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# Emulation of Non-Reciprocity applied in Load-Modulated Power Amplifier Architectures using Single Amplifier Load-Pull Measurements

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***Abstract*— An active load-pull measurement technique is exploited to test the performance of novel high-efficiency power amplifier (PA) concepts based on non-reciprocity. This technique allows new PA architectures, including its load-modulation, to be evaluated before any construction is necessary. Merely active load-pull measurements of a single representative device or PA, in combination with knowledge of the S-parameters of the output combiner, are needed. As a result of the technique, the load modulation on the branch PAs are exposed, thereby allowing PA designers to optimize PA performance. The technique is demonstrated by emulating a load-modulation PA, consisting of two branch PAs with their outputs combined using a non-reciprocal circulator. The resulting PA concept is designed and evaluated at 2.14 GHz.**

***Keywords*— Active load–pull, power amplifier (PA), circulator, emulation, measurement technique, non-reciprocal.**

## I. Introduction

New generation wireless communication systems rely on large active antenna arrays for multiple-input multiple-output (MIMO) [1] and advanced beamforming capabilities to further increase network capacity. However, moving to such complex systems brings additional challenges to power amplifier (PA) designers. Trade-offs between a multitude of stringent requirements need to be taken into account, further complicated by potential load variations due to mutual coupling and crosstalk [2], [3] in such a system.

Efficient PA architectures based on dynamic load modulation such as Doherty power amplifier (DPA) [4], outphasing scheme [5], load modulated balanced amplifier [6] and distributed DPAs [7], are receiving increased interest to be integrated in current and future wireless communication systems. They maintain high efficiency over a large output power range, resulting in higher average power efficiency for modulated signals with significant peak-to-average power ratio values. Nevertheless, the design of these multi-transistor systems is very challenging as several nonlinear active devices interact through a combiner. These interactions may result in even more design complications when novel load-modulation architecture concepts are investigated.

PA designers make use of simulation tools in combination with transistor models, or often use load pull data directly. Transistor model development may have significant development time and potential accuracy issues. Even a behavioral model's accuracy may be limited by the exact loading conditions under which the model was extracted, which may deviate significantly from the designers intent for novel PA architectures. Conventional load-pull techniques are not fully representative for the exact load-modulation as happens in e.g. a Doherty PA [8]. Consequently a discrepancy between real-world performance and the prediction during the design stage may occur. As such, PA designers yearn accurate performance prediction tools where the interaction between the nonlinear branch PAs is taken into account resulting in accurate load modulation prediction in the design stage.

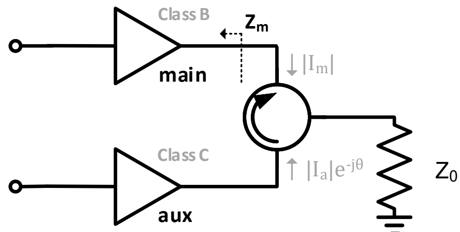



Fig. 1. Block diagram of the ideal high-efficiency circulator load modulated amplifier (CLMA) architecture.

An active load-pull measurement-based emulation technique was recently proposed for performance prediction. The technique was proposed in [9], [10] with the focus on coupling effects between PAs in antenna array systems. The technique was thereafter expanded to emulate the behaviour of load modulation Doherty PAs [11], where it was verified that the technique can predict the performance of multi-transistor systems in the design stage. Subsequently, the method was exemplified by emulating outphasing [12] differential [13] and multi-stage differential amplifiers [14]. However, these publications investigate already known PA architectures.

This work presents a measurement-based design methodology for novel PA architectures, demonstrated by verifying a load modulation PA concept using a non-reciprocal element in its output combiner network. A test board PA is used to act as representative branch PA. The described procedure employs the S-parameters of a commercial circulator as combiner. For the first time, a non-reciprocal element between branch PAs is emulated using active load-pull.

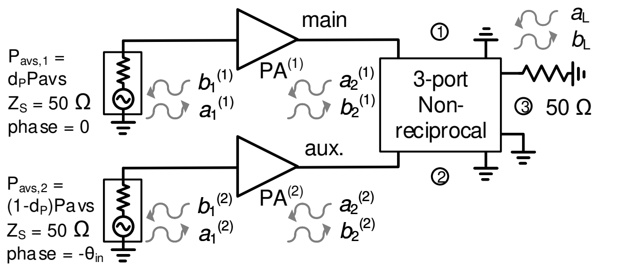
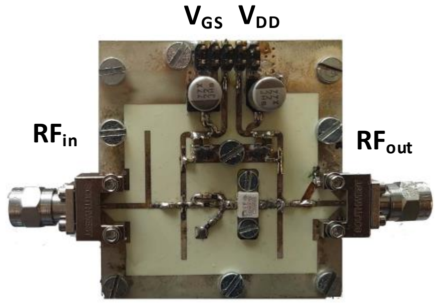
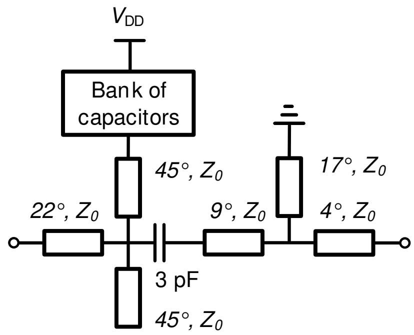



Fig. 2. Simplified schematic operation of a non-reciprocal load-modulated PA for the emulation technique.




(a)




(b)

Fig. 3. Photograph of the PA test board (a) and detailed schematic of the output matching network (b).

## II. Emulation Method using Non-Reciprocal Power Combiners

This section motivates the use of non-reciprocal components as power combiners in high-efficiency PA architectures and summarizes the procedure employed to emulate non-reciprocity.

### *A. Efficient PA Architectures based on Non-Reciprocal Power Combiners*

Traditionally, conventional high-efficiency load modulation based PA architectures are based on reciprocal combiners. Recently a PA architecture based on a non-reciprocal combiner, the circulator load modulated amplifier (CLMA), has been proposed [15] as a feasible solution to solve the existing efficiency-bandwidth-complexity compromise in these architectures.

The CLMA architecture (Fig. 1) consists of a main class-B amplifier, an auxiliary class-C amplifier and a 3-port non-reciprocal network acting as power combiner. According to Eq. (1) [15], it is possible to modulate the impedance seen by the main class-B amplifier, denoted as $Z_m$, by properly controlling the amplitude and phase of the current injected by the auxiliary class-C amplifier through a circulator as follows

$$Z_m = Z_0(1 + 2\frac{I_a e^{j\theta}}{I_m}). \tag{1}$$

being $I_m$ and $I_a$, respectively, the amplitudes of the main and auxiliary amplifier's currents, with a phase offset $\theta$ between them. $Z_0$ is the characteristic impedance of the circulator.

Moreover, the power injected by the main and auxiliary amplifiers can be fully delivered to the load [15]. Therefore, high efficiency over a wide output power control range can be maintained.

### *B. Emulation Methodology*

This work employs the load-pull measurement-based emulation technique presented in [11] to evaluate the novel CLMA architecture in an early design stage. The technique allows to validate the novel PA concept without the need of fabricating the complete PA architecture.

Fig. 2 shows a simplified schematic operation of a non-reciprocal load-modulated PA. Note that only a single representative branch PA is required in the active load pull setup, which represents both branch PAs by changing its bias conditions. The methodology is based on the fact that the $a_2$ waves depend on both the combiner and the $b_2$ waves, and vice versa.

For each input power level, one emulation set is iteratively completed until the wanted $a_2$ waves, $a_{2,\text{want}}$, for each branch PA have converged according to the two errors that are defined for each branch PA [11]. It should be noted that the $a_1$ waves are fixed for every emulation set.

Two separate measurements, one per branch PA, are done in each iteration in the emulation set. At the first iteration, $a_2$ is assumed to be zero. At iteration $n$, the desired $a_2$ waves, are determined by using the combiner S-parameters and the $a$ and $b$ waves from the previous iteration [11]. Afterwards, the $a_2$ and $b_2$ waves for both branch PAs are measured.

Finally, the performance at the load termination is calculated by computing the wave $b_\text{L}$ [11] once the emulation procedure has converged.

## III. Experimental Results

The emulation of non-reciprocal load-modulated PA architectures is performed using an extended version of the measurement setup RF Weblab at Chalmers [10].

The DUT is a PA test board based on a 10-W GaN HEMT CGH40010F packaged transistor from Wolfspeed. Fig. 3 shows a photograph and a detailed schematic of the output matching network of the test board.

The same branch PA, at different bias points, is employed in the constituting amplifiers of the CLMA architecture by

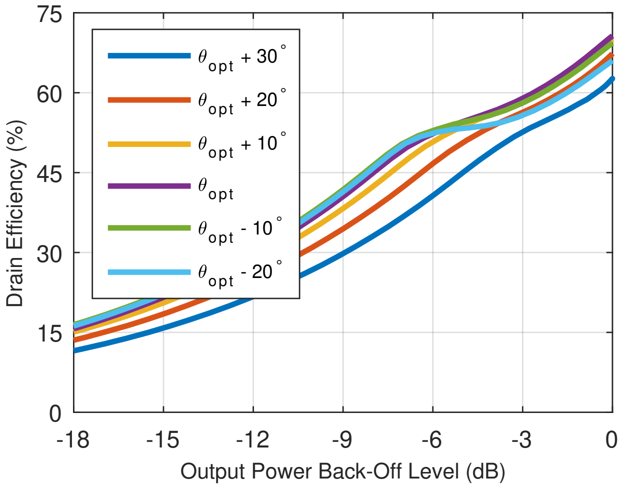



Fig. 4. Measured emulated efficiency vs output power back-off level performance for the CLMA PA at 2.14 GHz, for different phase delays between the constituting amplifiers.

properly selecting the gate supply voltage, whilst the drain supply voltage is set to 20 V due to hardware limitations.

A high isolation (34 dB) and low insertion loss (0.26 dB) three-port SM2040C09 circulator from Quest Microwave is selected to act as the output combiner. The combiner is characterized at 2.14 GHz obtaining the following matrix of scattering parameters:

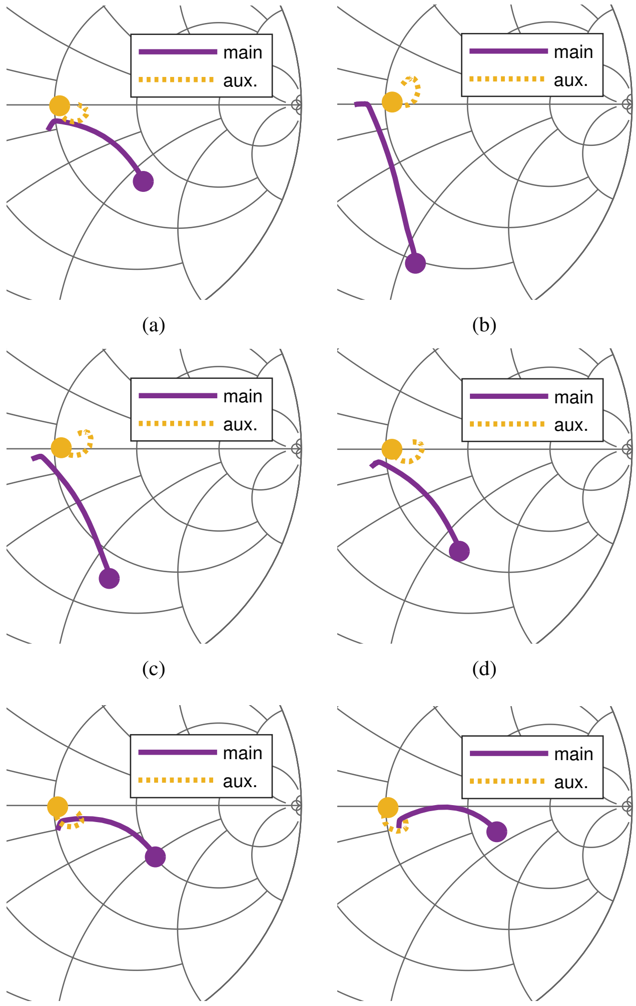
$$[S] = \begin{bmatrix} 0.016\angle{-86^\circ} & 0.019\angle{-37^\circ} & 0.974\angle{-70^\circ} \\ 0.970\angle{-71^\circ} & 0.025\angle 125^\circ & 0.004\angle 55^\circ \\ 0.018\angle{-29^\circ} & 0.971\angle 19^\circ & 0.024\angle 131^\circ \end{bmatrix}. \quad (2)$$

Conventional active load-pull is employed to complete load-pull measurements in iterations on the test board. In each iteration, the same PA test board acting as main and auxiliary PAs is measured separately. Consequently, the PA test board is biased at $-3$ V and $-5.5$ V to behave as main and auxiliary PA, respectively.

A set of emulation is done for each input power level, whilst the angle between the constituting amplifiers is maintained fixed. Moreover, the input power splitting ratio into the two branch PAs is set to be $0.5$.

First, the emulation method is performed considering an optimal phase delay between the main and auxiliary PAs, which is denoted as $\theta_{opt}$. Afterwards, the CLMA is also emulated under non-optimal phase delay condition to further demonstrate the high potential of the emulation technique to test and verify novel PA concepts and/or architectures.

Fig. 4 shows the emulated performance, in terms of drain efficiency versus output power back-off level, for $\theta_{opt}$ and several non-optimal phase delays. A high efficiency peak can be observed at back-off. Moreover, high drain efficiency values (as high as $50\%$) can be maintained for an output power control range of 6 dB. As expected, the same drain efficiency for the low output power region is obtained independently of the phase delay between the constituting amplifiers due to the fact that the auxiliary amplifier is not conducting current and therefore is not modulating the load of the main amplifier. The effect of providing a non-optimal phase delay can be appreciated in Fig. 4 where the CLMA performance is degraded as far as the main amplifier deviates from its optimal load modulation trajectory.




(a) (b) (c) (d) (e) (f)

Fig. 5. CLMA PA at 2.14 GHz. Measured emulated load modulation trajectories for (a) $\theta_{in} = \theta_{opt}$, (b) $\theta_{in} = \theta_{opt} + 30^\circ$, (c) $\theta_{in} = \theta_{opt} + 20^\circ$, (d) $\theta_{in} = \theta_{opt} + 10^\circ$, (e) $\theta_{in} = \theta_{opt} - 10^\circ$ and (f) $\theta_{in} = \theta_{opt} - 20^\circ$. The dot indicates the maximum input power level.

In contrast to conventional techniques, the emulation method provides essential information on the non-linear interaction of the active devices. The technique predicts the behaviour of both constituting PAs by determining their authentic dynamic loading condition [11]. The mutual load modulation trajectories in the plane before the combiner are presented in Fig. 5 for several phase delays between main and auxiliary amplifiers.

Due to the high isolation from main to auxiliary ports provided by the circulator, it should be noted that the impedance seen by the auxiliary amplifier is approximately maintained constant, and equal to the characteristic impedance of the combiner. Nevertheless, small load variations can be observed, Fig. 5, which are negligible in comparison to a typical Doherty PA, where the aux branch may even dissipate power in deep back-off. Furthermore, these results highlight that the main amplifier only needs to be matched at $Z_0$ to provide its highest efficiency. Thereby providing a high-efficiency peak at the considered output power back-off level slightly before the auxiliary amplifier switches on.In addition, the load modulation caused by the auxiliary amplifier in the main amplifier should reach the maximum output power impedance point at the maximum input power level.

The results at 2.14 GHz confirm the CLMA to be a suitable candidate for future wireless transmitters.

## IV. Conclusion

An active load-pull technique has been employed to emulate novel efficient power amplifier architectures based on non-reciprocity. The technique is shown to allow quick validation of innovative concepts such as the recently proposed circulator load modulated amplifier. Additional characterization of the architecture, by deteriorating its performance, is provided to demonstrate the high potential of the emulation technique.

It should be noted that the emulation technique provides direct information on the interaction between the non-linear active devices, and provides the intrinsic loading conditions of the constituting PAs. The method can be exploited by PA designers either to optimize their designs or to test new concepts and/or combiners.

To the best of the authors' knowledge, a highly-efficient PA architecture based on a non-reciprocal combiner is emulated, for the first time, using active load-pull.

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