Millimeter-Wave Load-Pull Measurements of GaN HEMTs: Driving the next Generation of Advanced Power Amplifiers

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***Abstract*—This paper will discuss three of the load-pull measurement systems available at Cardiff University and the CSA Catapult, all capable of harmonic load pull and pulsed RF and bias, with passive implementations up to 110 GHz, and active up to 67 GHz, through three measurement campaigns on different GaN and GaAs technologies supporting advanced PA design (harmonically tuned, Doherty) for up- and down-link satellite frequencies. With Power Amplifiers (PAs) remaining a crucial component in the high frequency front-end of all wireless systems, the increased interest in millimetre-wave frequency bands for a variety of applications poses more new challenges to device manufacturers and circuit designers. The systems here described can hence support, by providing experimental characterisation capabilities, the rich UK habitat in the microwave sector, from small design houses to large multinationals providing PA design services and products, as well as the increasing investments to try and establish a sovereign source of compound semiconductor technology.**

I. Introduction

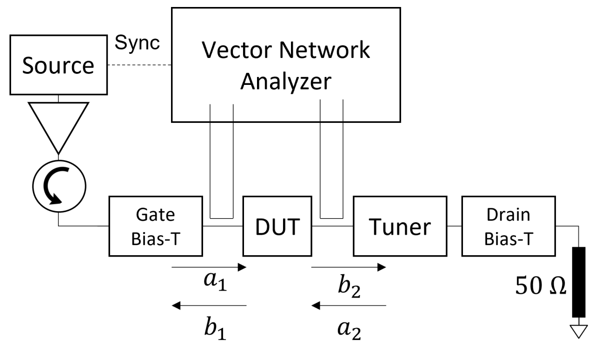
The evolution of high frequency systems at microwave and millimetre-wave frequencies requires analogue components such as the Power Amplifier (PA) to improve in terms of output power, gain, linearity and efficiency. This is true for all applications, from digital communications to radar, from imaging to power transfer, and due to the high consumption of the PA and its impact on the transmitted signal quality, being the last electronic component in the transmitter chain and the one that has to operate in large signal condition for its consumption to be acceptable. To improve the PA performance, there are two necessary requirements: firstly, that the transistor technology underpinning the PA design is good enough in terms of intrinsic properties so that the final design can achieve the performance targets; secondly, that the large-signal behaviour of the transistor is known well-enough to enable the design of the circuitry around it to make the PA perform. Both requirements lead to the need of characterising the transistors accurately in conditions that mimic the operation in the PA circuit. In this context, experimental load-pull characterisation is the most logical choice as it gives a direct indication of the performance and of the boundary condition needed, in terms of impedance terminations, to achieve that performance.

This paper discusses the provision of load-pull characterisation systems for millimetre-wave frequencies available in South Wales at Cardiff University and the Compound Semiconductor Applications Catapult (CSA-C), which are supporting the CS-Connected cluster in developing III-V technologies in the UK for the RF market. After a recall of the basics of load pull and the steps needed to prepare these systems for accurate characterisation, three different systems will be described highlighting their peculiar features through actual measurements example of advanced GaN High Electron Mobility Transistor (HEMT) technologies.

II. Recall of Load Pull Measurements

Load-pull measurements are a common tool in the PA design process to identify the optimal design space on the Smith Chart. Load-pull measurement involves systematically varying the impedance presented to the Device Under Test (DUT) under large signal excitation. The DUT's nonlinear response is then captured at each point which allows the PA designers to study the DUT's behaviour over a wide range of load conditions. For example, load-pulling a device can reveal the location of the load on the Smith chart where the optimum load for maximum power and efficiency can be found. However, designers often face a trade-off between optimising for maximum efficiency and maximum power, as the optimal load for each can be different. To meet design specifications for both parameters, a compromised load impedance must be selected. Load-pull contours provide a useful tool for identifying the optimal load condition, where power and efficiency contours overlap.

Load-pull setups can be broadly classified into two types: ”passive” and ”active”. Fig. 1 shows the block diagram for both passive (a) and active (b) load-pull setups.



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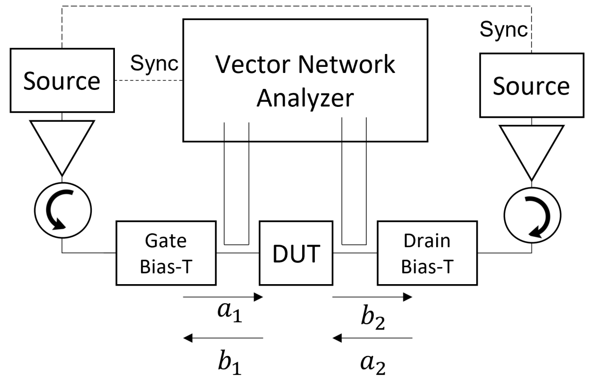


(b)

Fig. 1. Block diagram of passive (a) and open-loop active (b) load pull setup. In the passive load-pull setup, a stub tuner impedance transformer is typically placed between the DUT and the 50 Ω system impedance. In the active setup, the reflected signal is generated from a separate source that is in sync with the input signal.

A. Passive load-pull

In a passive load-pull a tuner, which is typically a stub tuner impedance transformer, is placed between the DUT and the $50\,\Omega$ measurement system impedance [1]. Adjusting the length of a stub changes the magnitude of the reflection coefficient ($|\Gamma_L|$), while adjusting its position alters its phase, ($\angle\Gamma_L$). By adding two or more stubs, harmonic load-pull control can be achieved in addition to controlling the fundamental frequency [2]. To achieve repeatability and computer-controlled precision, the variation of the terminal impedance can be controlled using a stepper-motor-driven mechanical system [1], [3]. The main drawback of passive load-pull systems is their limited load-pull range, which cannot target high values of $|\Gamma_L|$. This limitation is due to the insertion loss caused by both the tuner and the connection between the DUT and the tuner.

B. Active load-pull

The general principal of active load-pull is to overcome the losses in the system by amplifying the reflected signal 'a_2'; hence, providing an unrestricted coverage of the impedance plane on a Smith Chart [4]–[6]. In open-loop active load-pull techniques, an output source that is synchronised (phase-locked) with the input source is used to generate a reflected signal (a_2). By adjusting the magnitude and phase of the injected a_2 signal, it is possible to target different load reflection coefficients (Γ_L). A driver amplifier can be used to amplify the injected signal's magnitude so high values of $|\Gamma_L|$ can be targeted. To perform multi-harmonic load-pull measurements, multiple signal generators, and driver amplifiers, are used at the harmonic frequencies. One major drawback of using active load-pull techniques is the cost of the measurement setup, which involves the use of multiple signal generators and driver amplifiers which can be very expensive.

C. Calibration

The Vector Network Analyzer (VNA) is a crucial component in load-pull measurement setups, especially when used in what is called a "real-time" configuration, meaning that the VNA is used during the measurement and not only for calibrating the passive tuners. In order to obtain accurate measurements, it is crucial to calibrate the VNA to compensate for the inevitable "systematic" errors within the instrument. Vector calibration algorithms, such as Thru-Reflect-Line (TRL) and Short-Open-Load-Thru (SOLT), can be used with calibration standards to correct the VNA at the measurement reference plane (i.e., DUT's input and output port).

To accurately determine the input and output absolute power levels of the DUT, it is necessary to perform an additional power calibration step. This calibration involves connecting an RF power meter to the calibrated port and measuring the absolute power simultaneously with the VNA's scatter measurement. The load-pull software includes an embedded power calibration feature that can calculate the power correction error factor and provide real-time measurements of the DUT's output power.

Before vector calibration can take place in passive load-pull setups, it is essential to calibrate the load tuner. This calibration stage characterises the load tuner by measuring its two-port S-parameters at specific stub positions for a given frequency, using a VNA that has been previously calibrated. The load-pull software facilitates the load tuner calibration process, automatically saving the resulting calibration file for each frequency.

The calibration procedure serves to minimise systematic errors in load-pull measurement. However, it is also important to implement good practices that help to minimise drift and random measurement errors, like selecting low IF bandwidths for the receivers, and maintaining a stable ambient temperature in the testing environment.

III. 10-67 GHz Passive Load Pull system

Fig. 2 shows the passive load-pull measurement setup at CSA-C, which is capable of covering frequency range of 10 GHz to 67 GHz.

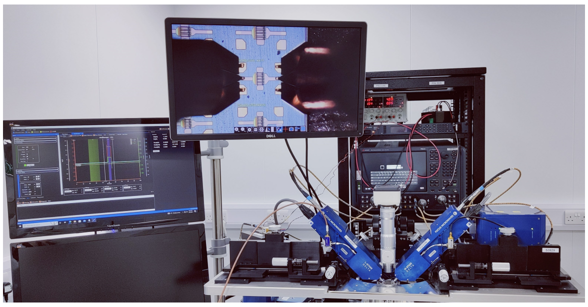
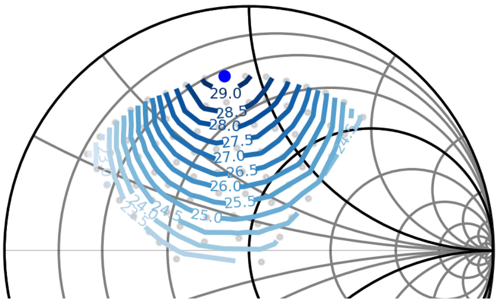


Fig. 2. The passive multi-harmonic source and load-pull measurement setup at CSA Catapult. This system is capable of performing load-pull measurements across a frequency range of 10 GHz to 67 GHz.



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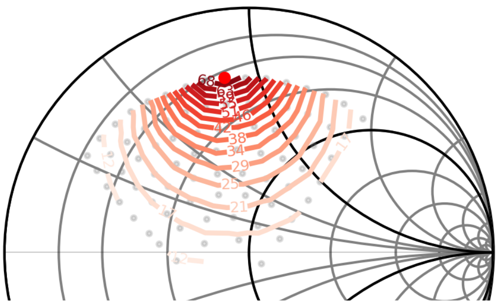


(b)

Fig. 3. Load-pull measurement results of a GaN-on-SiC HEMT device at 30 GHz. (a) Power contours with 0.5 dB step with the maximum of 29.5 dBm; (b) efficiency contours with 5% step and the maximum of 72%.

The measurement system has the capability to perform multi-harmonic measurements of up to the third harmonic for both source and load-pull. The "Delta" tuners from Focus Microwave are connected directly to the probes, which a significant reduction of the insertion loss between them and allows to target high $|\Gamma_L|$ values (up to $|\Gamma_L| = 0.9$). The measurement system is coupled with the Auriga DC-IV pulsed-IV system, which enables load-pull measurements with both pulsed bias and RF stimuli.

Fig. 3 depicts the output power and efficiency load-pull contours obtained from measuring the large signal performance of a GaN HEMT at 30 GHz, using the setup in Fig. 2. The measurements were conducted using pulsed bias and RF stimuli, with the RF pulse width set at 5 μs, and a duty cycle of 5%.

These measurements can be useful to optimize the design of SatCom and 5G FR2 PAs which work at around 30 GHz, and provide useful information to the designers for example to double check the accuracy of the foundry large signal models.

IV. 24-110 GHz Passive Load Pull system

Fig. 4 shows the picture of the passive load-pull system at Cardiff University capable of multi-harmonic source/load-pull over the 24-110 GHz band. The system is world-unique as it also allows to measure the waveforms at the device level thanks to an oscilloscope that works as phase meter. The ZVA67 from Rodhe and Schwarz is the underpinning VNA. Four of its eight receivers are used to measure the

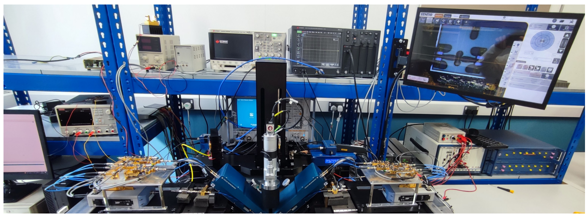
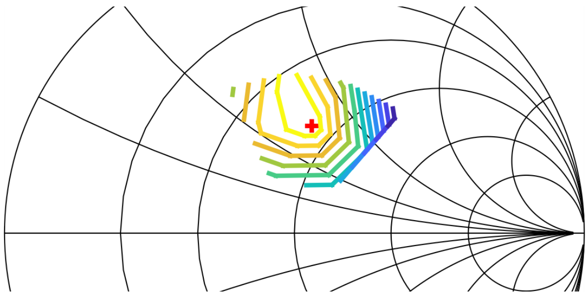


Fig. 4. The passive multi-harmonic source/load-pull measurement setup at Cardiff University. This system is capable of performing load-pull measurements across a frequency range of 24 GHz to 110 GHz, offering waveform measurements up to 100 GHz.



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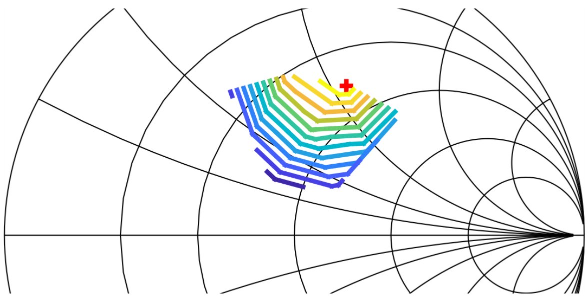


(b)

Fig. 5. Load-pull measurement results of a 90 nm GaAs pHEMT device at 27.5 GHz. (a) Power contours with 0.1 dB step with the maximum of 16.7 dBm; (b) efficiency contours with 2% step and the maximum of 67%.

DUT power waves up to 67 GHz, while the other four receivers are connected to downconverting units to cover the remaining bandwidth. This, alongside multipliers for input and output ports, allows for a seamless frequency sweep over the whole band. This is a clear difference compared to other millimetre wave systems that use banded, waveguide extenders.

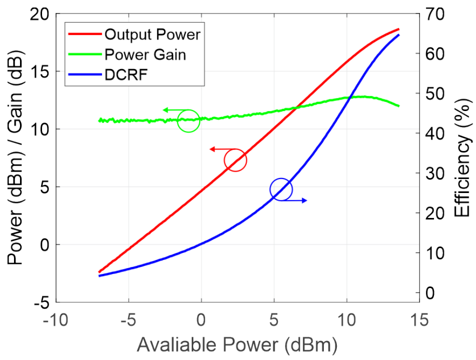


Fig. 6. Power sweep results on the GaAs pHEMT, at 27.5 GHz, on the optimum fundamental load for output power.

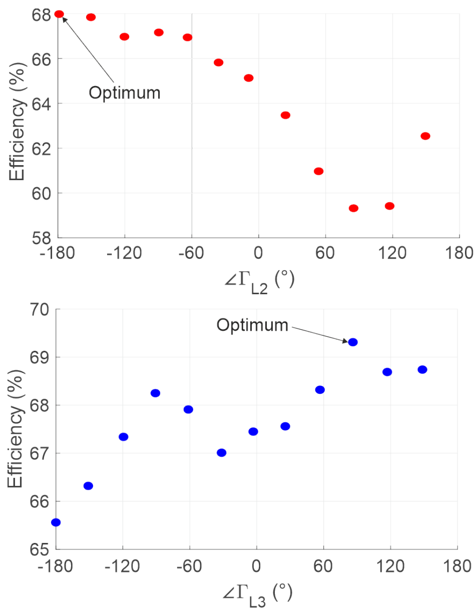


Fig. 7. Harmonic load pull results on the GaAs pHEMT, at 27.5 GHz, on the optimum fundamental load for output power. DCRF vs. second harmonic phase (top) and third harmonic phase (bottom).

The measurement directional couplers are integrated with the impedance tuner and mounted as closed as possible to the 1 mm coaxial connector on which the wafer probe can be mounted. This minimises the insertion losses that affect the reachable reflection coefficient, as well improving the quality of the measurement.

Fig. 5 shows an example of fundamental load pull on a small-size GaAs pHEMT with 90nm gate length, biased at 3.5 V in class AB, performed at 27.5 GHz, showing an optimum output power of 16.7 dBm and an optimum efficiency of 67%. Fig. 6 shows the power sweep performed at the corresponding optimum load for maximum output power. The input power for the power sweep was swept at values higher than the one used for load pull, therefore a higher output power of 18.7 dBm is achieved, with a corresponding efficiency of 64.7%. Second harmonic load pull was then performed by maintaining the fundamental on the same optimum, and finally third harmonic load pull was executed with the lower harmonic terminations fixed at their optimum. Harmonic load pull is performed with the highest possible reflection coefficient and varying the phase. Fig. 7 summarises the harmonic load pull results in terms of maximum efficiency vs. phase of the harmonic reflection load. The efficiency can be increased up to 69.3% with harmonic tuning, with an improvement of 5% points compared to fundamental only matching. More importantly, if harmonics are not controlled there is a potential for the efficiency to drop down to 59.3%, which highlights the importance of harmonic tuning also for millimetre-wave PA design.

V. 2-67 GHz Active Load Pull system

Fig. 8 shows a picture of the active load-pull system up to 67 GHz at Cardiff University.

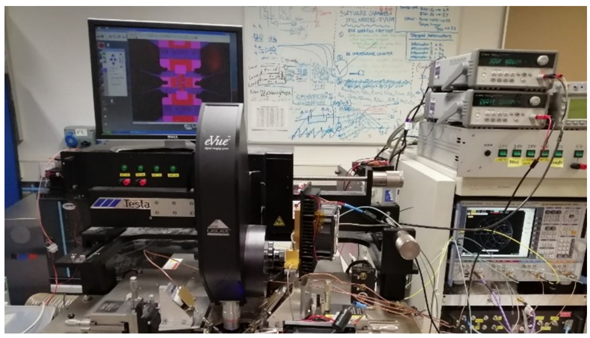
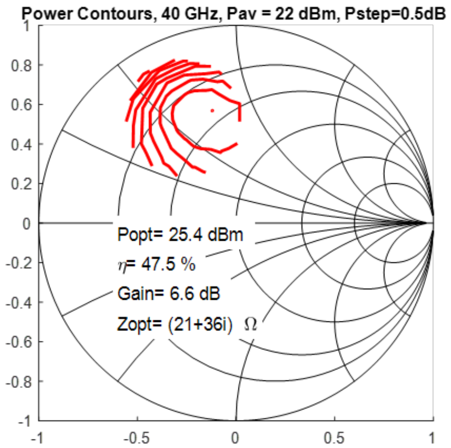


Fig. 8. The active multi-harmonic source/load-pull measurement setup at Cardiff University. This system is capable of performing load-pull measurements across a frequency range of 1 GHz to 67 GHz, offering waveform measurements on the same band.

Based on the ZVA67 VNA, it uses the four reference receivers to measure the waves, and exploits the four digitally-driven sources for accurate and repeatable open-loop active load pull. Being based on open-loop load-pull, the software iterative algorithm for active load pull plays a key role in driving the sources to converge to a target load. Waveform measurements can also be performed by reconstruction of the wave via inverse Fourier transformation, which requires phase coherence and calibration when measuring harmonic components. This is achieved by performing a phase calibration of the receivers alongside the power calibration, and an initial measurement of the phase of a phase reference. During the measurement itself, the phase reference is not needed as the digital clock of the ZVA67 maintains the phase coherence when the receivers hop to the harmonic frequencies.

The probe station used with this system includes a 200 mm thermal chuck for positive temperature measurements, up to 200 degrees Celsius.

Fig. 9 shows an example of load pull measurement at 40 GHz of a 2x50 um GaN HEMT in 60 nm GaN on Si technology, while Fig. 10 shows a power sweep taken on the optimum load for output power.



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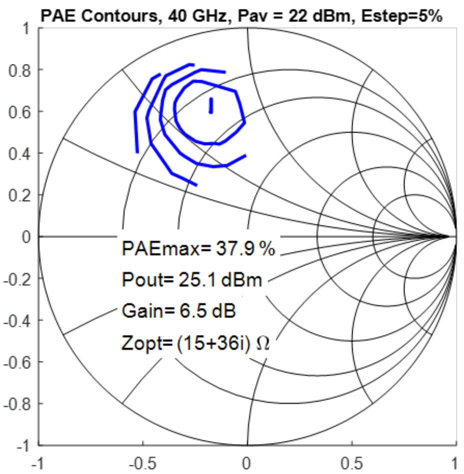

(b)

Fig. 9. Load-pull measurement results of a GaN-on-Si HEMT device at 40 GHz. (a) Power contours; (b) PAE contours.

The output power achieved is 25.5 dBm, with corresponding efficiency of 47%.

Fig. 11 shows the measured efficiency in another measurement campaign performed at 18 GHz for a 8x100 um GaN HEMT in 100 nm GaN on Si technology. In this case, after having identified the optimum load at fundamental, the phase of the second harmonic termination at source and load was swept, while maintaining the reflection coefficient magnitude close to unity, to identify the best terminations for efficiency. This shows again the relevance of correct harmonic loading also at millimetre-wave frequencies, in this case for the design of a PA for satellite down-

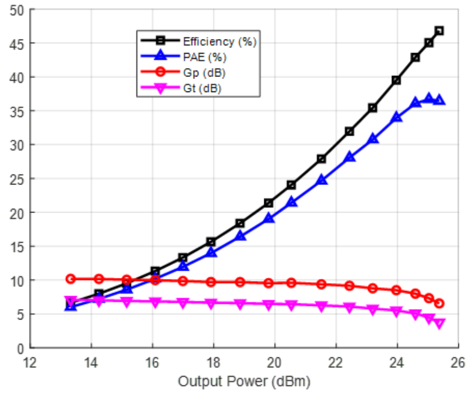

Fig. 10. Power sweep measurement results of a GaN-on-Si HEMT device at 40 GHz on the optimum load for output power.

link applications [7], where the gap between optimum second harmonic terminations and the worst case is 10% efficiency points.

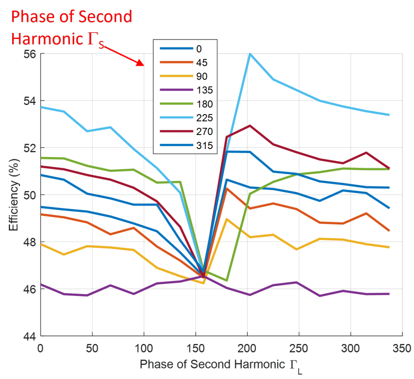

Fig. 11. Maximum efficiency vs. second harmonic load phase, at different second harmonic source terminations. GaN-on-Si HEMT 8x100 um device at 18 GHz, on the optimum fundamental load for output power.

VI. Conclusion

The paper has shown some examples of millimetre-wave load pull measurements performed using the systems at Cardiff University and CSA Catapult. The access to accurate experimental data without having to export the devices to other countries which can offer a clear competitive advantage to the UK institutions and companies involved in compound semiconductor technology development and its applications. Cardiff University and CSA Catapult are working towards an easier access to these facilities while continuing to improve their offering and know-how.

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