Active Harmonic Source-/Load-Pull Measurements of AlGaN/GaN HEMTs at X-Band Frequencies

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Abstract — Active harmonic loadpull measurements investigation for a 1-mm AlGaN/GaN HEMT power transistor at X-Band frequencies are in this paper reported. The paper highlights the transistor performances in terms of maximum PAE, P_{OUT} and Gain achieved at 8.7 GHz together with the application of a systematic source-/load-pull measurement procedure including wafer-mapping capability.

The measurements were carried out using an active harmonic loadpull test system with four control loops. In particular, fundamental and second harmonic "loads" as well as second harmonic "source" terminations have been properly varied and optimized. The 1-mm GaN power device delivered very high efficiency of DE=71.2% and PAE=66.1%, together with high P_{OUT} and power gain of 35 dBm (3.2 W) and 11.5 dB, respectively.

Index Terms — Active, efficiency, harmonic, loadpull, tuning.

I. Introduction

Nowadays more and more high-efficiency power amplifiers (PAs) are needed in order to save energy and to reduce costs e.g. for cooling systems. As the load and the source impedances seen by the transistor at harmonic frequencies significantly affect the overall performance in terms of output power, gain and efficiency [1-2] these impedances have to be valuated to be delivered by the matching networks. The PA designer needs to know the optimum terminations in order to achieve the best efficiency with low trade-off in output power and gain [2]. Furthermore the right source and load terminations obtained through loadpull measurements lead to accurate nonlinear models [3] which are then used in the simulation environments. Other than the optimum fundamental terminations, the optimum magnitudes of the higher harmonic reflection coefficients are typically near to unity with different phases depending on the PA classes, e.g. class-J [2], class-F or inverse class-F [4-5]. With passive tuner setups these high reflection conditions equal to unity cannot be set due to losses introduced by the various components such as couplers, diplexers, cables and probes. This issue becomes more pronounced when increasing the frequency, e.g. X-band frequencies. Therefore, special care needs to be taken during the high frequency measurement calibration and activity in order to avoid stability issues, to allow proper measurements with improved accuracy as well as for an improved overall power transistor performance. Because of the requirement for high gain and power-efficiency at X-band frequencies typically used for space applications as satellite or radar communication systems, the accurate measurement activity has to be accompanied with a highly performed technology. For this reason, the development of active harmonic loadpull measurement systems capable of presenting highly reflective fundamental and harmonic terminations at both the transistor input and output side [6-7] together with a systematic measurement procedure [8] needs to be accompanied with the continuous development of GaN technology capable of providing high performance at high frequency [9-10].

In this paper an in-house IAF AlGaN/GaN HEMT power transistors with gate length of 250 nm and gate width of 1 mm [9-10] together with a systematic source-/load pull measurement procedure has been investigated in order to achieve and deliver very high power-added-efficiency at X-band frequencies [11-12].

II. Modified Test System

Figure 1 shows a simplified block diagram of the commercially available Anteverta MT2000 active harmonic loadpull system [6, 13]. The test system covers the frequency range 0.5 - 26.1 GHz and can handle 100 W of CW RF power at 2 GHz of fundamental frequency with the built-in test-set couplers and even more in pulsed mode. This power range can be extended by using external couplers when measuring for example packaged high-power devices. The test system supports up to four loops. One of these loops is needed for the input signal at fundamental frequency ($1\times f0$) and a second one for the tuning of the output load at $1\times f0$. The two remaining loops can be used to control the 2nd ($2\times f0$) and 3rd ($3\times f0$) harmonic loads at the output or both 2nd harmonics at input and output.

The MT2000 external control software [13] option together with IAF in-house software allows automated wafer mappings combined with any loadpull configuration. RF- power amplifiers are needed for the fundamental frequency input signal and for each load which has to be tuned or set to a defined value. Diplexers or triplexers are needed in order to combine two or three harmonics to be fed into the DUT (device-under-test) ports, respectively. In order to supply sufficient RF-power to the DUT, the loop amplifiers have to deliver significantly more power than the DUT itself. Even at the input of the DUT the available power delivered from the

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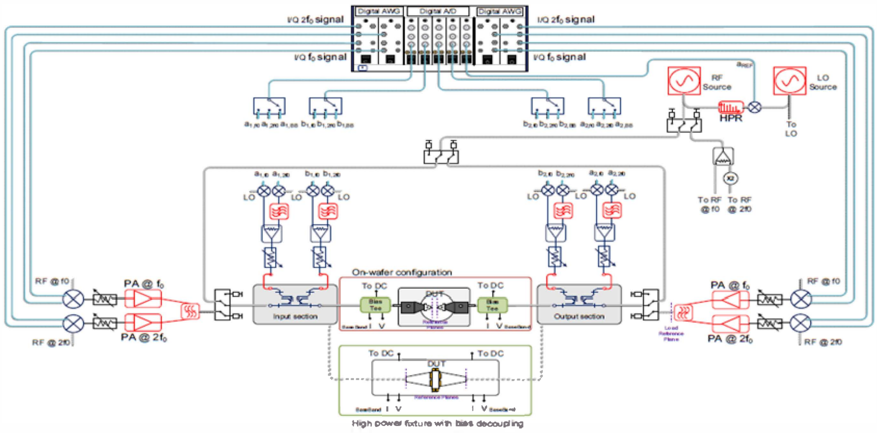

Fig. 1. Simplified block diagram of the commercially available Anteverta MT2000 mixed-signal active harmonic loadpull system [6, 13].

fundamental loop amplifier can be critical when measuring devices without matching networks at high frequency, e.g. X-band frequencies. As an example, for the 1 mm GaN power transistor used in this experiment, an input reflection magnitude of 0.94 leads to a mismatch loss of 9.3 dB. Therefore, these losses need to be compensated by the loop amplifier. Due to these aspects, the attenuation of the "high power paths" which again include probes, cables, directional couplers, diplexers, and/or triplexers and bias-tees has to be minimized. For this reason, cable lengths of both input and output were reduced by placing the external couplers as near as possible to the wafer probes. The use of external couplers as near as possible to the wafer probes also improve the calibration accuracy as well as reduce stability considerations.

III. MEASUREMENTS

The following measurements have been conducted by using two loops in the input (fundamental and second harmonic source) and two loops in the output (fundamental and second harmonic load) following a systematic measurement procedure in order to optimize the power transistor performance. The measurements have been conducted on the IAF 1 mm (8×125 µm) AlGaN/GaN power HEMT in CW (continuous wave) mode at 8.7 GHz of fundamental frequency, V_{DS}=30 V of drain bias voltage and an quiescent bias setting of I_{dq}=10 mA.

- ***Fundamental Tuning***

In the first step, only fundamental impedance 1×f0 was swept (area shown in the Smith chart of Fig. 2) in order to find the region for optimum device efficiency. In this case the 2×f0 source and load loops were set to the passive system impedance, meaning that the DUT is terminated with the impedance defined by the test setup hardware without injecting any loops signal, therefore 50 Ω. As shown in Fig. 2, the 1×f0 loadpull is combined with an input power sweep as PAE depends also on input power [2]. Despite the higher harmonics are not optimized high PAE up to 59.7% is already achieved while delivering an high output power of 36.1 dBm (4.1 W) and a power gain of 13 dB (related to the $Z_{L,F0}$=13.0+ j28.0 Ω as given by the blue cross in the Smith chart). The maximum output power of the 1 mm AlGaN/GaN HEMT device at another load reflection point ($Z_{L,F0}$=19.5+ j20.4 Ω - red cross) is 37.3 dBm (5.4 W) where lower PAE of 48.2 % is delivered with power gain decreased to 8.6 dB.

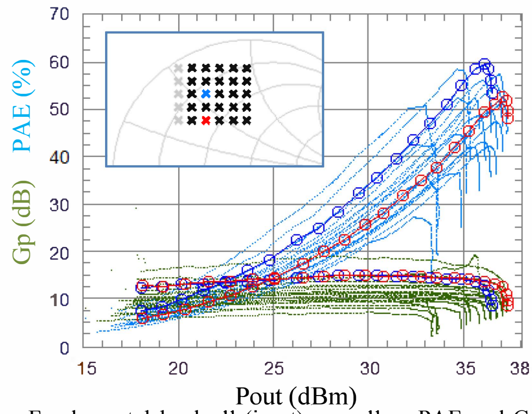

Fig. 2. Fundamental loadpull (inset) as well as PAE and Gp as a function of P_{OUT}. Blue markers: load reflection of PAEmax. Red markers: load reflection of P_{OUT}max.

- ***Second Harmonic Load Tuning***

After optimizing the 1×f0 load where keeping the higher terminations to 50 Ω, the second step is to conduct a 2×f0 loadpull sweep while the 1×f0 load is set to the $Z_{L,F0}$=13.0+ j28.0 Ω (optimum PAE) previously obtained. The 2×f0 source termination is still set to the passive 50 Ω impedance. At harmonic frequencies, reflection magnitudes near to unity deliver the best efficiencies since no energy lost occurs. This means that the only phase sweep with constant magnitude equal to one is now sufficient. Such 2×f0 load has been swept all around the Γ=1 edge of the Smith chart and a successive fine phase variation was set, as shown in the zoomed Smith chart of Fig. 3.

The power performances related to those loads are also reported in Fig. 3 where PAE and gain are function of the power sweep as well as the 2×f0 loadpull. In this case higher performance is obtained as compared to the one where only the 1×f0 load was optimized. Here the maximum PAE yields 61.3%, Pout=36.2 dBm (4.1W), and an associated power gain Gp = 13.2 dB, proving the importance of the proper setting of the 2×f0 load.

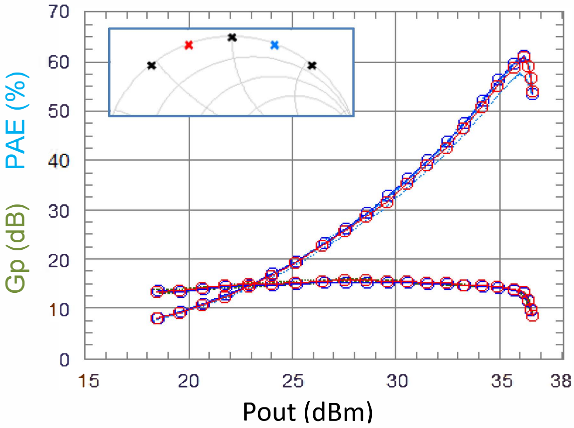

Fig. 3. Second harmonic loadpull (inset) as well as PAE and Gp as a function of P_{OUT}. Blue markers: load reflection of PAEmax. Red markers: load reflection of P_{OUT}max.

- ***Fundamental Retuning***

After optimizing the 2×f0 load while maintaining a constant optimum 1×f0 load achieved in step 1, a re-optimization of the fundamental load is needed. This is due to the fact that in non-linear power transistors, the harmonic contents are directly related to the fundamental one; therefore, being the superposition principle not valid, the variation of the 2×f0 load would inevitable vary the optimum impedance at 1×f0.

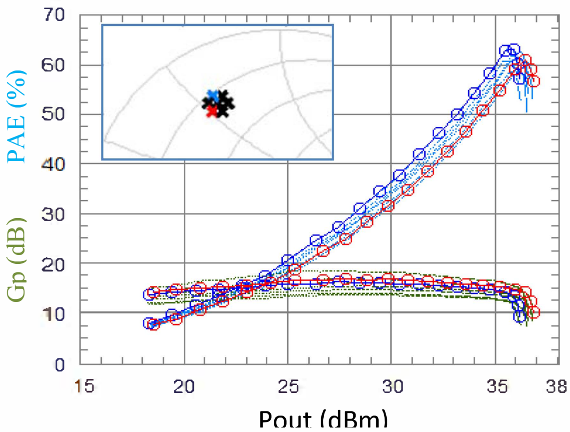

Fig. 4. Fundamental loadpull retuning (inset) as well as PAE and Gp as a function of P_{OUT}. Blue markers: load reflection of PAEmax. Red markers: load reflection of P_{OUT}max.

Therefore the 1×f0 load impedance is retuned in a small area around the optimum value found during the previous 1×f0 load sweep where the optimum PAE value is found at Z_{F0}=10.8+j28.5 Ω with higher PAE value equal to 63.4% as illustrated in Fig. 4.

- ***Second Harmonic Input Tuning***

Once the impedances have been optimized in the transistor output side, an optimization of the input impedance is also necessary in order to achieve the best overall output performance. In this case a 2×f0 source-pull is conducted while the 1×f0 and 2×f0 loads are set to the optimum PAE previously achieved. Fig. 5 shows the Smith chart segment where the 2×f0 source impedance has been swept and the associated output performance.

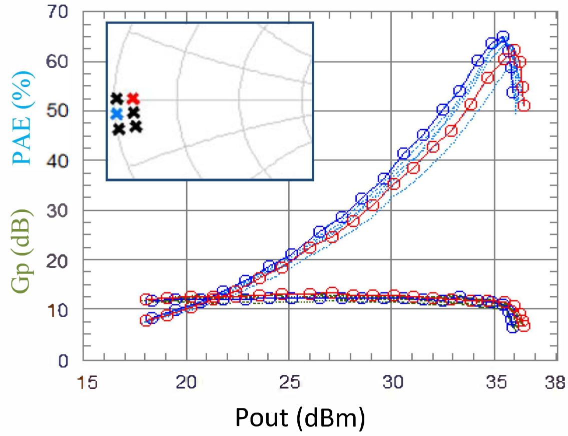

Fig. 5. Second harmonic sourcepull (inset) as well as PAE and Gp as a function of P_{OUT}. Blue markers: load reflection of PAEmax. Red markers: load reflection of P_{OUT}max.

Here, by source-pulling the 2×f0, even better performance is achieved as compared to the only output terminations optimization where in this case: PAE=65.3%, P_{OUT}=35.4 dBm (3.5 W) and Gp=10.9 dB. After optimizing the source 2×f0 a fundamental loadpull is again needed, as shown in Fig. 6. Final optimum performance shows very high efficiency of DE=71.2% (not displayed) and PAE=66.1% while delivering high P_{OUT}=35 dBm (3.2 W) and Gp=11.5 dB.

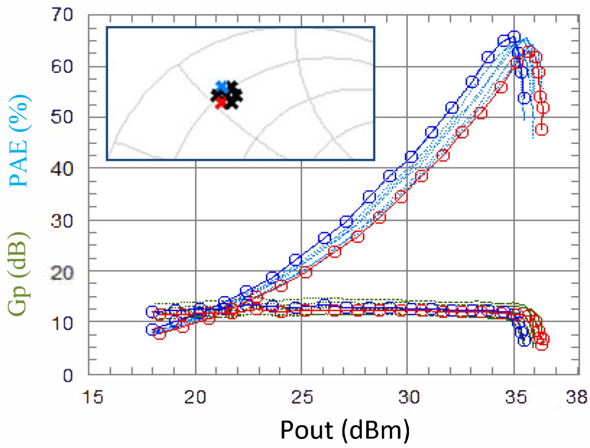

Fig. 6 Final power sweeps and fundamental impedances sweep at optimum 2×f0 source impedance. Blue trace: load set to PAEmax Red trace: load set to P_{OUT}max.

IV. WAFER MAPPING

The measurement procedure with the optimum impedances and results so far described, have been carried out on a few on-wafer devices. These optimum impedances are then set and used together with an IAF in-house software for the complete wafer-mapping at (in this case) X-band frequencies. Thanks to the wafer mapping measurement capability, the devices of the whole wafer can be measured in a fully automated approach. This means that at the fixed frequency, bias condition and optimum source and load terminations previously achieved, automated power sweep can be conducted on the full wafer and yield investigation with respect to maximum gain and power-efficiency can be conducted in a very time efficient process.

The distribution of the most important parameters are shown in Fig. 7 where the devices deliver the same output power and gain of > 35 dBm and > 12dB with an average PAE of 65%.

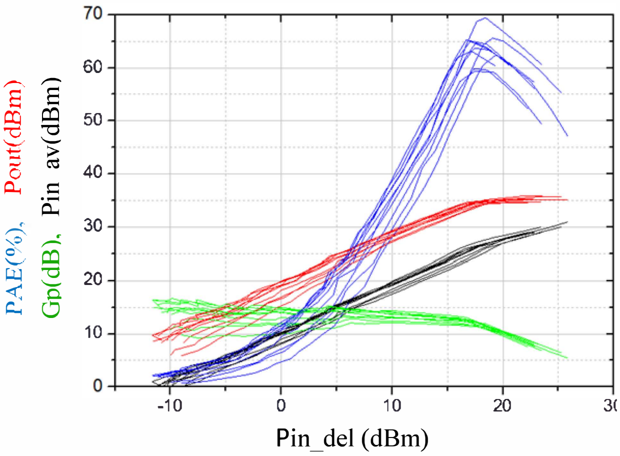

Fig. 7. PAE, Pout, Gp and Pin_available as a function of Pin_delivered traces of several wafer cells in one plot - performance variation.

V. CONCLUSIONS

This paper has shown the measurement results of a 1 mm power HEMT in AlGaN/GaN technology delivering very high power-efficiency at X-band frequencies. By using an active harmonic loadpull system capable of performing accurate measurements at X-band frequencies together with a systematic measurement procedure for the DUT matching optimization, optimum fundamental and second harmonic output- as well as second harmonic source- terminations have been found which deliver valuable information for the design of high-efficiency RF-power amplifiers at 8.7 GHz. The step by step procedure shows the influence of the single impedances on the transistor performance and from here final tuning around the known optimum areas can be done with simultaneous load/source pull of several loops successfully. The optimization of the second harmonic terminations seen by the 1-mm GaN power transistor both at input and output increases the PAE by approximately 6% from 59.7% to 66.1% where also the 2×f0 load and source terminations were optimized.

The paper highlights the high performance of the IAF 1 mm AlGaN/GaN power transistor at X-band frequencies together with a systematic load/source pull measurement procedure for which four RF power loops have been properly varied and optimized for high power-efficiency PAs.

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