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Analysis of Optimal Outphasing Load Trajectories for GaN PAs

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Abstract—This paper presents an analysis of the optimal Z_{f_0} load trajectories of saturated GaN PAs through Z_{f_0} and Z_{2f_0} load-pull measurements under constant input power on a 900 MHz 10 W PA. It is shown that a DE >50% at 10 dB back-off can be obtained for a range of 160° of $\angle Z_{2f_0}$ when Z_{f_0} is set to its optimal point. The black box combiner design equations are used as a tool to determine the complete outphasing load trajectories for outphasing systems designed for different back-off levels and extract drain efficiency performance for a range of $\angle Z_{2f_0}$ terminations. When the suboptimal outphasing load trajectories are considered, Z_{2f_0} is demonstrated to have a greater impact compared to the case Z_{f_0} follows the optimal load trajectories.

Index Terms—outphasing, harmonically tuned PAs

I. INTRODUCTION

In modern high data-rate wireless communication systems, strict requirements are set for the RF power amplifier (PA) due to the need to transmit RF signals with large peak-to-average power ratios (PAPR) and the need to operate the transmitter at different average power levels. For the RF designer, this translates into maintaining a high PA drain efficiency (DE) over a large P_{OUT} dynamic range. At the same time it is critical to maximise the gain of the PA and achieve the largest saturated P_{OUT} for a given device. Load modulated architectures such as Doherty [1] and outphasing [2] are powerful ways this can be achieved. Fig. 1 (a) shows the potential for efficiency enhancement of a load modulated architecture over 12 dB P_{OUT} from Z_{f_0} and Z_{2f_0} load-pull of a 900 MHz GaN PA under constant input power. The dependency of back-off efficiency of GaN PAs on Z_{2f_0} was analysed in [3] with simulations and experiments considering PAs operating at fixed compression (1 dB). In order to achieve the largest possible back-off efficiency load modulated architectures, such as outphasing, operate the constituent branch PAs at much larger compression levels, pushing the device to exhibit switch-like behaviour. Fig. 1 (b) shows that even operating in deep saturation as the PA is driven with constant input power, the optimal $\angle \Gamma_{2f_0}$ for DE of a single-ended GaN PA increases from 50° to 250° . The aim of this experiment is to investigate the optimal Z_{f_0} load trajectories of a highly saturated GaN PA for different Z_{2f_0} terminations. Extensive load-pull measurements are presented for a 900 MHz GaN HEMT single-ended PA, which are de-embedded to the current generator (CG) plane of the device. The optimal Z_{f_0} load trajectories for fixed Z_{2f_0} terminations are compared to the real loading condition achievable with outphasing operation, for different output power back-off (OPBO) levels.

Fig. 1: Performance of PA subject to Z_{f_0} and Z_{2f_0} load-pull (a) and variation in optimal Z_{2f_0} over P_{OUT} (b).

II. EXPERIMENT OVERVIEW AND SET-UP

Fig. 2 (a) shows a block diagram of the experiment set-up and measurements of the pre-matching network. The single-ended PA was designed using a 10 W GaN device with 0.76 mm Duroid 5880 substrate. The PA, which is shown in Fig. 2 (b), is pre-matched at the output for DE at Z_{f_0} only with a high-pass lumped LC network. The PA was biased in class-B ($V_{GS} = -3V$ and $V_{DS} = 28V$). Throughout the measurements the source tuner presented to the input of the PA a fixed conjugate match impedance while the output third harmonic Γ_{3f_0} was set for maximum DE at saturation and also fixed. The PA, fed with a pulsed single-tone at a constant power level (27dBm), was load-pulled at Z_{f_0} for 72 values of Γ_{2f_0} corresponding to $|\Gamma_{2f_0}| = 0.92$, the $|\Gamma|$ limit of the set-up, and with $\angle \Gamma_{2f_0}$ swept from 0° to 360° with 5° resolution. The matching network, connectors, intrinsic and extrinsic device parasitic s-parameters were cascaded and used so to be able to de-embed the impedances presented during load-pull by the

Fig. 2: Set-up block diagram (a), photograph of RF PA (b), optimal load trajectories for different Z_{2f_0} (c) and DE vs P_{OUT} performance (d).

load tuner, calibrated to the output of the PA, to its CG plane.

III. OPTIMAL LOAD TRAJECTORIES WITH FIXED Z_{2f_0}

The optimal load trajectories and respective performance, for three different $\angle\Gamma_{2f_0} = [20^\circ; 100^\circ; 260^\circ]$ corresponding respectively to a short, a capacitive reactive and inductive reactive impedance, after de-embedding to the CG plane of the device, are shown in Fig. 2 (c). The optimal Z_{f_0} trajectories with a fixed Z_{2f_0} are defined as the load trajectories which, starting from the maximum P_{OUT} point, $Z_{f_0,p}$, pass through the optimal DE point $Z_{f_0,\eta}$ and follow the convex hull of the DE vs P_{OUT} profile, resulting from Z_{f_0} load-pull. The first finding evident from Fig. 2 (c) and (d) is that, following the optimal Z_{f_0} load trajectory with a fixed Z_{2f_0} , a DE > 50% at 10 dB OPBO can be maintained for a range of 160 $^\circ$ of Γ_{2f_0} . Additionally, it is noted that an even larger region of efficiency exists as DE > 40% at 10 dB OPBO over 260 $^\circ$ Γ_{2f_0} . As Γ_{2f_0} approaches a intrinsic CG short, DE at OPBO progressively degrades, and the DE vs P_{OUT} profile changes substantially as evidenced in Fig. 2 (d). Although in the high efficiency region DE at 10 dB OPBO presents small variation, a degradation of 1 dB in P_{OUT} is evident moving from $\Gamma_{2f_0} = 100^\circ$ to $\Gamma_{2f_0} = 260^\circ$. The continuity of modes of operation [4] is a well-known concept in the PA design community and reflects the possibility of obtaining quasi-identical P_{OUT} for a range of different Z_{2f_0} conditions. This concept was expanded to PAs in switch-mode operation [5]. The results presented in

this paper show that through a continuum of switch-mode of operation conditions, which correspond to the Γ_{2f_0} high efficiency region in Fig. 2 (c), high DE can be achieved over a 10 dB P_{OUT} dynamic range, once the PA is highly saturated. As the input power is fixed during load-pull, performance in terms of DE is shown to demonstrate a measure of waveform shape integrity; however it is expected that with mixed-mode approach PAE could be restored by improving the system gain.

IV. OUTPHASING LOAD TRAJECTORIES

When Z_{f_0} follows the optimal load trajectories, the DE can be kept high over a large dynamic range with a fixed Z_{2f_0} . However, during outphasing operation the two branch PAs are loaded identically only at two outphasing angles which correspond to the intersection of their load modulation trajectories: at the peak power point, and the chosen OPBO point. At these points performance can be ensured when designing from load-pull and using the optimal load trajectory for the chosen Z_{2f_0} . However, no information is known on the performance of the system throughout the rest of outphasing operation. It is possible to extract the performance of the outphasing PA for a chosen Z_{2f_0} and OPBO, using $Z_{f_0,p}$ and $Z_{f_0,\eta,OPBO}$ with the black box combiner design equations [1]:

$$Z_{11} = \frac{Z_{f_0,\eta,OPBO} - Z_{f_0,p}}{1 + e^{j2\theta_1}} + Z_{f_0,p} \quad (1)$$

$$Z_{12} = \frac{1}{2}(Z_{f_0,p} - Z_{f_0,\eta,OPBO}) \sec(\theta_1) \quad (2)$$

Fig. 3: P_{OUT} and PAE load-pull contours, optimal Z_{f_0} and outphasing load trajectories optimised for 6 and 10 dB OPBO.

Fig. 4: DE vs P_{OUT} for different outphasing load trajectories for $\Gamma_{2f_0} = 100^\circ$ (a), $\Gamma_{2f_0} = 180^\circ$ (b), $\Gamma_{2f_0} = 260^\circ$ (c).

$$Z_{22} = \frac{Z_{f_0, P} - Z_{f_0, \eta, OPBO}}{1 + e^{j2\theta_1}} + Z_{f_0, \eta, OPBO} \quad (3)$$

The complete outphasing load trajectories are determined by approximating the PA branches as voltage sources with the two-port combiner found from (1)-(3). The outphasing trajectories and performance are extracted for an outphasing system designed for: OPBO = 6 and 10 dB. The performance of the upper branch PA only is extracted for simplicity to calculate an approximate system DE. Three Γ_{2f_0} are considered, chosen from the high efficiency region found in Section III. The outphasing load trajectories considered for $\angle \Gamma_{2f_0} = 100^\circ$ are shown in Fig. 3. The outphasing performance is compared to the performance of the optimal Z_{f_0} load trajectory with fixed Z_{2f_0} and to that of an outphasing system with a dynamic

Fig. 5: Variation of optimal $\angle \Gamma_{2f_0}$ for 6 dB outphasing upper and lower branch trajectories optimised for $\angle \Gamma_{2f_0} = 100^\circ$.

optimal Z_{2f_0} at each point of its trajectories, as shown in Fig. 4. As expected the trajectories optimised for 6 dB OPBO present a DE closer to the optimal Z_{f_0} case at small OPBO levels, with the DE quickly dropping off at larger OPBO. Conversely, when optimised for 10 dB OPBO, the efficiency of the system is lower at smaller P_{OUT} , due to the greater deviation of the load trajectories from the optimal Z_{f_0} . The performance of the outphasing system with optimised Z_{2f_0} outperforms all other cases. Tuning of Z_{2f_0} restores the maximum P_{OUT} capability of the device for each case considered. In Fig. 5 the region of optimal DE for upper and lower branch outphasing trajectories are shown. Due to the shape of the outphasing trajectories, the Z_{2f_0} high efficiency region shifts with the optimal Z_{2f_0} for the upper and lower branches following opposite trends.

V. CONCLUSION

This paper has presented Z_{f_0} and Z_{2f_0} load-pull measurements on a 900 MHz 10 W GaN HEMT single-ended PA presenting and comparing the optimal load trajectories over output power, with fixed Z_{2f_0} . A wide Z_{2f_0} high efficiency region corresponding to large inductive and capacitive intrinsic loading is demonstrated. A simple way to extract outphasing performance from load-pull contours using the black box design equations is shown and used to demonstrate the significance of Z_{2f_0} tuning when the PA is presented with real suboptimal outphasing trajectories.

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