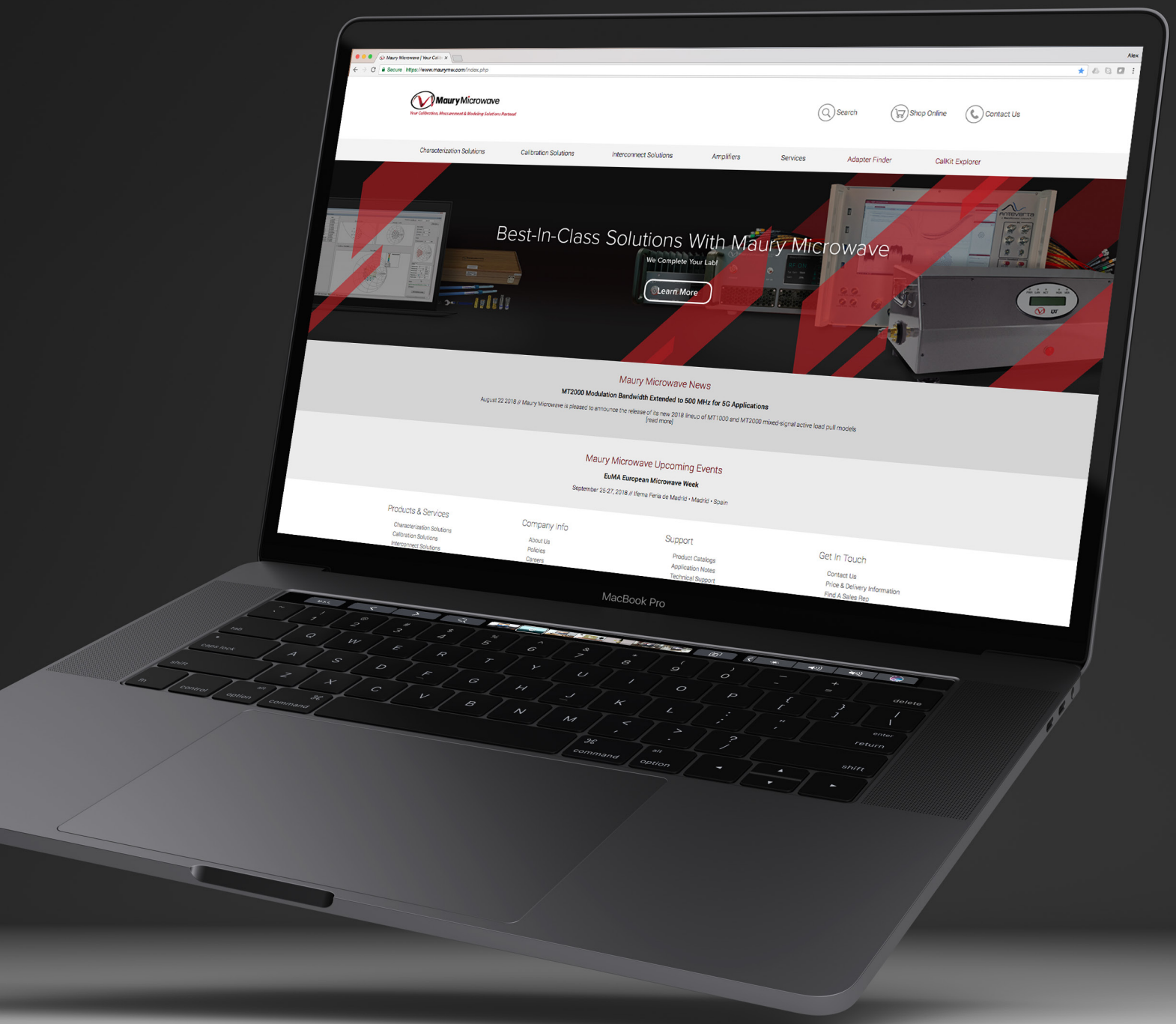

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