Abstract — This paper presents a method for systematic power amplifier design using a multi-objective interactive visualization method to analyze trade-offs between multiple output performance metrics. By observing load and source pull data, one can select nondominated solutions (decision variables). These have associated input and output reflection coefficients for desired output power, large signal gain, and power-added efficiency over bandwidth and drain supply voltages. A Qorvo discrete GaN device is used for validating the method, under varying frequency (2.5–5 GHz) and supply voltage (14–26 V), as well as input power. Parallel plots of nondominated designs are generated to determine the gate and drain reflection coefficients that result in the best tradeoff between output power and efficiency with a 50-Ω load. From the impedances obtained by the optimization, a circuit is designed with a measured 10-W output power and peak efficiency of 69% at 14 and 20 V, validating the approach.

Keywords — power amplifiers, multi-objective, visualization, power-added efficiency, nondominated.

I. INTRODUCTION

Design of an RF power amplifier (PA) often involves tradeoffs between a large number of input parameters such as device size, frequency range (RF bandwidth), input power range, supply voltage, and gate bias [1]. The input and output matching networks are then designed for, e.g. a specified output power ($P_{out}$) with maximized power-added efficiency ($PAE$) and saturated gain. The output impedance for highest power is usually not the same for best efficiency, so the designer is faced with a trade-off. This is usually done by an observation of load-pull power and efficiency contours [2]. When additional input variables, such as supply voltage in efficiency-enhanced envelope tracking amplifiers [3], gate bias for linearization [4], frequency or multiple gain stages are a part of the design, the trade-off is not intuitive. The motivation for the work presented here is to explore a method that can help PA designers determine input and output target impedance from a large solution set to choose those that effectively balance multiple performance parameters, as illustrated on a single-stage single-ended PA in Fig. 1.

In this paper, we demonstrate a new method for systematic PA design based on multi-objective optimization using an interactive visualization method. This approach is based on other optimization methods for black-box multi-variante problems, meaning when no analytical function can be formulated, such as in the case of PA design. The method builds on a general interactive multi-objective visualization method to aid designers in selecting a solution from a nondominated set [5]. A related approach for small-signal amplifier design is presented in [6], [7], but does not aid designers in understanding critical trade-offs. We demonstrate this new method for PA design by selecting source and load reflection coefficients from a large set of simulated source and load-pull data. We then validate the design process by manufacturing and characterizing a PA. We also compare simulated performance to measured and validate against published results for the same Qorvo GaN transistor.

II. MULTI-OBJECTIVE PA DESIGN METHOD

A common method for PA design involves simulating (or measuring) output parameters for a range of input and output reflection coefficients, referred to as automated source and load-pull. These are plotted as constant valued contours on a Smith chart, and for most transistors, a trade-off is required even when only two parameters $P_{out}$ and $PAE$ are considered, since their peak values do not occur for the same impedance. A designer typically selects an input and output reflection coefficient magnitude and angle ($|\Gamma_S|$, $\angle \Gamma_S$) and ($|\Gamma_L|$, $\angle \Gamma_L$), by observing the contours and choosing points that meet the design trade-off between power and efficiency. Adding design goals, such as a range of supply voltages $V_{DD}$ or a large RF bandwidth, create busy contours on the Smith chart that make it difficult for designers to choose a solution that will meet their design goals. This is illustrated in Fig. 2, where load-pull

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The design decisions and objectives are incorporated into the following multi-objective problem:

\[
\text{maximize } \quad [F_{\text{min PAE}}(x), F_{\text{min Pout}}(x), F_{\text{max Pout}}(x)] \tag{1}
\]

This formulation does not rely on weighting the vector of objectives. Instead, it seeks to find solutions that capture different compromises among the three objectives, defined by the set of nondominated solutions. For this problem, a vector of the three objectives corresponding to decision vector \( x_1 (F(x_1)) \) dominates \((\succ)\) a vector of the three objectives corresponding to decision vector \( x_2 (F(x_2)) \) if and only if

\[
F_{\text{min PAE}}(x_1) \geq F_{\text{min PAE}}(x_2) \tag{2}
\]

\[
F_{\text{min Pout}}(x_1) > F_{\text{min Pout}}(x_2) \tag{3}
\]

\[
F_{\text{max Pout}}(x_1) \geq F_{\text{max Pout}}(x_2) \tag{4}
\]

and there exists at least one

\[
F_{\text{min PAE}}(x_1) > F_{\text{min PAE}}(x_2) \tag{5}
\]

\[
F_{\text{min Pout}}(x_1) > F_{\text{min Pout}}(x_2) \tag{6}
\]

\[
F_{\text{max Pout}}(x_1) > F_{\text{max Pout}}(x_2) \tag{7}
\]

In other words, for a solution to dominate another solution, each objective in the objective vector must perform better on at least one of the objectives. Conversely, nondominated solutions must perform better than or equal to all other solutions on at least one objective. To produce a final set of nondominated solutions, a nondominated sort is performed for all solutions. Practically, the set of nondominated solutions represents a variety of compromises among the three objectives.

**III. DESIGN PROCESS FOR A HYBRID PA**

To examine the usefulness of this method for PA design, we constrain some of the input variables. We fix \( V_{\text{DD}} = -2.8 \text{ V} \) and \( P_{\text{in}} = 28 \text{ dBm} \), prescribe a range for \( V_{\text{DD}} = [14 - 26] \text{ V} \) and \( f = [2.5 - 5] \text{ GHz} \). The output variables are \( \text{PAE} \) and \( P_{\text{out}} \) across all frequencies and values of drain supply voltage. Fig. 3 shows all of the solutions for input and output reflection coefficients with \( \text{PAE} \) between 13.5% and 60.3% obtained from load-pull of the transistor from dc to 18 GHz. There are a large number of solutions shown in Fig. 3, and the optimization method highlights in color the nondominated solutions.

We next choose our desired solution from this subset using “brushing” to interactively filter the nondominated set based on designer intuition. Based on the nondominated performance, we wanted to achieve \( F_{\text{min PAE}} \) values greater than 55%, thus brushing was applied to that objective (depicted as rectangle in Fig. 4). Then we choose an allowed range for \( P_{\text{out}} \), as is depicted by the brushing of the \( F_{\text{min Pout}} \) and \( F_{\text{max Pout}} \) objectives in Fig. 4. This sub-selection results in the colored lines in Fig. 4. Among these, the selected solution is the one represented by the red line, giving \( \Gamma_S = 0.75 \angle 180^\circ \) and \( \Gamma_L = 0.5 \angle 150^\circ \). Once the parallel plots are created, this process takes only a few minutes to select a desired solution.
The PA is implemented with the Qorvo die on a 0.76-mm thick RO4350B substrate, for $Z_S = 8.82 \Omega$ and $Z_L = 17.72 + j11.81 \Omega$ input and output impedances, chosen for a low Q factor to increase bandwidth. The circuit is designed using Cadence AWR MWO to minimize loss in the passive networks across 2.5–5 GHz, and incorporating biasing circuits into the single-line input matching network and a nonuniform 3-section line output matching network. To reduce coupling between the input and output matching networks, tapers are added leading to the device plane. This decreases the performance of the input and output networks independently, but improves performance of the entire circuit when analyzed using the Axiem full-wave 2.5-D simulator.

**IV. Prototype PA Measurements**

The circuit is fabricated and gold-plated for wirebonding of the die. The substrate and a stack of CuMo die carriers are silver-epoxied to a metal heat sink and the transistor is epoxied onto the carriers. The drain and gate pads are wire bonded with six and four 24.5-µm diameter gold bond wires, respectively. A parallel RC stability network is implemented with an 0402 100Ω resistor and 1 pF capacitor in series at the gate, with additional low-frequency capacitors and resistors on the bias lines. A series inductance of 0.5 nH is added to the bond-wire inductance from the Modelithics model. This takes into account the slightly different die mounting from that shown in the Modelithics library. The fabricated circuit is shown in Fig. 5.

![Fig. 5. Photograph of 2.5-5GHz power amplifier designed using nondominated $\Gamma_S$ and $\Gamma_L$ found from the interactive visualization method.](image)

The measured and simulated frequency response is shown in Fig. 6 for three supply voltages, while the measured drive-up curves at three frequencies are shown in Fig. 7. The measured output power is within 3 dBm from 2.5 to 4.9 GHz. The highest PAE is 69% around 3.5 GHz at the lower supply voltages. The simulations predict the measured trends, except all measured parameters drop at 5 GHz.
Fig. 6. Measured (solid) and simulated (dashed) frequency performance. (a) $P_{\text{in}} = 24\,\text{dBm}$ and $V_{\text{DD}} = 14\,\text{V}$ (b) $P_{\text{in}} = 26\,\text{dBm}$ and $V_{\text{DD}} = 20\,\text{V}$ (c) $P_{\text{in}} = 28\,\text{dBm}$ and $V_{\text{DD}} = 26\,\text{V}$.

Fig. 7. Measured PAE and Gain for $V_{\text{DD}} = [14,20,26]\,\text{V}$ at (a) 2.5 GHz, (b) 3.7 GHz and (c) 4.9 GHz.

V. CONCLUSIONS

In summary, a method for fast determination of input and output reflection coefficients that meet a wide range of PA performance goals is presented. The method is based on a standard load-pull simulation, and allows for interactive choice of design parameters in a matter of minutes. Validation is shown on a hybrid PA covering an octave bandwidth, with a comparison to published PAs shown in Table 1. Additionally, this PA is designed with specifications across a wide range of drain supply voltages, enabled by the multi-objective interactive visualization method.

Table 1. Amplifiers in literature using TGF2023-2-02.

<table>
<thead>
<tr>
<th>Reference</th>
<th>PAE (%)</th>
<th>Frequency (GHz)</th>
<th>Output Power (dBm)</th>
</tr>
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<tbody>
<tr>
<td>2010 [8]</td>
<td>84.9</td>
<td>2.15</td>
<td>39.14</td>
</tr>
<tr>
<td>2013 [9]</td>
<td>70</td>
<td>2.5</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>2011 [10]</td>
<td>80</td>
<td>3.5</td>
<td>38.45</td>
</tr>
<tr>
<td>2019 [12]</td>
<td>61</td>
<td>1.75-2.05</td>
<td>41.2 ±0.5</td>
</tr>
<tr>
<td>This work</td>
<td>69</td>
<td>2.5-5</td>
<td>40</td>
</tr>
</tbody>
</table>

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REFERENCES


