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PA Output Power and Efficiency Enhancement Across the 2:1 VSWR Circle using Static Active Load Adjustment

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***Abstract*— This paper proposes a power amplifier (PA) correction technique to recover from load mismatch. It utilizes a main PA, two auxiliary PAs, and a coupler. By adjusting the input drive levels of the PAs it can recover the output power and to a great extent the efficiency of the main PA even when exposed to 2:1 VSWR mismatch conditions. When connected to $50\,\Omega$ loading, only the main PA is active, for impedances below or above $50\,\Omega$, besides the main amplifier, one of the auxiliary PAs is also activated. The power generated by the auxiliary PA adds in phase to the output power of the main PA, as such allowing the output power to be constant at the expense of a minor efficiency penalty.**

***Keywords*— Power Amplifier, VSWR, Coupler, Gallium Nitrite (GaN), HEMT.**

I. Introduction

5G communication systems offer spatial multiplexing of their mobile users by adopting phased-array/mMIMO techniques [1]. Unfortunately, the (undesired) antenna mutual coupling in these systems, yields the feed impedances of the antennas to change with the beam steering angle. Power amplifiers (PA) driving the antenna elements are very sensitive to load changes, yielding performance degradation in mismatch conditions [2]. Typically, isolators are used to break the reciprocity of the PA-antenna network, such as presenting a constant impedance-matched load to the PAs. However, isolators are expensive and difficult to integrate. To avoid suboptimal PA performance under impedance mismatch, tunable matching networks (TMN) [3] are employed for low-power applications. To reduce the insertion loss of the TMN and to relax the tuning range requirements, a combination of a TMN, supply, and input drive adjustment was proposed in [4]. Supply adjustment was used in [5] for higher power applications. However, these two latter techniques require the use of a DC-DC converter that can adjust the PA supply voltage to the applied mismatch condition in combination with an input drive adjustment.

In this work, a mismatch adjustment technique is proposed to recover the main PA performance under load mismatch by only adjusting the input drive levels of the active devices/PAs. The presented technique makes use of a main PA, two auxiliary PAs, namely PA_{low}, PA_{high}, and a coupler (see Fig. 1). The drive levels of the main and auxiliary PAs are adjusted based on the applied loading. Three scenarios are considered,

1) R_{L} is $50\,\Omega$ load, only PA_{main} is activated as shown in Fig. 1a

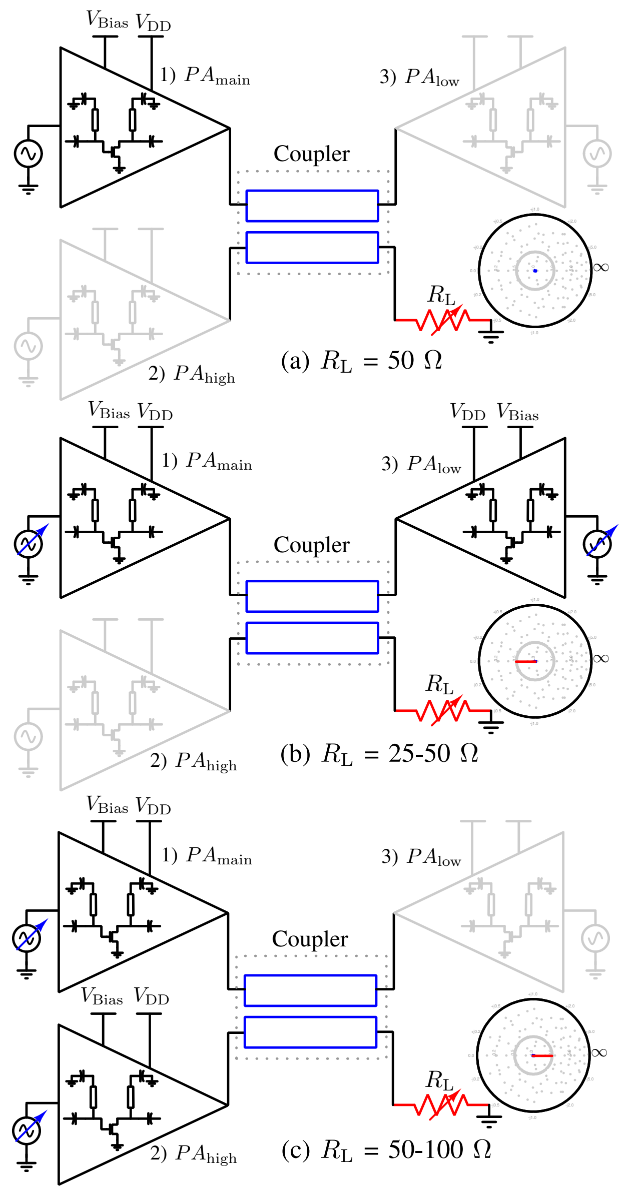


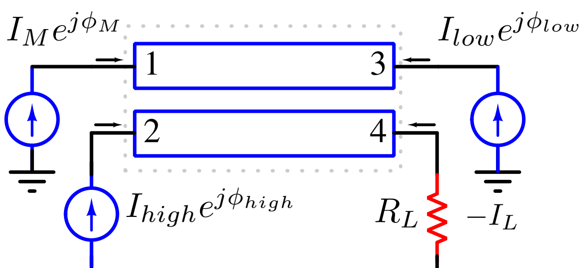
Fig. 1. The proposed concept of using active auxiliary devices for static load adjustment. (a) case 1: PA_{main} is active only to drive the matched load, (b) case 2: for a load mismatch between $25\,\Omega$-$50\,\Omega$ PA_{main} and PA_{low} are active with adjusted input drive levels and (c) case 3, for a load mismatch between $50\,\Omega$-$100\,\Omega$ PA_{main} and PA_{high} are both active with customized drive level.

2) R_L is between 25 Ω-50 Ω, PA_main and PA_low are both active as shown in Fig. 1b. In this operation mode PA_low adjusts the loading impedance of PA_main. Two operation modes are possible, namely;
   - Both PA_main and PA_low are kept out of voltage clipping.
   - Only PA_main is kept out of voltage clipping.
3) R_L is between 50 Ω-100 Ω PA_main and PA_high are both active as shown in Fig. 1c, PA_high adjusts the loading impedance of PA_main. Two operation modes are possible, namely;
   - Both $\mathrm{PA}_\mathrm{main}$ and $\mathrm{PA}_\mathrm{high}$ are kept out of voltage clipping.
   - Only $\mathrm{PA}_\mathrm{main}$ is kept out of voltage clipping.

In the cases that both PAs are kept out of voltage clipping, the output power can be kept constant at the cost of a (small) efficiency penalty. In the case that only the $\mathrm{PA}_\mathrm{main}$ is kept out of voltage clipping, the efficiency penalty is even less while the output power only marginally fluctuates.

The outline of this paper is as follows. In section II, the static load adjustment technique to recover the PA performance is introduced and the equations for the idealized case are derived and verified in simulation. In section III a measurement-based proof of concept is given using a commercially available coupler and GaN-based evaluation boards. The paper is concluded in section IV.

II. Theory



(a)

$$\begin{bmatrix} V_M \\ V_{high} \\ V_{low} \\ V_L \end{bmatrix} = \frac{Z_0}{\sqrt{1-C^2}} \begin{bmatrix} 0 & 0 & \text{-j} & \text{-jC} \\ 0 & 0 & \text{-jC} & \text{-j} \\ \text{-j} & \text{-jC} & 0 & 0 \\ \text{-jC} & \text{-j} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_M e^{j\phi_M} \\ I_{high} e^{j\phi_{high}} \\ I_{low} e^{j\phi_{low}} \\ -I_L \end{bmatrix}$$

(b)

Fig. 2. The proposed circuit (a) coupler with current sources representing the PAs and the connected variable load. (b) Z-matrix of the coupler used in the analysis.

We will assume the use of a coupled line coupler with the three PA sources connected for analyzing the proposed concept in Fig. 2a. The Z-matrix [6], [7] is given in Fig. 2b, where C is the coupling coefficient. The current supplied by the PA_main and the two auxiliary PAs are represented by current sources and are I_M, I_low, and I_high respectively. We can write the following voltage equations from the Z-matrix in terms of I_M, I_low, and I_high currents while making use of the relation $V_\mathrm{L} = I_\mathrm{L} R_\mathrm{L}$.

$$V_\mathrm{M} = \frac{Z_0}{\sqrt{1-C^2}}(-jI_\mathrm{low}e^{j\phi_\mathrm{low}} + \frac{C^2 Z_0}{R_l\sqrt{1-C^2}} I_\mathrm{M} e^{j\phi_\mathrm{M}} + \frac{C Z_0}{R_\mathrm{L}\sqrt{1-C^2}} I_\mathrm{high} e^{j\phi_\mathrm{high}}) \quad (1)$$

$$V_\mathrm{high} = \frac{Z_0}{\sqrt{1-C^2}}(-jCI_\mathrm{low}e^{j\phi_\mathrm{low}} + \frac{C Z_0}{R_\mathrm{L}\sqrt{1-C^2}} I_\mathrm{M} e^{j\phi_\mathrm{M}} + \frac{Z_0}{R_\mathrm{L}\sqrt{1-C^2}} I_\mathrm{high} e^{j\phi_\mathrm{high}}) \quad (2)$$

$$V_\mathrm{low} = \frac{Z_0}{\sqrt{1-C^2}}(-jI_\mathrm{M}e^{j\phi_\mathrm{M}} - jCI_\mathrm{high}e^{j\phi_\mathrm{high}}) \quad (3)$$

$$V_\mathrm{L} = \frac{Z_0}{\sqrt{1-C^2}}(-jCI_\mathrm{M}e^{j\phi_\mathrm{M}} - jI_\mathrm{high}e^{j\phi_\mathrm{high}}) \quad (4)$$

From (1), (2), (3), and (4), we can observe that to add constructively, ϕ_M and ϕ_high need to be in phase, so we set them both to zero. Furthermore, the impedances offered to the PAs should be ohmic. Consequently, ϕ_low + 90° = ϕ_M, i.e., ϕ_low = -90°. The delivered power (P_out = ${V_\mathrm{L}}^2/2R_\mathrm{L}$) to the load is given by,

$$P_\mathrm{out} = \frac{Z_0^2}{2R_\mathrm{L}(1-C^2)}(CI_\mathrm{M} + I_\mathrm{high})^2 \quad (5)$$

Furthermore, the resulting impedance offered to the PAs is,

$$Z_\mathrm{M} = \frac{C^2}{1-C^2}\frac{Z_0^2}{R_\mathrm{L}} + \frac{C}{1-C^2}\frac{Z_0^2}{R_\mathrm{L}}\frac{I_\mathrm{high}}{I_M} - \frac{Z_0}{\sqrt{1-C^2}}\frac{I_\mathrm{low}}{I_\mathrm{M}} \quad (6)$$

$$Z_\mathrm{high} = \frac{1}{1-C^2}\frac{Z_0^2}{R_\mathrm{L}} + \frac{C}{1-C^2}\frac{Z_0^2}{R_\mathrm{L}}\frac{I_\mathrm{M}}{I_\mathrm{high}} - \frac{C}{\sqrt{1-C^2}} Z_0 \frac{I_\mathrm{low}}{I_\mathrm{high}} \quad (7)$$

$$Z_\mathrm{low} = \frac{Z_0}{\sqrt{1-C^2}}(\frac{I_\mathrm{M}}{I_\mathrm{low}} + C\frac{I_\mathrm{high}}{I_\mathrm{low}}) \quad (8)$$

With these voltages and impedances, we can obtain the driving profile versus the loading R_L, while setting Z_0 = 50 Ω and C = $1/2^{0.5}$,

a) Case 1, R_L = 50 Ω: Only PA_main is active (see Fig. 1a). Therefore, I_low, and I_high are both zero. Consequently, the impedance seen by the main stage and the power delivered using (6) and (5) are,

$$Z_\mathrm{M} = 50\ \Omega; \quad P_\mathrm{out} = \frac{1}{2} I_\mathrm{M}^2 R_\mathrm{L} \quad (9)$$

As a result of this matched condition, PA_main can achieve maximum output power and efficiency simultaneously.

b) Case 2, R_L is between $25\,\Omega$-$50\,\Omega$: PA_{main} and PA_{low} are both active (see Fig. 1b). Consequently, I_{high} is zero. Since, P_{out} needs to be constant, substitution of R_L in (5) yields the new value of I_M. Furthermore, since V_M should not clip after substitution of R_L in (1), I_M and I_{low} are found as,

$$I_M = \sqrt{\frac{P_{out}2R_L}{Z_0^2}}; \quad I_{low} = \frac{I_M}{\sqrt{2}}\left(\frac{Z_0}{R_L} - \frac{V_{DD}}{\sqrt{2P_{out}R_L}}\right) \quad (10)$$

However, since the voltage V_{low} depends on I_M its voltage swing is given as,

$$V_{low} = \sqrt{2}Z_0 I_M \quad (11)$$

Using these conditions the output power can be kept constant for variation of R_L in the interval of $25\,\Omega$-$50\,\Omega$.

c) Case 3, R_L is between $50\,\Omega$-$100\,\Omega$: In this case both PA_{main} and PA_{high} are active (see Fig. 1c). Since, P_{out} needs to be constant, substitution of R_L in (5) yields the new value of I_{high} while keeping I_M equal to the previously discussed $50\,\Omega$ loading condition. Furthermore, since V_{high} should not clip after substitution of R_L in (2), I_{high} and V_{high} are found as,

$$I_{high} = \frac{I_M}{\sqrt{2}}\left(\sqrt{\frac{R_L}{Z_0}} - 1\right); \quad V_{high} = Z_0\sqrt{\frac{2Z_0}{R_L}}I_M \quad (12)$$

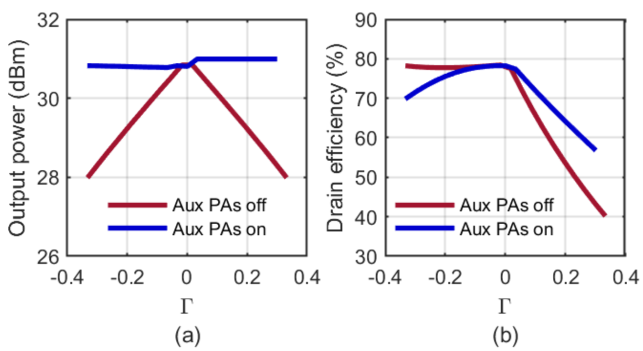


Fig. 3. Simulated (a) output power and (b) drain efficiency of the proposed concept across the Γ range from [-0.333 0.333] with and without the auxiliary PAs activated.

A. Simulation-based verification of the proposed concept

The proposed concept is verified in simulation using an ideal 3 dB coupler and ideal class-B operation with all harmonics short-circuited for the main and auxiliary PAs. Using the previously derived drive conditions for PAs for the various loading conditions. Fig. 3a and 3b show the simulated output power and drain efficiency for a Γ sweep over the real axis of the Smith chart from [-0.333 0.333]. When avoiding voltage clipping for both the main PA and auxiliary PAs, as such ensuring perfectly linear operation, e.g., by using two constant supply voltages ($V_{DD_{main}} = 11\,V$ and $V_{DD_{Aux}} = 15.56\,V$) the RF output power can be kept perfectly constant at the cost of a (small) penalty in efficiency. Moreover, for the in-between loading conditions in the range $25-50\,\Omega$ [-0.333 0.0], and the range of $50-100\,\Omega$ [0.0, 0.333], the proposed technique yields significant improvements in both the output power and efficiency. Note that, using a matching network in connection to the auxiliary PAs. The proposed concept can also work with a single supply.
When considering complex varying loads, ideally a compensating low loss susceptance is placed in parallel to the presented load (see Fig. 1) [4]. However, since these are not yet (commercially) available for larger power levels, an alternative approach is to use a somewhat higher static supply voltage for the auxiliary PAs compared to PA_{main} to accommodate the extra voltage swing, needed to handle reactive part of the loading without any voltage clipping. It turns out that this technique only yields a limited efficiency penalty.

III. PA Concept and Measurement

A. Prototype PA Concept

The measurement setup of Fig. 4a was assembled to validate the proposed concept. Three Cree's CGH40006P evaluation boards, housing the 28 V 6 W GaN HEMT devices, are used for the main and the two auxiliary PAs. These boards are broadband matched from $0.8-6.0\,\mathrm{GHz}$. The broadband coupler ($0.5-3.0\,\mathrm{GHz}$) used in these experiments is from Innovative power products (IPP-2160). A Keysight M8190A 4-Channel AWG generates the control signals with excellent phase coherence. These input signals are amplified using instrumentation amplifiers in the feeds that connect to the PAs. A Maury load tuner provides the varying load impedance (Z_L). A power meter monitors the RF output power delivered to the load.

B. Measurement Results

For the VSWR circle measurement, the PA_{main} operates with a 17 V supply, while the auxiliary PAs uses 21 V supplies. When an auxiliary PA is supposed to be inactive, its gate voltage is set to $-4.1\,\mathrm{V}$ to switch it off, as such zeroing its power consumption. While active, the auxiliary PAs operate at $\approx 65\,\mathrm{mA}$ quiescent drain current. The measured overall PA configuration performances, in terms of output power and drain efficiency at $2\,\mathrm{GHz}$, are shown in Fig. 4b, 4c and 5, respectively. Moreover, the drain efficiency of the overall PA configuration is calculated as follows.

$$\eta_D = \frac{P_{out}}{P_{DC_M} + P_{DC_{low}} + P_{DC_{high}}} 100\ \% \quad (13)$$

a) Case 1, $Z_L = 50\,\Omega$: Using a 17 V supply, the PA_{main} delivers for the matched condition an output power of $33.7\,\mathrm{dBm}$ at an efficiency of $51\,\%$. When operated standalone (without coupler etc.), the PA_{main} efficiency is $59.5\,\%$ at an output power level of $34.8\,\mathrm{dBm}$. The reduction in output efficiency and output power is due to the coupler losses ($\approx 0.7\,\mathrm{dB}$) and the losses in the outputs of the auxiliary PAs when they are switched off (their gate voltages set to $-4.1\,\mathrm{V}$). Yielding a total loss of $1.3\,\mathrm{dB}$. The loss can be reduced by co-designing the PAs with the coupler in future work.

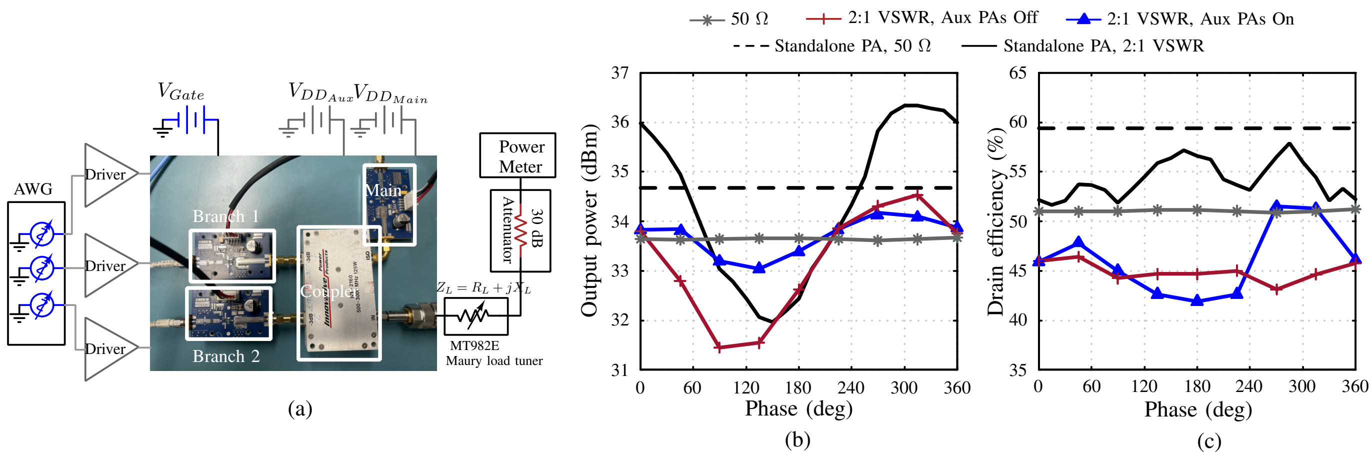


Fig. 4. (a) Test setup used to evaluate the proposed PA load adjustment concept using a commercially available coupler and evaluation boards. Measured (b) output power and (c) drain efficiency of the proposed concept across the whole 2:1 VSWR circle in phase steps of 45° with and without the auxiliary PAs activated. Also shown is the standalone PA performance for the same loading conditions.

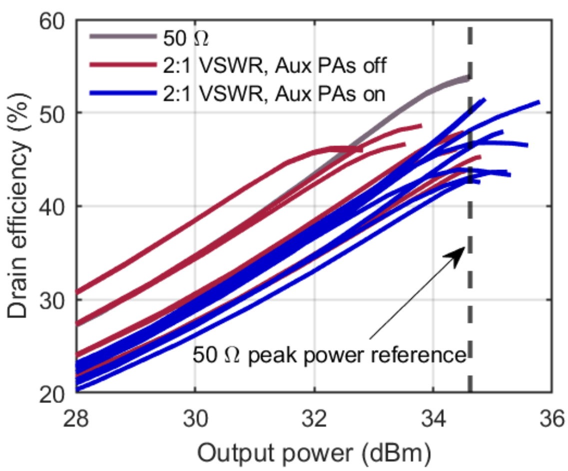


Fig. 5. Measured drain efficiency vs. output power of the proposed concept across the whole 2:1 VSWR circle in phase steps of 45° with and without the auxiliary PAs activated.

b) Case 2: When the proposed PA configuration is exposed to a 2:1 VSWR loading condition with $45°$ phase steps of Γ_L when the auxiliary PAs are not activated, the PA output power varies more than 3 dB (see Fig. 4b). Also, the efficiency is degraded (see Fig. 4c). Using an intelligent activation scheme for the drive levels of the main and auxiliary PAs, the PA output power can be significantly enhanced (see Fig. 5 and 4b), yielding a variation of only 0.6 dB worst case (see Fig. 4b). Also, while improving the output power, the overall efficiency of the PA configuration has been enhanced (Fig. 4c) at some of the $\angle\Gamma_L$ points. Furthermore, the reduced efficiency is linked to the extra bias current required by the auxiliary PAs when active and the complex loading across both the main and auxiliary PAs. However, the worst-case efficiency degradation due to the varying load is only $8.5\,\%$ with reference to the $50\,\Omega$ loading. In a more advanced implementation, an impedance sensor [4] in combination with a variable gain pre-driver stage can be used to control the main and auxiliary PAs input drive dynamically. Note that in case of fast-changing VSWR conditions, smooth transitions (soft turning on and off the Aux. PAs) must be applied to avoid discontinuities when making the transitions in activation of the various PAs.

IV. Conclusion

This paper proposes an active load adjustment technique to recover the power amplifier (PA) performance due to load mismatch. Using a combination of the coupler, main PA, and auxiliary PAs and an intelligent driving scheme, the PAs output power and efficiency can be simultaneously enhanced under varying loading conditions. Since the proposed technique only relies on adjustments of the input signals, it is suitable for applications with very fast-changing loading conditions.

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