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Vectorial Harmonic Load Pull for mm-Wave Frequency Power Device Characterization and Compact Model Verification

Summary

This application note revises the load pull measurement techniques with an emphasis on a vectorial load pull method. Advanced impedance harmonic tuner (M-67100 DELTA) from Focus Microwaves, operating from 10 GHz to 67 GHz with four port network analyzer ZVA 67 from Rohde & Schwarz were used. Direct connection of low-loss TITAN™ Probes T67A GSG100 from MPI Corporation to the Delta tuners enabled lower loss and higher tuning range on a Smith chart. High-speed SiGe Heterojunction Bipolar Transistors (HBT) based power cells featuring maximum oscillation frequency (fmax) beyond 300 GHz were measured and verified on a compact model with carefully extracted model parameters. Possible transfer of vibrations of mechanical tuner carriage and inside probes to the RF probe tip were measured and found negligible. Model-based simulations confirmed the necessity of circulator usage at the input in the setup.

Chapter 1: Introduction

Recent technology advances in SiGe HBT performance [1] and predictions [2] enabled the realization of mm-wave frequency power applications such as stacked power amplifiers, transceivers, and MIMO radars [3]-[11]. One of the most critical components in an RF transceiver is the power amplifier (PA). It consists of an array of high-speed power cells, which typically correspond to a multi-finger transistor. Interconnections between power cell transistors significantly determine the performance of the PA, such as power added efficiency (PAE%), output power (POUT), and transducer power gain (GT) [12],[13]. The linearity and gain of PA are limited by parasitic effects like mutual self-heating, the influence of interconnection parasitics, cell positioning, etc. [13]. Careful optimization of the power-cell layout is required for PA improvement with the given process technology [13].

Device compact model (CM) development and verification of related circuits require accurate and direct measurements of power characteristics such as: 1 dB compression point (P1dB), power of harmonics (PO2H, PO3H), third order interception point of output power (OIP3), available power gain (PA), GT, PAE%, POUT and the maximum frequency of oscillation (fmax) at high frequencies in 50 ohms system environment and in matched to the device under test (DUT) conditions. This implies a need for Load Pull (LP) measurements at possibly the highest frequencies: V-band and beyond (W, D, G).

Load pull measurement is a tool for optimizing circuit parameters to obtain linearity for PA. Linearization is done by terminating harmonics, especially the third one, which cannot be canceled using differential circuitry. Harmonic termination requires knowledge of impedance, which can be obtained from harmonic LP measurements. The Harmonic tuner offers the most efficient way to find the optimal termination impedance of a DUT. LP system with harmonic tuner can find matching impedances of all three harmonics (in the range of tuner defined frequency). This enables PA linearity improvement using the harmonic termination transmission line technique [15]. It was shown previously that the DUT operating in nonlinear (class A-B, B, C) conditions, the control of harmonic impedances was of great importance: Load pull of DUT in nonlinear class of operation without controlling of harmonic impedances leads to false results [16, p.5].

Focus Microwave offers a wide range of the Delta impedance harmonic tuners (HT) covering frequencies from 6 GHz to 110 GHz: M-5060 DELTA, M-5080 DELTA, M-67100 DELTA, M-110240 DELTA. One of the most interesting impedance tuners is M-110240 DELTA, operating from 24 GHz to 110 GHz [14]. It allows for matching DUT output impedance up to 110 GHz at the fundamental, the second, and the third harmonics simultaneously. The pioneering design of the Delta tuner enabled the direct connection of the RF probes to its output. The last reduces unwanted losses between the tuner and the device under test (DUT) and drastically extends coverage of impedance states on a Smith chart at mm-wave frequencies.

Device compact model verification

Compact model development grounds up on the accurately measured data of the device current/voltage, capacitance/voltage characteristics, and biased S-parameters measured up to the highest possible frequencies. Nevertheless, the prediction of the DUT's linear performance and model verification is not enough when the device is operating in the large-signal mode and the presence of nonlinear currents. Nonlinear currents impact power performance, introducing signal distortion. Therefore, device CM requires verification of equations under the large-signal operation regime. Harmonic distortion (HD) in HBTs and circuits was investigated in a number of publications, e.g. [17]-[19].

However, analysis of harmonic distortion in most cases was limited to an unpractical linear power region with Volterra series terms. Vector LP along with compact model simulation enables model verification of the DUT in matched conditions as well in the time domain. Knowledge of harmonic impedances and their control on fixed values enables correct LP data of the device operating in nonlinear conditions, which is a common use case for HBTs. Vector harmonic load pull yields a deep inside in nonlinearities of a DUT (SiGe and InP HBTs, CMOS), including signal harmonics and dynamic time domain output and input voltage and current waves for compact model verification and development [20],[21]. behave for a given bias point and frequency.

Chapter 2. Modern Load Pull Techniques

Scalar Load Pull

There are two load pull techniques: the scalar and the vector, (Fig.1, Fig.3, respectively). The scalar load pull allows measurements of PA, GT, Power Added Efficiency (PAE%), POUT, Adjacent Channel Power Ratio (ACPR), Error Vector Magnitude EVM. Vector LP allows, in addition, measurement of the DUT input impedance (ZIN), input reflection coefficient (ZIN), Power Gain (GP) and PAE%. The limitation of the scalar system is a tie dependence of the measurement accuracy from the tuner characterization file (the relationship between the carriage position and the tuner impedance at a particular frequency).

Modern VNAs, such as ZNA from Rohde & Schwarz, can have four signal sources that can generate the input power independently and thus replace a standalone signal generator. In the set-up shown in the Fig. 1, VNA is used to measure both the DUT S-parameters as well as the distribution of impedance states on the Smith chart. Integrated RF switches eliminate the need for system reconfiguration, and thus, both types of measurements can be completed in one probing cycle. As discussed later, the circulator plays a crucial role by blocking the reflected energy from flowing back to the source and damaging it.

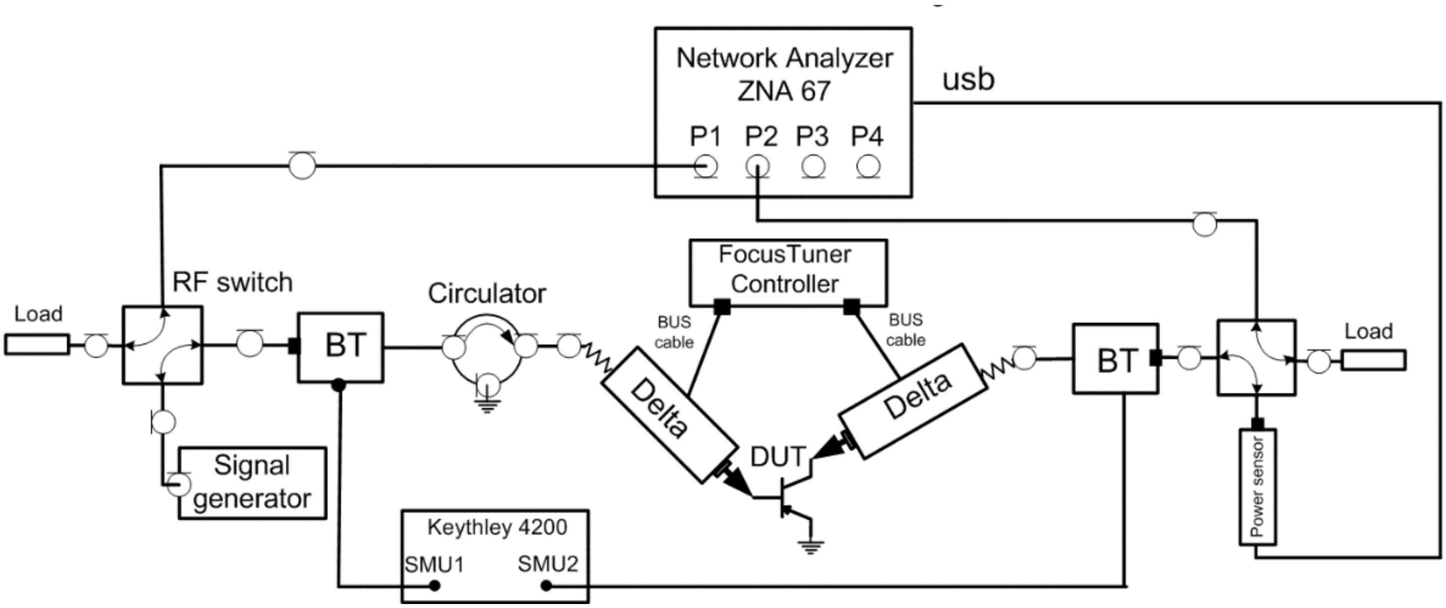

Figure 1. Schematic diagram of the scalar load pull system using a VNA and Focus Delta tuners.

Vector Load Pull

The vector LP characterization is enabled by using two bi-directional couplers between the tuner and the DUT, some configurations also support the use of couplers before and after the tuner for optimum tuning range for specific cases. The system can measure the incident and the reflected waves allowing for in-situ characterization of the tuner impedances presented to the DUT in real-time. Thus, the impact of the tuner characterization accuracy and its impedance state repeatability is eliminated, resulting in significant DUT characterization accuracy improvement [16].

Focus Microwaves' Delta tuners represent the further development of the vector LP concept and enable advanced vectorial load pull measurements. The need for an external signal generator is eliminated. Incident waves are taken for the ZNA sources, and reflected waves are delivered back to ZNA receivers. The system can further be enhanced by adding a phase reference that keeps in pace the phase of the incident and transferred waves, enabling the harmonic signal analysis in the time domain.

Passive Delta Tuners

At frequencies beyond K-band, the interconnections between power transistors of the multiple cells and the number of parallel emitter fingers introduce parasitic capacitors and inductors, which increase an internal output impedance (Z_{OUT}), which should be matched by optimizing the reflection factor. A good result for a mechanical impedance tuner is if it can reach 5 ohm impedance beyond K-band and VSWR ≈ 10:1.

In 2018, Focus developed a new family of tuners known as the Delta tuners. These tuners with their short inline slab line and small form factor allows direct connection with the RF probe, c.f. Fig. 2. Eliminating the need for a cable, therefore the only loss between the tuning probe and the DUT is the RF probe which has low loss compared to a RF cable. Due to the fine mechanics and high precision motors the carriage movement does not imply any mechanical vibration, like in conventional tuners. Note, that micro-vibration transferred to the probes is an issue for the on-wafer measurements, especially on the Al pads.

For frequencies from 100 MHz to 110 GHz Focus Microwaves uses the slide screw technique in which a reflective probe (slug) is inserted into the slot of a low loss slotted transmission line slab line . Electromechanical tuners have high-power handling, multi-octave bandwidths and tuning range of > 30:1 at the tuner reference plane. However, in the case of an on-wafer setup, when the tuner is connected to the RF probe through a small cable, the tuning range at the DUT reference plane is significantly reduced due to increased insertion loss between the DUT and the tuner. Tuners with extended slab lines have alleviated the problem to a good extent by being less lossy compared to the probe cables. However, the slug is still away from the DUT plane and affects the tuning range obtained at the DUT plane.

On Wafer Load Measurements

In the case of on-wafer applications, when a small probe cable is connected between the tuner and the RF probe, the gamma at the tuner reference plane Γ load is considerably reduced to gamma obtained at the DUT plane, DUT due to the insertion loss of:

1. the transmission line section inside the tuner
2. the test port adapter
3. the cable or bend line between test port and wafer-probe
4. the wafer-probe and its adapter

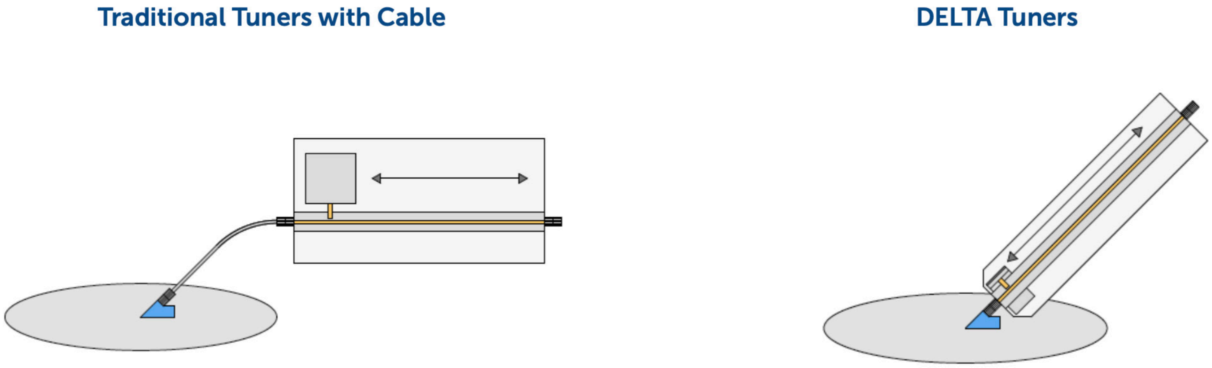

Figure 2. a) Conventional and b) DELTA impedance tuner and probe connection for on-wafer measurement [16]

An impact of losses does not allow to establish an impedance state, close to the Smith chart edge. It is known that with frequency losses increase significant and the coverage of available impedance states will shrink resulting to a poor LP result. Thus, direct tuner connection to the probe is highly important, especially for the V, W and D bands. Since Delta tuner is connected direct to the probe, the losses associated with the items 2 and 3 (Fig.2) are minimized or eliminated.

Focus has invested the time and efforst to eliminate all mecanical movement which could be translated tot the RF probe. Any movement could reduce the accuracy of measurements, especially for devices with Al contact pads metallization. Any small vibration of the probe may facilitate Al oxidation yielding to the increase of the contact resistance and, in the worst case, to the contact loss. The special design of Delta tuners ensures stable RF probes contact during the entire tuner operation cycle, including the tuner initialization mode (the whole coverage in X and Y axis of the tuner probe). The use of miniature carriages and small brackets allows for placing the tuning probes inside the tuner adjacent to the tuner test port. Such a feature enables in-situ calibration with great accuracy. Usually, this is not the case for the conventional electro-mechanical impedance tuners, where vibration is evident even if the tuner is located aside and connected to the probe with a flexible cable. Also, it is important to note that vibrations drastically reduce the lifetime of the DUT pads making device re-probing hard or impossible.

Vector Load Pull

The vector load pull allows measuring the large signal input impedance of the DUT, delivered power to the DUT, transducer, the power gain (GP=PDEL/PIN), PAE%, and all other spectral components, same as scalar load pull. Measuring <a> and <b> waves directly allows for calculating the real-time tuner impedances presented to the DUT and does not entirely rely on tuner characterization accuracy and repeatability. However, the tuner characterization helps to steer tuning into the right area of the Smith chart without a long search. For vector LP, directional couplers and a Vector Network Analyzer are required to measure forward and reverse traveling waves <a>, <b> and a phase reference calibrator for harmonic component and fully corrected time domain waveforms, c. f. Fig. 3.

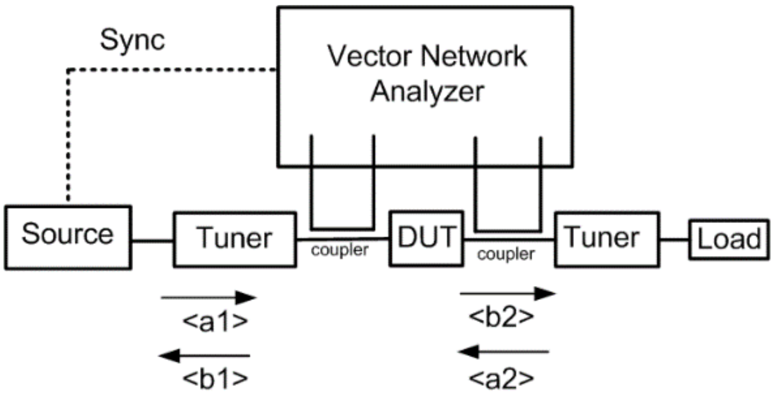

Figure 3. The schematic of Vector Load Pull system [16].

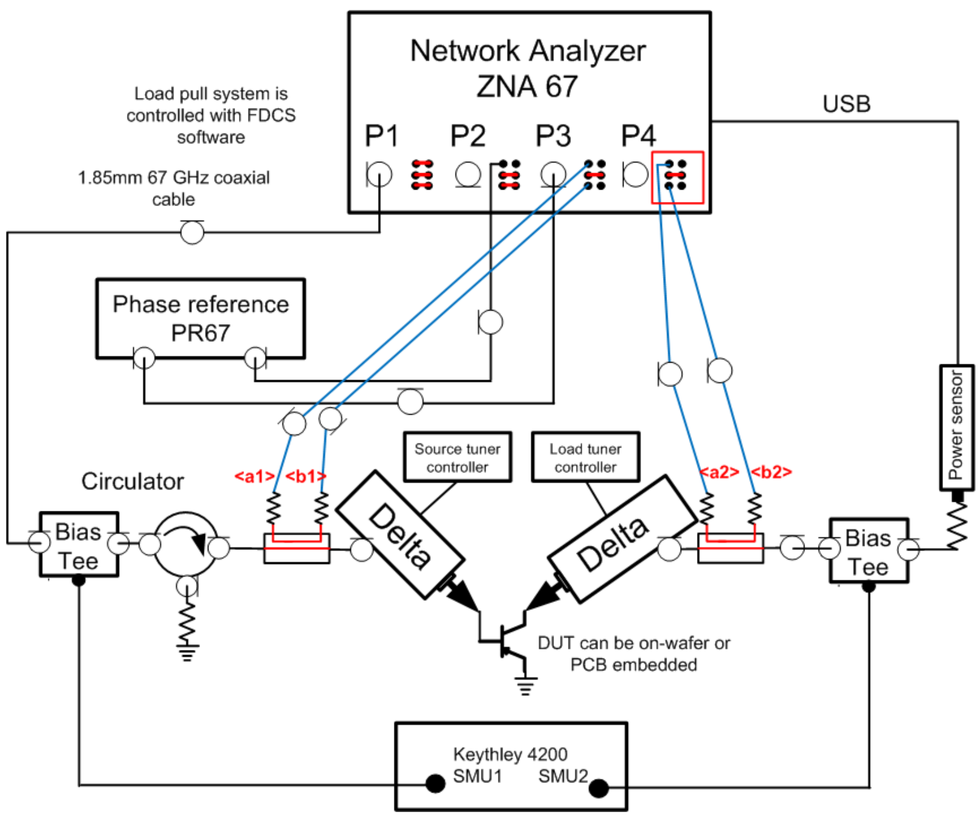

Figure 4. Detailed schematic of Vector Load Pull system with ZNA67 and Delta tuners.

A power sensor can be used instead of a 50 ohm load c.f. Fig. 4. Bi-directional couplers can easily be used with Delta tuners (as well a traditional tuners) to a four-port analyzer with direct access to its receivers. Fast in-situ calibration (including tuner characterization) enables very accurate measurements. A power sensor is used for the system power calibration. Since the power sensor is well matched to 50 ohms it can also be used as the termination load connected to the Bias Tee, c. f. Fig. 4. Incorporation of the Mesuro PR67 phase reference allows phase synchronization for the time domain measurement, what is extremely important for the analysis of harmonic distortion. Delta harmonic tuners allow measurements of harmonics and matching up to 110 GHz. Nonlinear network analyzers NVNA can also handle harmonic distortion measurements, including the time domain, however, in 50 ohms environment only and up to the maximal frequency of 67 GHz, due to the limit of the hardware.

Chapter 3 System Integration

The experimental system included the vectorial Load pull system from Focus Microwaves with Delta harmonic tuners (M-67100 Delta) mounted on the automated probe system TS3500-SE from MPI Corporation. The dedicated tuner integration solution for the MP80 micropositioner is available from MPI Corporation. It mounts the Delta tuner of the MP80 micropositioner and enables the direct mounting of the GSG TITAN™ Probes, like T67A-GSG100. TS3500SE was controlled by SENTIO® 3.6 Software Suite, providing very accurate probing and automated on-wafer probe tip VNA calibration with SENTIO-embedded QAlibria™ RF calibration software, c.f. Fig. 6. The tuners were controlled with Focus Microwave software FDCS.

Figure 6. A photo with Delta C-67100 tuners integration on TS3500-SE.

Load pull setup can be equipped with Mesuro PR67 phase reference unit for the time domain data extraction. Measured data can be easily imported into a circuit simulator like Keysight Advanced Design System.

Chapter 4 System Calibration

Before the load pull measurements, the tuner has to be calibrated or characterized, yielding a calibration file that contains the relationship between the tuner carriage and slug positions with the impedance values at fundamental frequency f0 and harmonics 2f0 and 3f0. It is crucial to select frequencies for calibration, which further will be used in measurement to prevent frequency interpolation. Tuner characterization can be done as a standalone or in-situ procedure. For in-situ characterization, the frequency selection should be reasonable to avoid the long-lasting procedure. Tuner characterization can be done with the VNA calibrated to the cable end using the coaxial calibration kit or an automated calibration unit. Reliable results are obtained when the VNA is calibrated using TRL calibration method. Another step is to characterize all setup components: input cable network, bias tees, probes, and couplers. Focus Microwaves recommends the use of in-situ tuner characterization [23]. Note that Vectorial Load Pull system calibration consists of similar first steps as Scalar LP calibration requires.

The following steps complete the Scalar Load Pull calibration [23]:

1. Coaxial VNA calibration on the RF cables between Port 1 and Port 2. The proper calibration kit, such as Focus Microwave TRL calibration kit, is recommended. After coaxial calibration is complete, the cables are connected to the input and output cables of the tuners, c. f. Fig. 7.

2. Connect the CPW calibration substrate, such as AC-2 from MPI Corporation, and execute Focus Microwave TRL calibration procedure to extract the losses of the tuner, the tuner interface cables, and the RF probe from the second-tier calibration. The second-tier calibration for CONA and CONB network extraction can also be done with software like QAlibria v.1.9 from MPI Corporation. It is important to keep the same selected frequencies for the tuner in-situ characterization, which follows. The in-situ tuner characterization is performed with the probes connected on the "Thru" standard from the calibration substrate. Note that pre-characterized tuner file also can be recalled.

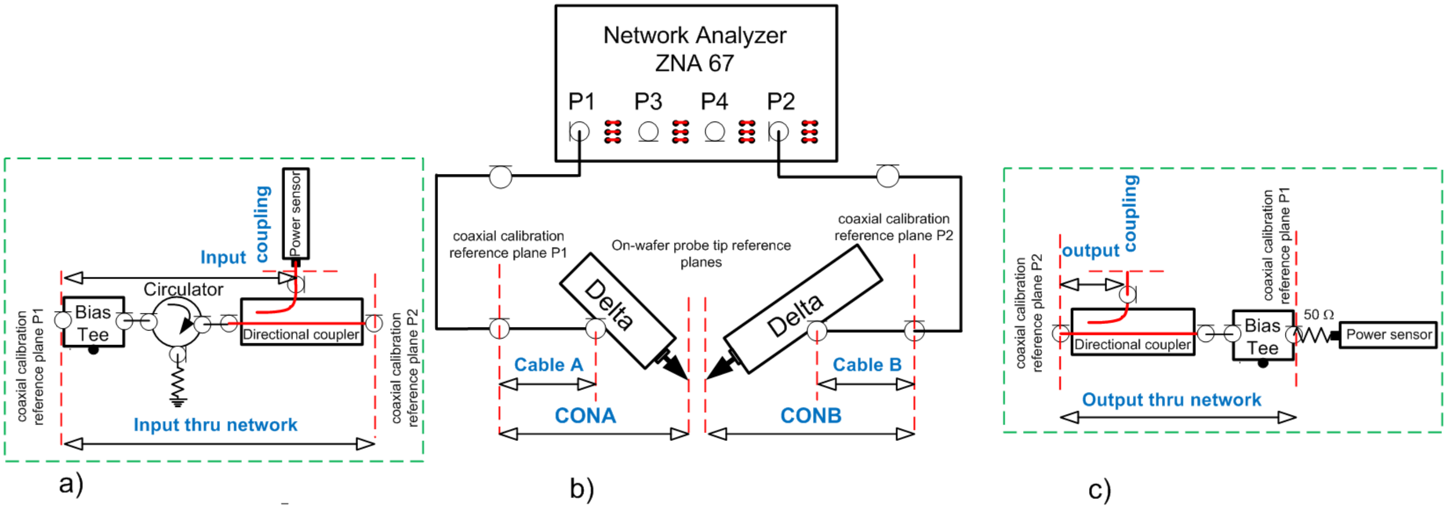

Figure 7. The schematic of Scalar Load pull system: a) input network, b) setup for two-tier calibration to get CONA and CONB files, c) output network.

The scalar load pull does not require VNA but a power source and power meter at the output. The power source of the VNA can be used as such a source. Focus Microwaves software FDCS controlls a wide variety of signal sources, including VNA sources. As Delta tuners have low loss, they can be easily used for vector load pull measurements in combination with a four-port VNA. Signal waves can be converted to input and output dynamic voltages and currents or powers of the DUT. In such case, a power sensor is not required, but the 50 ohm termination of the output is recommended to ensure system stability. Note that a circulator at the input is required to reject the reflected power back to the signal source. If the circulator is neglected, the incident power is not well-defined, resulting in erroneous load iso-power lines, output power POUT and transducer power gain GT. The importance of the circulator is demonstrated later by the model-based simulations in the following chapter.

Detailed steps for Vectorial Load Pull calibration are described in [23]. The vectorial Load pull setup is given in Fig. 8. The source of the ZNA at Port 1 is used as the CW power drive. Usually, the VNA can generate about 10 dBm of RF power, depending on the frequency. If the power is not sufficient to drive DUT to compression, a power amplifier needs to be added to the setup. It is highly recommended to use a circulator to prevent reflected waves return back to the source. RF power is injected thru the small low loss RF "cable A" directly to the tuner. Measurements are done on the couplers'output connectors. It is recommended to use attenuation on the coupler's connectors for the input (~10 dB) and for the output (~20 dB) to prevent the receivers from overload, receiver`s non-linear gain region, or possible damage. Note that the same files for the tuner CONA and CONB could be used as in scalar load pull.

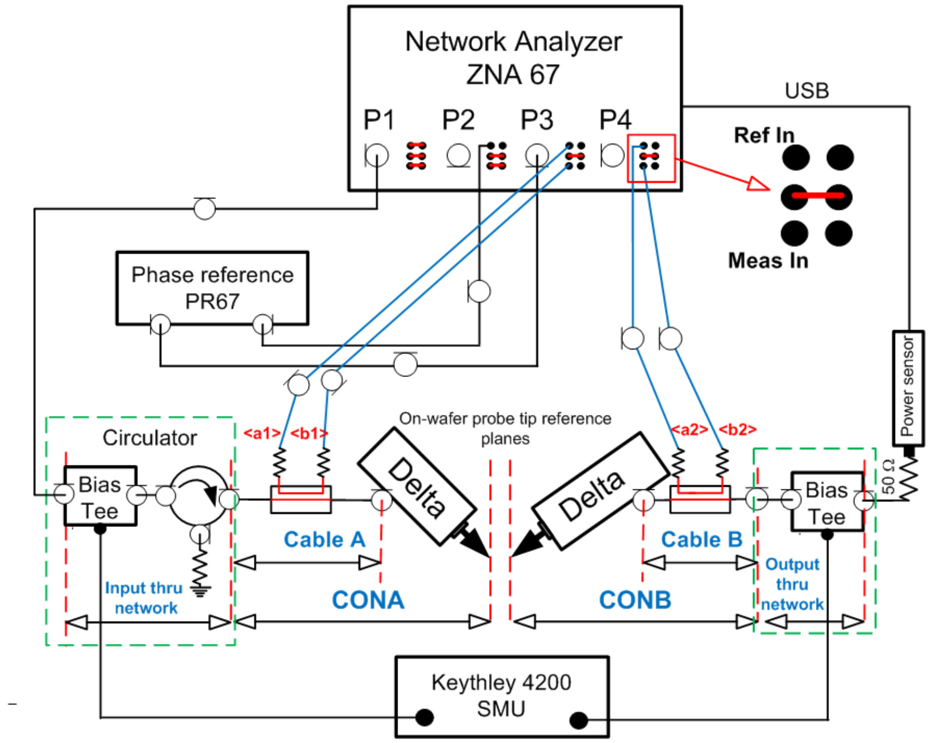

Figure 8. The schematic of Vector Load pull system with phase reference module PR67.

Vector Load Pull system calibration.

1. The first step is the same as in the scalar calibration procedure: Coaxial calibrated VNA is connected to short cables (cable A and cable B) at the tuners files CONA and CONB are extracted using Focus Microwave TRL procedure. Then tuners are calibrated in-situ.
2. Use coaxial calibrated VNA and measure input and output networks (".s1p") files, c.f. Fig 8, green dashed boxes. The data files are saved and located in FDCS.
3. Input and output couplers are connected to VNA, c. f. Fig. 8, respectively. Then two port on-wafer probe calibration for the system without input and output networks is performed.
4. The power meter is connected to CONB, and the power calibration is performed.
5. Input and output networks are connected to CONA, CONB, and probes are landed on calibration substrate "Thru" standard for verification. (For a detailed description refer to [23]).

Chapter 4. Load Pull measurement comparison and verification

Active hybrid measurement system at V, W and D-bands is a good option for modern high-speed power device LP characterization. Comparison of passive LP at K, V and W-bands to active and Hybrid is a hot topic. Measurements of LP of high-speed power cells at possibly highest frequency and using available active and passive or hybrid methods and harmonic tuning methods is of great importance to understand harmonic distortion, non-linear current sources and compact model verification. Verification can be done by a simulation of measured power cells (fT/fmax= 260/300 GHz) using the compact model. The compact model parameters are extracted from numerous measurements of DC and RF characteristics at different (reasonable range) temperatures. Model comparison on standard IV and RF characteristics can be found elsewhere [22]. Measured and simulated load pull based iso-power and iso-PAE contours are given in Fig. 9, a) and in Fig. 9, b), respectively. The simulated curve families are in perfect agreement with the measured data. S-parameters of the circulator and bias tee were separately measured and modeled. The extracted model was used in the power characteristics simulation. Fig. 9, a) and Fig. 9, b) shows measured and modeled S-parameters of the circulator and bias tee. Note that the specified bandwidth of the circulator was Δf = 20 GHz to 45 GHz.

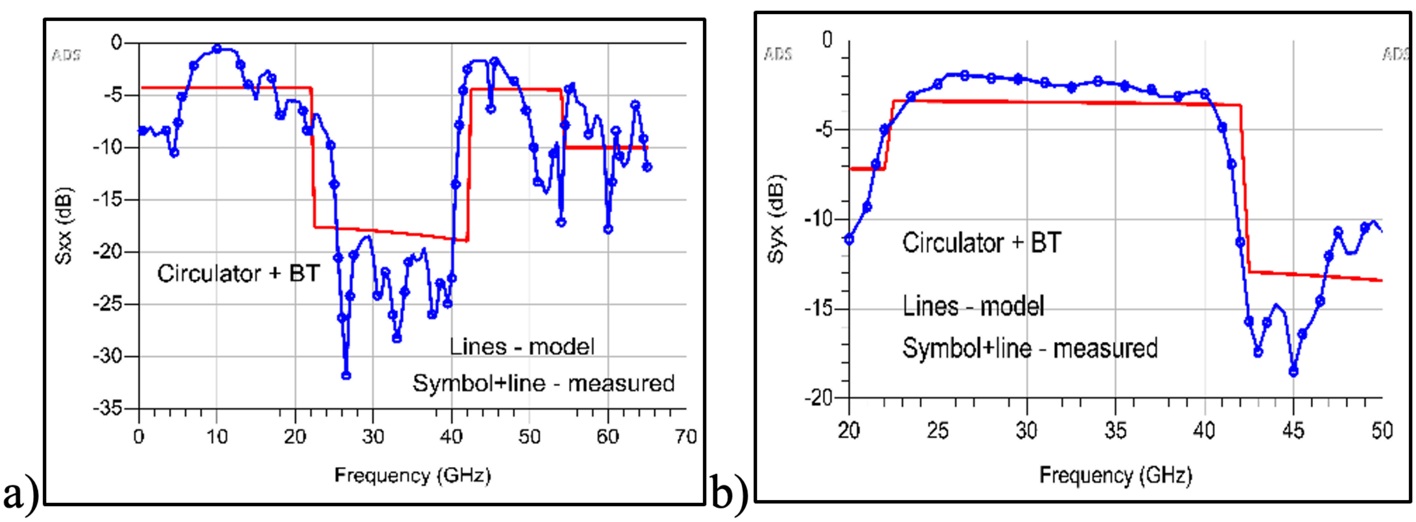

Figure 10. Reflection a) and transfer b) S-parameters of the circulator with connected bias tee (BT)

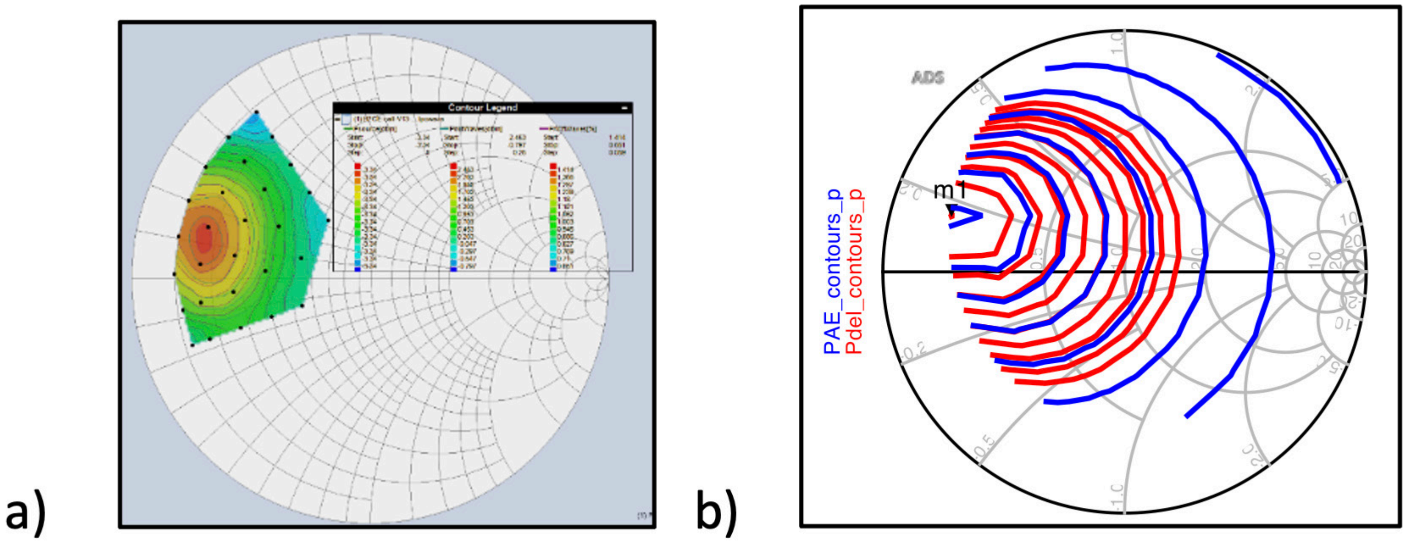

Figure 10. a) Measured load iso-power circles of the SiGe HBT power cell at 28 GHz and biased with VCE=1.8V and VBE=0.9V. b) Simulated iso-PAE and iso-Pdel (Output power delivered to load) with Keysight Advanced Design System (ADS) and compact model (HICUM L2 v3.4 in Verilog-A realization).

The loss of the system is already accounted by the Focus software, and there is no need to include losses to the simulator. Simulations show a significant impact if back reflection is permitted, i.e. the system does not include the circulator. In the Fig 11 a) the output power versus input power at 28 GHz is given.

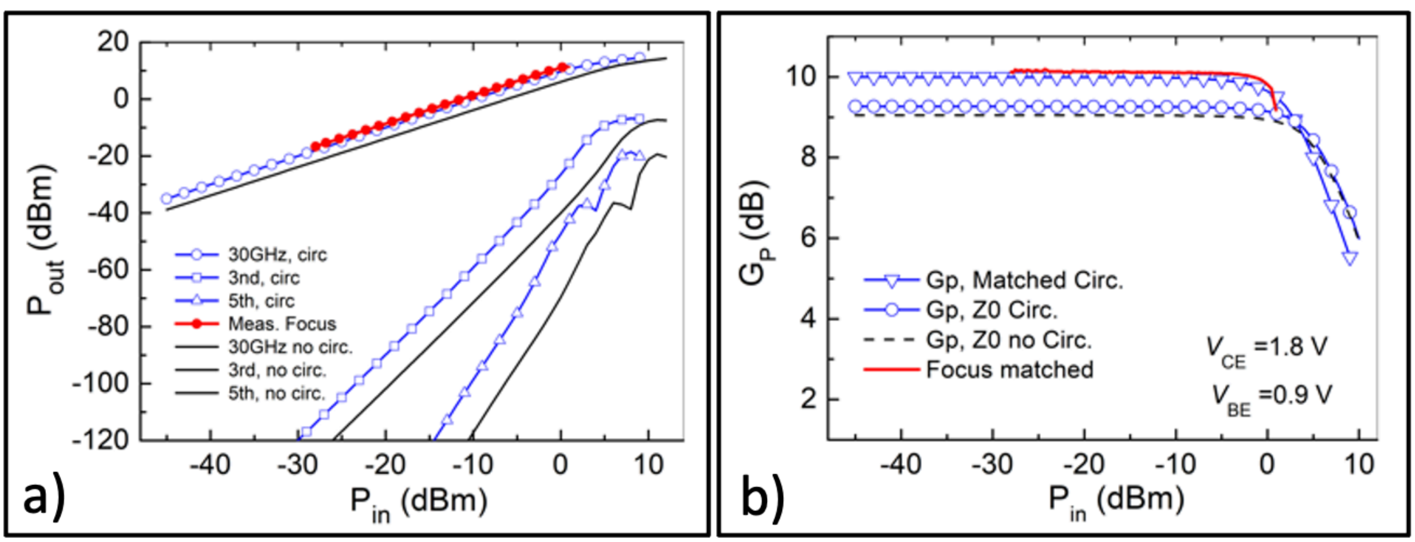

Figure 11. a) Measured and simulated output power of the SiGe HBT power cell with emitter area AE0= 0.13 μm x 10.16 μm x 2 x 2, biased with VCE=1.8 V and VBE=0.9 V versus input power. (Impact of circulator and harmonics are based on CM simulation with Keysight ADS and HICUM L2 v3.4). b) Measured and simulated power gain versus input power.

If the circulator is omitted, a significant part of power is reflected back, and GP drops c.f. Fig. 11 b). Nonlinearities of the device under test are shaped by the dynamic currents. An interesting observation can be made of the plot of the collector and base current dependence on input power c.f. Fig. 12. The base current drops with the power but the collector current increases after showing minimum, matched to the measured data currents obtained from the simulations, c.f. Fig. 12, b). A negative base current appears due to the influence of impact ionization, which turns on to positive with Pin due to the increase of non-linear current. This trend is frequency-dependent since non-linear dynamic currents (IB and IC) are frequency-dependent. This dependency is complex and has a capacitive nature: junction capacitances and substrate capacitance depend on frequency, input power, temperature, c.f. Fig. 12, c). Note that lower bias VCE=1 V, VBE=0.85 V avoids the impact ionization affected negative base current.

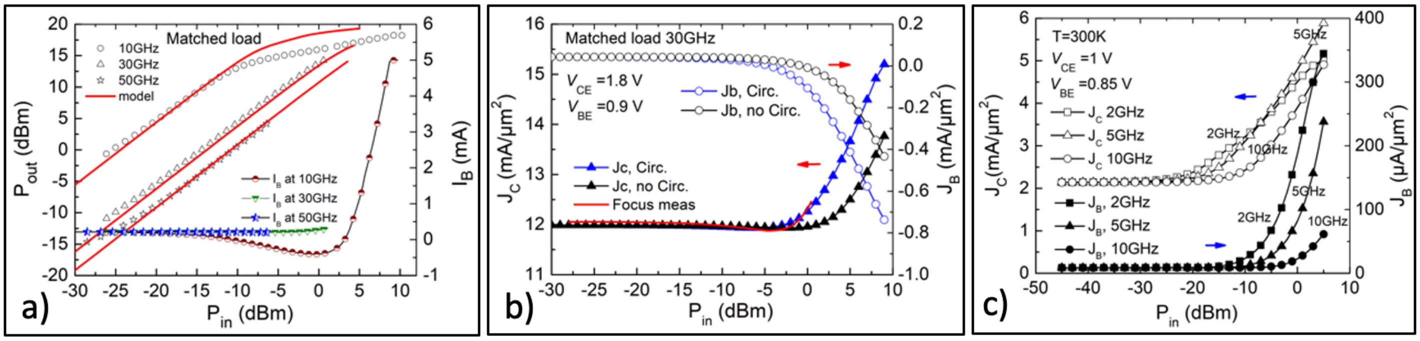

Figure 12. a) Frequency-dependent measured and simulated output power and base current density versus Pin of the SiGe HBT power cell, biased with VCE=1.8 V and VBE=0.9 V. b) Simulated base and collector current density with and without circulator. c) Frequency dependent SiGe HBT power cell collector and base current versus Pin at 2, 5,10 GHz at VCE=1 V, VBE=0.85 V.

Note that dynamic current, which shapes the total current at high power, is frequency dependent due to an impact of substrate capacitance and parasitic substrate transistor.

Conclusion

Vectorial harmonic Load Pull measurement of advanced semiconductor devices, operating at high frequencies beyond 300 GHz, enables deep inside the device for non-linearity analysis and model verification, development resulting to PA linearization. Review of the LP methods showed that vectorial LP method based on four port Network analyzer ZNA67 (also ZVA67) using direct Focus Microwaves Delta impedance harmonic tuner M-67100 Delta, covering frequency from 10 GHz to 67 GHz yields very accurate power characteristics. The discussed system is seamlessly integrated into the automated probe system TS3500-SE from MPI Corporation, enabling the maximal possible impedance tunning rage by the direct mount of the extra low-loss TITAN™ Probes on the Delta tuner output port. Measured data perfectly matches simulated ones. The simulation was based on the compact model HICUM L2 version 3.4. CM parameters were extracted from standard DC and RF, temperature-dependent measurements and verified. The importance of input network, particularly the circulator, is highlighted. At frequencies beyond 10 GHz and in matched conditions, it is highly recommended to use a circulator at the system input side.

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