Mixed-Mode Active Load-Pull Using one Single-Ended Device-Under-Test

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***Abstract*—A method to emulate differential transmitter architectures is presented. The technique, which is based on mixed-mode active load-pull measurements, predicts power amplifier (PA) performance while avoiding the need to manufacture the complete PA. The method is based on an iterative procedure using transistor/branch PA active load-pull measurements together with the S-parameters of the load network. Advantageously, real world performance of the complete differential PA can be evaluated in the design stage. Thereby, many different output combiners and configurations, e.g., biases, transistors, and branch phases, can be fully evaluated without fabrication. Compared to prior art, the method requires only a single representative device-under-test, while providing flexibility in the input signal and the target load network. Thus, a novel powerful measurement tool for PA designers is presented. The technique is demonstrated by performing mixed-mode load-pull and emulating a differential amplifier at 2.14 GHz using continuous wave signals.**

***Index Terms*—Active load–pull, differential, emulation, measurement technique, mixed-mode S-parameters, power amplifier.**

I. INTRODUCTION

Designing future wireless communication systems puts stringent requirements on measurements for power amplifier (PA) design. Transistor models and/or load-pull measurements are commonly used to predict PA performance in the design stage. This, however, is problematic when differential PA architectures are considered, since several transistors then interact via a potentially non-isolated combiner. Additionally, in some known cases, imbalances in phase and amplitude and/or the presence of common-mode signals will occur. Moreover, these imperfections may change due to non-linear interactions. It is therefore of importance to capture these effects in measurements at an early stage of the PA design.

While bipolar differential PA stages have been explored for a number of years [1]–[5], they are only recently making inroads into handsets [6], [7], especially as phone carriers migrate to 5G. The advantages of such a differential architecture are: the neutralization of Cbc, better isolation, and high stable gain [1], [2]. This architecture also allows better optimization of non-linearities, which is particularly important when maximizing PA efficiency [4].

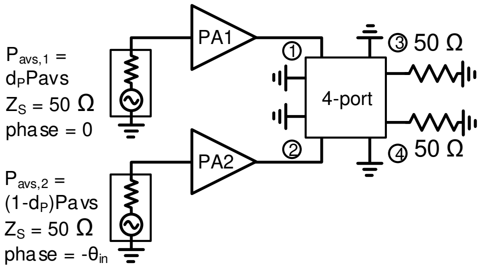

Fig. 1. The schematic operation of differential PAs.

For PA manufacturers, load-pull is often used for selecting technology parameters and providing designers guidance on unit cell selection. Since development teams may wish to focus on the basic technology, this load-pull almost exclusively uses simple single stage load-pull structures [8]. While active mixed-mode load-pull is possible [3], it is more appropriate closer to the circuit level. A technique that helps bridge the gap between the basic technology load-pull performance and the performance in the circuit application would greatly aid in technology and design decisions.

A suitable load-pull measurement-based emulation method was recently proposed. First, the technique analyzed coupling effects between PAs in antenna arrays [9]. Subsequently, the technique was broadened to emulate Doherty [10] and outphasing [11] PAs. However, prior art does not include the impact of the required 4-port differential load network on the behavior of the PAs.

In this work, we propose an emulation method to find the behavior of differential PAs. For the cases with imperfect components resulting in imbalances, the reflection coefficient of the exact loading of the branch amplifiers is unknown a priori. To enable the evaluation of different combiners and configurations (e.g. biases, transistors, branch phases), the procedure described in this paper utilizes branch amplifier measurements and S-parameters of the load network. We demonstrate the method's capabilities by performing differential, common and cross impedance load-pull, and by emulating a differential PA loaded by a hybrid combiner network, driven with unbalanced input signals.

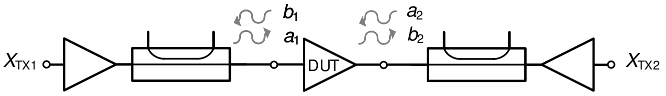

Fig. 2. Active load-pull measurement setup for the emulation of differential PAs. The DUT alternates between representing PA1 and PA2 in Fig. 1.

II. METHOD

The iterative procedure employed to perform mixed-mode active load-pull and emulation of differential PAs is explained in this section. The method follows the emulation technique presented in [10]. The differential PA shown in Fig. 1 is considered and measured in an active load pull system as shown in Fig. 2. Compared to conventional load-pull, the emulation technique allows load-pull of a target N-port S-parameter load matrix. This can be done using a multi-port active load pull system, or alternatively as demonstrated [9], [10] and here, using a single active load pull system, where the DUT alternates between representing PA1 and PA2. Below, we derived the S-parameter load matrices for differential load-pull.

The starting point is the well known formulation [12] of 2-port mixed-mode S-parameters S_{mm} and its standard 4-port S-parameter equivalent S.

$$S_{mm} = \begin{bmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd22} & S_{cc21} & S_{cc22} \end{bmatrix} \tag{1}$$

The equivalence between the two formulations is given by:

$$S_{mm} = MSM^{-1}, \text{where } M = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & -1 \\ 0 & 0 & 1 & 1 \end{bmatrix}. \tag{2}$$

From the waves around the DUT: a_1 and b_1 at the input and a_2 and b_2 at the output (Fig. 2), the common and differential waves of the mixed-mode formulation can be calculated [12]:

$$a_{d1} = \frac{1}{\sqrt{2}}\left(a_{1,PA1} - a_{1,PA2}\right), a_{d2} = \frac{1}{\sqrt{2}}\left(a_{2,PA1} - a_{2,PA2}\right) \tag{3}$$

$$a_{c1} = \frac{1}{\sqrt{2}}\left(a_{1,PA1} + a_{1,PA2}\right), a_{c2} = \frac{1}{\sqrt{2}}\left(a_{2,PA1} + a_{2,PA2}\right) \tag{4}$$

$$b_{d1} = \frac{1}{\sqrt{2}}\left(b_{1,PA1} - b_{1,PA2}\right), b_{d2} = \frac{1}{\sqrt{2}}\left(b_{2,PA1} - b_{2,PA2}\right) \tag{5}$$

$$b_{c1} = \frac{1}{\sqrt{2}}\left(b_{1,PA1} + b_{1,PA2}\right), b_{c2} = \frac{1}{\sqrt{2}}\left(b_{2,PA1} + b_{2,PA2}\right) \tag{6}$$

where the subscript d and c indicate differential- and common-mode, respectively, and $PA1$ and $PA2$ denote the two different branch amplifiers. The differential, common, cross-common to differential, and cross-differential to common-mode load reflection coefficients are given by:

$$\Gamma_{dd} = \frac{a_{d2}}{b_{d2}}, \Gamma_{cc} = \frac{a_{c2}}{b_{c2}}, \Gamma_{cd} = \frac{a_{c2}}{b_{d2}}, \Gamma_{dc} = \frac{a_{d2}}{b_{c2}}. \tag{7}$$

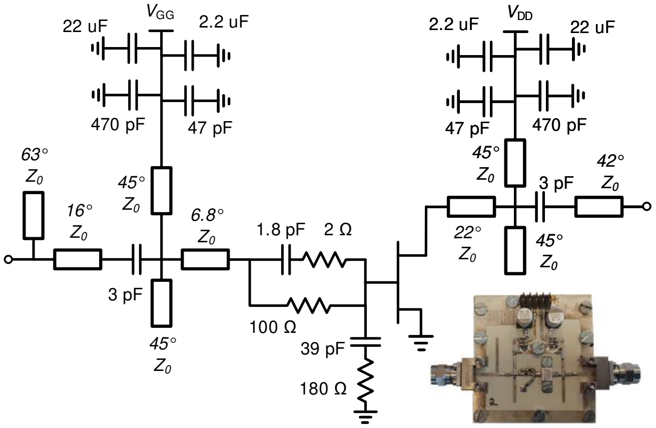

Fig. 3. DUT schematic and photograph.

The load reflection coefficients the individual branch amplifiers see are given by:

$$\Gamma_1 = \frac{a_{2,PA1}}{b_{2,PA1}}, \Gamma_2 = \frac{a_{2,PA2}}{b_{2,PA2}}. \tag{8}$$

To independently load-pull Γ_{dd}, Γ_{cc}, Γ_{cd} and Γ_{dc}, knowledge of how port 1 and port 2 of the load network interact for these load impedances is required. This interaction can be found by setting the corresponding S-parameters S_{dd11}, S_{cc11}, S_{dc11} or S_{cd11} to their respective reflection coefficients $\Gamma_{dd}, \Gamma_{cc}, \Gamma_{cd}, \Gamma_{dc}$ and by translating the S_{mm} to the S matrix, where the load impedances at port 3 and 4 are included. The resulting S_{11}, S_{12}, S_{21} and S_{22} describe the interaction between the two branches and are given here:

$$S_{load} = \frac{1}{2}\begin{bmatrix} \Gamma_{dd} + \Gamma_{cc} + \Gamma_{dc} + \Gamma_{cd} & -\Gamma_{dd} + \Gamma_{cc} + \Gamma_{dc} - \Gamma_{cd} \\ -\Gamma_{dd} + \Gamma_{cc} - \Gamma_{dc} + \Gamma_{cd} & \Gamma_{dd} + \Gamma_{cc} - \Gamma_{dc} - \Gamma_{cd} \end{bmatrix}. \tag{9}$$

The iterative procedure employed to emulate PAs, where the DUT alternates between acting as PA1 and PA2, is explained in [10]. However, handling of the input phase is important to mixed-mode load-pull and is summarized here. For each iteration point, the measured waves are normalised to a_1. This way, any changes in the phase of the DUT as function of the load impedance is included. The target matrix S_{load} is modified according to the requested input phase as

$$S_{12,new} = S_{12}e^{j\theta_{\text{in}}}, S_{21,new} = S_{21}e^{-j\theta_{\text{in}}}, \tag{10}$$

where $-\theta_{\text{in}} = \angle(a_1^{\text{PA2}}/a_1^{\text{PA1}})$ is the input phase difference between the branch PAs which controls the mode of the input signal. Note that once the iteration is completed, this input phase needs to be added to the output waves of a branch to obtain the correct output wave phase.

Once the iteration is completed, the waves at the output fulfil the target S_{load} matrix, and all resulting waves can be stored. Then, as an example: power, efficiency and all reflection coefficients can be calculated. These calculations can be done both for each branch and for the whole emulated amplifier [10]. Note that here we see a fundamental difference compared to conventional load-pull: the actual reflection coefficient seen

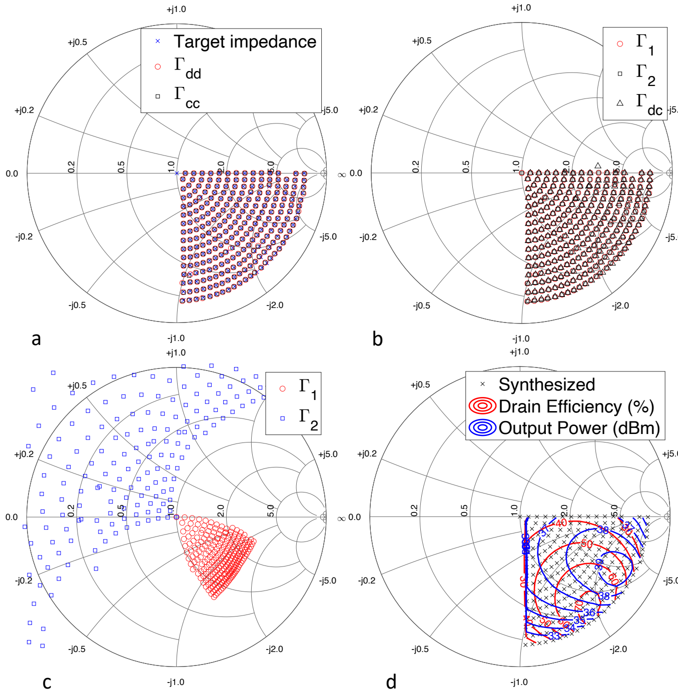

Fig. 4. Load-pull measurement results: a) Differential and common load-pull, b) Γ_1 and Γ_2 from Γ_{dd} load pull and cross load pull Γ_{dc} c) Γ_1 and Γ_2 from Γ_{dc} load pull d) Power and efficiency contours of Γ_{dd}.

by the amplifier branches is only known at the end of the measurement procedure.

III. EXPERIMENTS

A 10-W GaN HEMT CG2H40010F packaged transistor from Wolfspeed is used as the active device. The drain supply voltage is set to 20 V. The branch PA testboard in Fig. 3 includes everything except the fundamental output matching. Thus, it includes bias networks and supply feeds, stabilisation, fundamental input matching networks, and input and output second harmonic terminations. The gate bias is set to -3.2 V. This PA testboard was selected due to its availability in our measurement setup RF WebLab[1]. However, the emulation method is not limited to such testboards and can be applied to single devices. All experiments are performed using continuous wave signals at 2.14 GHz.

An overview of all possible load-pull cases is given in Table I, where both the expected and measured values are given for a target Γ of 0.5. Observe the good agreement between expected and measured quantities. This indicates good orthogonality in all cases. In fact, the measured ratio between differential and common mode input signals is in excess of 80 dB.

In Fig. 4, for each load-pull case with corresponding input signal, the resulting impedances, reflection coefficients on the branches, and other load-pulled quantities are shown. The common and differential load-pull results are as expected, i.e., the branches see the target impedance. However, the cross load-pull shows a very interesting behavior: the branch load impedance are separated by roughly 180 degrees. The distribution depends on the non-linear behaviour of the branches and is a consequence of the load-pull maintaining an a_2 wave with 0 or 180 degrees phase difference for the differential and common input signals, respectively.

TABLE I
MIXED-MODE LOAD-PULL CASES (TARGET Γ=0.5).

Case		Γ_{cc}	Γ_{dd}	Γ_{dc}	Γ_{cd}	Γ_1	Γ_2
Diff. LP w.	1	-	0.5	-	0.5	0.5	0.5
diff. input	2	-	0.50	-	0.50	0.50	0.50
Diff. LP w.	1	0	-	0	-	0	0
comm. input	2	$1e^{-4}$	-	$1e^{-4}$	-	$2e^{-5}$	$2e^{-5}$
Comm. LP w.	1	-	0	-	0	0	0
diff. input	2	-	$6e^{-5}$	-	$1e^{-4}$	$2e^{-5}$	$8e^{-5}$
Comm. LP w.	1	0.5	-	0.5	-	0.5	0.5
comm. input	2	0.50	-	0.50	-	0.50	0.50
Cross. dc LP	1	-	0	-	0	0	0
diff. input	2	-	$4e^{-5}$	-	$4e^{-5}$	$1e^{-4}$	$4e^{-5}$
Cross. dc LP	1	0	x	0.5	0	x	x
comm. input	2	$1e^{-4}$	0.8-0.8i	0.50	$4e^{-3}$	0.4-0.1i	-0.5-0.3i
Cross. cd LP	1	x	0	0	0.5	x	x
diff. input	2	0.8-0.8i	$1e^{-4}$	$5e^{-4}$	0.50	0.4-0.1i	-0.7-0.2i
Cross. cd LP	1	0	-	0	-	0	0
comm. input	2	$7e^{-5}$	-	$5e^{-4}$	-	$4e^{-5}$	$1e^{-4}$

^{1}expected value, ^{2}measured value, $^-$undefined, ^{x}depends on PA.

Finally, we demonstrated the emulation of a differential amplifier, as if the branches are connected to an imperfect 180 degrees hybrid coupler, with S-parameters based on a commercial coupler with 16-dB isolation. Its output ports 3 and 4 are terminated with 50 Ω. Lossless matching networks are added in the emulation to match the hybrid coupler to the PAs. This intentionally preserves differences between S_{11} and S_{22} of the hybrid coupler. The emulated S-parameters of the described hybrid coupler with matching networks and terminations are as follows: $S_{11} = 0.38\text{-}0.75i$, $S_{12} = S_{21} = 0.16\text{-}0.02i$ and $S_{22} = 0.41\text{-}0.78i$. A power sweep over a 15-dB output power range is performed with an ideal differential signal, as well as with an input phase imbalance of ±10 degrees. The resulting branch load impedances Γ_1 and Γ_2 are shown in Fig. 5. These changes in the load impedance for the branch amplifiers will influence power, efficiency and linearity and are critical information for PA designers.

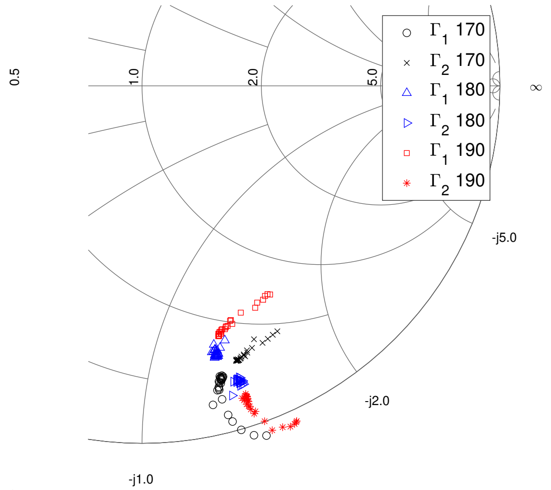

Fig. 5. Emulated differential amplifier branch load measurements.

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[1] www.dpdcompetition.com/rfweblab

IV. CONCLUSION

It has been demonstrated that the emulation technique works for differential power amplifiers. Its potential impact has been shown by performing mixed-mode load pull as well as emulating a differential amplifier. The presented measurement technique enables the early prediction of real-world performance and brings measurement-based understanding, thus leading to better circuits as required in future wireless systems.

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