SMWD 2023, KTH Royal Institute of Technology, Stockholm, 23rd – 25th May 2023

Advancements in Vectorial Harmonic Load Pull Measurements for mmWave Device Characterization and Compact Model Verification

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1. Introduction

Recent advancements in transistor technologies enabled the realization of mm-wave frequency power applications such as stacked power amplifiers, transceivers, and MIMO radars. 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) [1]. The linearity and gain of PA are limited by parasitic effects like mutual self-heating, the influence of interconnection parasitic, cell positioning, etc. [1]. Careful optimization of the power-cell layout is required for PA improvement with the given process technology [1].

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 [2]. 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 [1], [3].

2. A Unique Vector Load Pull solution in Ka, V, E & W band in a Coaxial Environment

mmWave on wafer load pull has always been a challenge for both test and design engineers as the inherent loss at high frequencies would limit the tuning and dynamic range on any load pull system. Focus Microwaves, new DELTA series of electro-mechanical tuners are designed specifically for high frequency on wafer measurements. The tuner's low profile allows it to be placed within the wafer perimeter and allows for a direct connection between the probe tip and the tuner, eliminating all possible insertion loss between the DUT and the tuner. This revolutionary new tuner design enables the engineer to achieve optimum tuning range, with a tuner whose footprint and weight has been dramatically reduced. Focus Microwaves offers a wide range of the Delta impedance harmonic tuners covering frequencies from 5 GHz to 110 GHz. One of the most interesting impedance tuners is M-110240 DELTA, operating from 24 GHz to 110 GHz [2]. It allows for matching DUT output impedance up to 110 GHz at the fundamental, the second, and the third harmonics simultaneously. In a joint collaboration with Keysight, Focus Microwaves has developed a turn key solution which makes possible to perform high frequency fundamental and harmonic load pull up to 110 GHz with great accuracy using the with Keysight's very small footprint N52xxA frequency extenders and the Delta tuners.

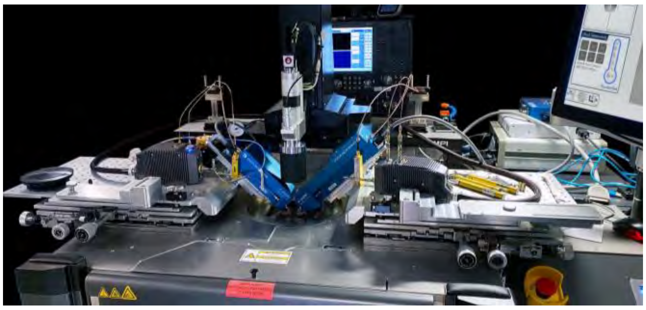

Figure 1. Ka band vector LP setup with Harmonic impedence control

This unique approach of accessing the internal receivers of the frequency extenders offers a very simple and efficient system which elegantly integrates on wafer to measure the real time fully calibrated forward and reverse travelling waveforms at the DUT reference plane.

3. D-Band Vector Loadpull Setup

Pushing the boundaries of passive tuners beyond coaxial connectors while 6G frequencies and applications are still being defined, Focus took the initiative and developed a new family of waveguide tuners designed for frequencies greater than 110GHz. Leveraging the success and technology of the DELTA tuners and combining it with the micro-metric accuracy and repeatability of the small footprint tuners, these new waveguide tuners will revolutionize the Sub-THz bands. Focus Microwaves small footprint waveguide tuners and state of the art on-wafer integration with the leading probe station manufacturers (MPI and Form Factor) allow for direct connecting to all subTHZ waveguide probes providing maximum tuning range. With built-in reflectometers for input and output travelling waveforms ($a_{1,2}$, $b_{1,2}$) measurements and custom designed downconverter receivers the subTHZ tuners can be used for fully calibrated vector load pull measurements. This approach also allows for easy adaption to hybrid techniques often used to increase the tuning range of passive load pull system.

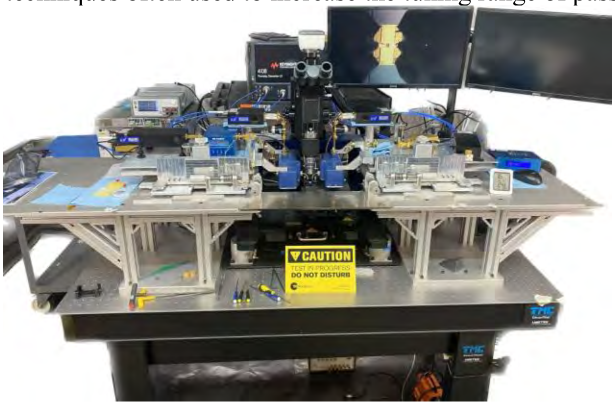

Figure 2. D band fully calibrated vector LP setup with external downconvertors

4. 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 Compact model requires verification of equations under the large-signal operation regime. Harmonic distortion (HD) in HBTs and FETS was investigated in a number of publications, e.g. [4]. However, analysis of harmonic distortion in most cases was limited to an unpractical linear power region with Volterra series terms due to fundamental only loadpull setups. 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. Vector harmonic load pull yields a deep insight in nonlinearities of a DUT including signal harmonics and dynamic time domain output and input voltage and current waves for compact model verification and development [4] valid for a given bias point and frequency.

References

[1]. P. Sakalas, A. Mukherjee, M. Schröter, "Noise and Linearity of High-Speed SiGe HBT Cells in CE and CB Configuration", Proc., Noise and Fluctuations: 25th International Conference (ICNF): IEEE proceedings, 18-21 June 2019, Neuchatel, Switzerland. https://archiveweb.epfl.ch/icnf2019.epfl. ch/

[2]. https://focus-microwaves.com/wp-content/uploads/2020/01/M-110240_V02.pdf

[3]. C. Tsironis, "Load Pull characterization", Application note Focus Microwave group, White paper #64, 56 p., 2019.

[4]. G. Niu et al., RF Linearity Characteristics of SiGe HBT", IEEE Trans. on MTT, vol.49, No.9, pp. 1558- 1565, 2000