A Broadband Asymmetric Doherty Power Amplifier Design Based on Multiobjective Bayesian Optimization: Theoretical and Experimental Validation

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ABSTRACT In this paper, a new multi-objective Bayesian optimization (BO) algorithm is applied to design a broadband gallium nitride (GaN) based Doherty power amplifier (DPA). The optimization process can be automatically implemented by combing the proposed methodology with a commercial simulation software. The performance of the DPA optimized by the proposed method is compared with those obtained with the initial designed DPA, the DPA optimized by existing BO method, and DPA optimized by the optimizers built-in using the commercial software advanced design system (ADS). The comparison results reveal that the DPA designed with the proposed method can achieve better performance with less optimization time than other optimization methods. The measured results show that the optimized DPA with the proposed method achieves a 9-dB back-off efficiency of 44.6%–65% and a saturated efficiency of 60.5%–78% from 2.0 GHz to 2.6 GHz, with saturated output power varying from 43.8 dBm to 45.2 dBm.

INDEX TERMS Bayesian optimization, Doherty power amplifier, asymmetric, broadband, continuous-mode, high backoff efficiency.

I. INTRODUCTION

In order to save spectrum resources, high-order modulation technology is widely used in modern wireless communication systems, which typically have a high peak to average power ration (PAPR). As the core component of the radio frequency (RF) system, the power amplifiers (PAs) must ensure the wide operation bandwidth and high back-off efficiency at the same time [1].

However, the efficiency of traditional PAs is low at the back-off condition. To solve this problem, many new techniques have been proposed, such as outphasing technology [2], envelope tracking technology [3], [4], and Doherty technology [5], [6], [7]. Among them, DPA technology has been widely concerned by the academic community, due to its simple structure and great performance. However, its bandwidth is limited, due to the using of quarter-wavelength impedance transformer [8]. In order to solve this problem, several novel structures have been proposed, such as post-matching structures, continuous PAs and so on [9], [10], [11], [12], [13], [14], [15]. Besides, the asymmetric Doherty power amplifier (ADPA) structure has also been proposed to achieve high efficiency performance for large PAPR applications [16], [17], [18].

With the development of the design methods, the structure of DPA is also becoming more complex, which makes the optimization of DPA more important and challenging. To surmount this problem, there are built-in optimizers in
commercial electronic design automation (EDA) software to optimize circuits, such as random optimization technique, gradient optimization technique, and so on [19]. Nevertheless, they are time-consuming and easy failed to find a satisfactory solution, due to non-convergence, especially when dealing with complex active circuits or optimizing with a lot number of targets [20]. Therefore, it is considered valuable to develop the simulation driven optimization platform tailored for complex active circuit designs, such as DPA.

In [19], a high efficiency broadband PA is designed using the optimization-oriented technique, named BO. In [21], a new forward automatic optimization system for RF PAs design is introduced based on the clustering guided BO algorithm. An ultra-broadband PA was successfully implemented, maintaining the output power and efficiency at a high level, which demonstrates the effectiveness of the method. In [22], a broadband DPA is designed by optimizing the matching networks with BO strategy. In this work, further improvements for the work proposed in [21] has been made, which make it suit for ADPA design. The model accuracy is effectively improved by increasing the number of modeling times in each optimization iteration. Finally, a high performance ADPA based on GaN high-electron mobility transistors (HEMTs) is designed with a short optimization time.

This paper is organized as follows. Section II presents briefly the theoretical analysis of: 1) The principle of load modulation of traditional DPA; 2) The idea of ADPA and the design method of continuous-class amplifiers. Based on the above principles, a strategy for ADPA design using an improved BO algorithm is proposed in Section III. In Section IV, the detailed design procedure of ADPA with multi-objective optimization is illustrated. In Section V, to verify the effectiveness of the proposed approach, an ADPA is designed using the proposed optimization method. In addition, the simulation results corresponding to the ADPAs obtained by different optimization algorithms are compared. Furthermore, the measurement results for the fabricated ADPA designed by the proposed BO algorithm are presented. Conclusions are, finally, drawn in Section VI.

II. THE THEORY OF BROADBAND DPA
A. THE ADPA CONCEPT

The ADPAs are widely used as an effective back-off performance improvement technology in situation where a big back-off operation is required. Different devices are typically utilized for the carrier PA and peak PA to realize the asymmetric operation, which may lead to phase inconsistency between the two circuits [23]. Therefore, the asymmetric operation is achieved by different drain biases between the carrier PA and peak PA in this paper [24], [25], [26].

The basic structure of ADPA is shown in Fig. 1. The ADPA also uses active load modulation, but its carrier amplifier has a different saturated output current than the peak amplifier.

Suppose \( I_{\text{max},c} \) and \( I_{\text{max},p} \) represent the saturated output current of the carrier amplifier and that of the peak amplifier, respectively. The \( V_{d,p} \) and \( V_{d,c} \) represent the drain bias voltage of the carrier amplifier and that of the peak amplifier, respectively. Then, the saturation output current ratio and drain bias voltage ratio of both PAs can be expressed as follows:

\[
\frac{I_{\text{max},p}}{I_{\text{max},c}} = \delta \tag{1}
\]

\[
\frac{V_{d,p}}{V_{d,c}} = \alpha \tag{2}
\]

In order to avert the limitation of bandwidth, the post-matching architecture is employed to provide the broadband impedance transformation in this paper. The transformed impedance at the combing node is represented as \( Z_L \). Then, the real load impedances of carrier amplifier at the combing node in the saturation and the backoff can be expressed as follows:

\[
Z_C = \begin{cases} 
(1 + \delta) Z_L, & \text{Saturated} \\
Z_L, & \text{OBO}
\end{cases} \tag{3}
\]

Similarly, the load impedances of the peak amplifier at the combing node in the saturation and the backoff can be expressed as follows:

\[
Z_p = \begin{cases} 
(1 + \frac{1}{\delta}) Z_L, & \text{Saturated} \\
\infty, & \text{OBO}
\end{cases} \tag{4}
\]

It is assumed that the saturated output current of both amplifiers can reach the maximum value of the transistor output current, \( I_{\text{max}}/2 \). Moreover, the output impedance of the peak amplifier is infinite at the backoff point. Thus, at the backoff point, the output power of DPA is provided only by the main amplifier. It can be expressed as follows:

\[
P_{\text{OBO}} = \frac{I_{\text{max},c}}{2\sqrt{2}} \cdot \frac{V_{d,c}}{\sqrt{2}} = \frac{I_{\text{max},c} V_{d,c}}{4(1 + \delta)} \tag{5}
\]

In the saturation, the total output power can be expressed as follows:

\[
P_{\text{sat}} = \frac{I_{\text{max},c}}{2\sqrt{2}} \cdot \frac{V_{d,c}}{\sqrt{2}} + \frac{I_{\text{max},p}}{2\sqrt{2}} \cdot \frac{V_{d,p}}{\sqrt{2}} = \frac{I_{\text{max},c} V_{d,c}}{4}(1 + \delta \alpha) \tag{6}
\]
Based on the above derivation and power calculation, the amount of backoff can be expressed as follows:

\[ OBO = -10 \log \left[ (1 + \delta \alpha) (1 + \delta) \right] \]  

(7)

As can be seen from (7), an ADPA with a large amount of backoff can be designed when the appropriate output current ratio and drain bias voltage ratio are selected. Thus, achieving the effect of improving the corresponding efficiency in the backoff.

**B. THE CONTINUOUS PA DESIGN**

There is also bandwidth limitation in traditional ADPAs. For example, in the process of designing the output matching circuit of the carrier PA, it is difficult to simultaneously convert the actual load impedance to the ideal load impedance corresponding to the saturation and the backoff over a wide bandwidth range. In this paper, we combine the mixed continuous working mode with the ADPA design to provide good initial values for subsequent optimization design. The core theory of the continuous-class mode to effectively extend the broadband is that the mode introduces the imaginary part into the fundamental optimal impedances [27].

The structure of the DPA in this paper is presented in Fig. 2. The structure consists of a Wilkinson equal power divider, input matching networks, and output matching networks of both PAs. Moreover, two phase offset lines are added to compensate the phase imbalance in two amplifiers. Most importantly, the post-matching network is used to replace the quarter-wavelength impedance transformer in traditional DPA.

In order to illustrate the impedance transformation relationship more graphically, the output matching network of the carrier PA is presented by its scattering parameters. As shown in Fig. 3, The \( \Gamma_{c-obo} \) and \( \Gamma_{c-sat} \) are reflection coefficients at port 1, \( \Gamma_{L-obo} \) and \( \Gamma_{L-sat} \) are reflection coefficients at port 2. In this paper, we firstly match the load impedance \( R_L \) corresponding to the combing node of the main PA in the backoff to the optimal load impedance \( (1 + \delta)R_{opt} \) in the backoff. It is assumed that the above network is lossless.

As mentioned earlier, in the saturation, the load impedance corresponding to the carrier amplifier at the combing node is \( (1+\delta)R_L \). Then the \( \Gamma_{L-sat} \) can be expressed as follows:

\[ \Gamma_{L-sat} = \frac{(1+\delta)R_L - R_L}{(1+\delta)R_L + R_L} = \frac{\delta}{\delta + 2} \]  

(8)

As shown in eq. (9), the reflection coefficient of the carrier PA changes with respect to \( \theta \), but its absolute value remains constant. In other words, the load impedance is not a constant and it changes with frequency. Obviously, according to the theory of traditional DPA design, we can only find the ideal load impedance value and the corresponding reflection coefficient at the center frequency point at a certain value of \( \theta \).

In this paper, the main PA adopts the mixed continuous mode of Class-J and Class-F, and its effective load impedance range is vividly shown in Fig. 4.

The \( \Gamma_{c-sat} \) can be expressed as follows:

\[ \Gamma_{c-sat} = \frac{\delta}{\delta + 2} e^{i\theta} \]  

(9)

As shown in Fig. 4, the normalization impedance is set to \( (1 + \delta)R_{opt} \). The red curve represents the circle of reflection coefficients \( \Gamma_{c-sat} \). The green curve and blue curve represent the corresponding load impedance region in continuous class-J and class-F modes, respectively. The red curve contained in the orange ellipse is the impedance region corresponding to the continuous Class-J and continuous Class-F amplifiers [28]. Then, the corresponding impedance region of the mixed continuous mode is indirectly calculated by using the correspondence between the reflection coefficient and the impedance and the phase \( \theta \) in the Smith chart [29], [30], [31], [32].
III. IMPROVED OPTIMIZATION STRATEGIES

A. THE CONCEPT OF BO ALGORITHM

As discussed in [21], the traditional built-in optimizers may fail to find the satisfactory solution for broadband high-efficiency PA designs, which generally have plenty of design variables [33]. Recently, the optimization of circuits has been realized by evolutionary algorithms, such as differential evolution (DE) [34], genetic algorithm (GA) [35], and particle swarm optimization (PSO) [36]. However, these algorithms typically require a large amount of CPU time to find global optima [37]. Compared with the above algorithms, BO algorithms use a probabilistic surrogate model (PSM) to proxy complex black-box functions, which greatly reduces the running time [38], [39]. The prior knowledge of the target to be optimized is introduced into the PSM, so that the model can more accurately meet the behavior of the black box function, effectively reduce unnecessary sampling, and improve the optimization efficiency.

The BO algorithm consists of two main parts, the PSM and the acquisition function. In this paper, we chose Gaussian process regression (GPR) as the PSM, which may obtain satisfactory prediction results due to its flexibility as well as its scalability [40], [41], [42]. In addition, the clustering guided Gaussian process upper confidence bound (CG-GPUCB) method is selected as the acquisition function that is proposed in [21].

As discussed in [21], a wideband high-efficiency PA can be successfully designed by using the above PSM and acquisition function. However, it is unrealistic to design broadband DPA using the approach alone, since there are multiple optimization functions in the optimization of the broadband DPA. Therefore, in this paper, we have made further improvements to the method proposed in [21], resulting in the successful design of a broadband high-efficiency DPA with a large back-off range.

B. THE IMPROVED OPTIMIZATION CRITERIA

In [21], we optimized the performance of the single-stage PA. In each iteration, a complete model was built. The input parameters of the model were the value of the length and width of the transmission lines of the PA, and the output parameter of the model was the root mean square of the power and efficiency of the PA. Due to the simplicity of its structure, the satisfactory model accuracy and the optimization target value were obtained with fewer iterations.

However, in the design of DPA, there are more optimization goals that need to be considered with a more complex structure. The relationship between different objective functions and input parameters corresponds to different function expressions. Therefore, if multiple objective functions are replaced by a single model, it is likely to make the model inaccurate [43].

In this paper, we model multiple objective functions separately to obtain the predicted mean and predicted variance of the target value corresponding to each set of parameters in different models. Then, the root mean square of the multiple predicted mean corresponding to multiple models of a set of parameters is used as the new mean. Similarly, the root mean square for the multiple prediction variance corresponding to multiple models of a set of parameters is used as the new prediction variance. Subsequently, the acquisition function CG-GPUCB proposed in [21] is used to sample and obtain a set of parameters that maximize the target value. Finally, similar to the single objective optimization, after obtaining the training data corresponding to the sample point, the model is updated and a new round of iteration begins.

Compared with the algorithm in [21], this algorithm performs modeling three times during one iteration, while the algorithm in [21] performs modeling only once. Undoubtedly, for Doherty circuits with more input parameters and complex functions, this method will increase the model accuracy to a great extent and speed up the decrease of normalization error, thus improving the optimization efficiency.

IV. DESIGN PROCEDURE OF DPA WITH MULTI-OBJECTIVE OPTIMIZATION

A. THE INITIAL DESIGN OF DPA

The proposed DPA consists of a power divider, a carrier PA, a peak PA, and a combiner network. In this paper, the combiner network is constructed using a post-matching structure, which transfers $Z_L$ from 50 Ω to 10 Ω. Its bandwidth can be effectively widened compared with the traditional quarter-wavelength impedance transformer. In addition, the two impedance offset lines are added to the carrier PA and peak PA, respectively. For carrier PA, the function of the compensation line is to ensure the two current $I_C$ and $I_P$ at the junction are in phase (see Fig. 2). As for peak PA, it is turned off at low power levels, at which point the offset line is used to prevent power leakage from the carrier PA. In order to ensure the high level of backoff with high efficiency, ADPA is designed with asymmetric drain voltage in this paper. Based on eq. (7), the drain voltage of the carrier PA and that of the peak PA are set as 20 V and 32 V, respectively. Meanwhile, the saturation output current ratio of the carrier and peak PA, i.e., $\delta$, is adjusted to 1.4 in order to achieve the 9 dB backoff.

In addition, the load impedance of the carrier PA is matched to the optimal impedance region corresponding to the mixed continuous PA in the current plate, as mentioned in Section II. The equivalent circuit corresponding to the package model
of the GaN transistor is shown in Fig. 5. The specific design process is as follows.

Firstly, the impedance $Z_L$ corresponding to the combing node of the carrier PA in the backoff state is matched to the optimal load impedance $(1 + \delta)R_{opt}$ in the current source plane. Furthermore, the red curve contained in the orange curve in Fig. 4 is the impedance region corresponding to the mixed continuous J/F class mode. Subsequently, the phase of the output matching circuit is automatically optimized while ensuring that its impedance match condition in the backoff state remains unchanged. The matching network of peak PA is designed in the package plane. The initial structure of DPA is shown in Fig. 6.

**FIGURE 6.** The topology of the initial DPA.

**B. THE EXISTING BO ALGORITHM**

A broadband DPA design needs to satisfy multiple desired goals at dynamic power levels over a wide frequency band, resulting in a quite complex optimization problem. The traditional built-in optimizers in commercial EDA software often fail to search the satisfactory results, due to the poor convergence performance. Therefore, it is valuable to develop an optimization method to deal with the problem.

In order to compare the effectiveness of the optimization method in [21] and the proposed optimization method in this paper, we optimized a DPA by using, firstly, the former method.

Similar to [21], the objective function used in this method is the root mean square of the efficiency at saturation and backoff and the output power at saturation in the frequency band. The expression for the objective function is shown as (10), at the bottom of the page, where $n$ represents the number of frequency points, $DE_{obo,i}$ denotes the drain efficiency at 9 dB backoff, $P_{out, sat, i}$ and $DE_{sat, i}$ are the output power and drain efficiency at saturation, respectively. This method directly takes the predicted mean and predicted variance corresponding to the objective function $Y$ as the corresponding mean and variance for sampling. During each iteration, modeling is performed only once.

**C. THE PROPOSED IMPROVED BO ALGORITHM**

Unlike the methods in [21], the algorithm proposed in this paper further improves the accuracy of the model. By improving the objective function, GPR regression was performed three times in one iteration and three sub-models were built.

In this paper, the transmission lines of Wilkinson equal power divider and the post-matching network are fixed. The width and length of transmission lines in match networks and bias networks are input variables in the optimization. Then, the multi-objective functions for the broadband DPA are given by:

$$Y_1 = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (DE_{obo,i})^2}$$

$$Y_2 = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (DE_{sat,i})^2}$$

$$Y_3 = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_{out, sat,i})^2}$$

The definition of the variables in eqs. (11)-(13) are same as the definition of the variables in eq. (10). During each
iteration, the above three objective functions are modeled separately using the GPR regression model. Thus, each set of input parameters corresponds to three predicted means and three predicted variances of three objective functions. Then, the root mean square of the three predicted means of each set of parameters corresponding to three models is used as the new mean. Similarly, the root mean square for the three prediction variances of each set of parameters corresponding to three models is used as the new variance. Finally, the sampling process is performed.

Compared with the method proposed in [21], it only models the DPA circuit once in one iteration. In DPA circuits, the number of transmission lines is large, which means that the number of input parameters is huge. And there is no direct function relationship between the input parameters and the output parameter Y. However, the method proposed in this paper, power and efficiency in the backoff and saturation states are modeled separately during each iteration. Compared with the integrated objective function in eq. (10), the new objective function in eqs. (11)-(13) has a direct correspondence function relationship with the input parameters, which will undoubtedly make the predicted value closer to the true value. This will greatly improve the efficiency of optimization. Moreover, the detailed illustration of the difference between the method in [21] and the method proposed in this paper is added in Fig. 7.

The method proposed in [22] sets the minimization of the mismatch between the desired and simulated impedance trajectories as the objective functions, which relies more on the accuracy of the large signal model and the reliability of

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**TABLE 1. The detailed geometry size of the initial DPA.**

| Parameter | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 | W10 | W11 |
|-----------|----|----|----|----|----|----|----|----|----|------|------|
| Value     | 13.2 | 0.7 | 5.3 | 15.0 | 1.7 | 4.1 | 2.3 | 5.8 | 1.6 | 1.6 | 7.2  |
| Parameter | W12 | W13 | W14 | W15 | W16 | W17 | W18 | W19 | W20 | W21 |
| Value     | 4.1 | 13.7 | 19.2 | 1.9 | 13.7 | 9.8 | 3.5 | 2.9 | 1.6 | 1.6  |
| Parameter | L1  | L2  | L3  | L4  | L5  | L6  | L7  | L8  | L9  | L10 | L11 |
| Value     | 1.9 | 3.4 | 2.0 | 4.3 | 2.8 | 7.8 | 1.0 | 0.6 | 12.0 | 12.3 | 0.3 |
| Parameter | L12 | L13 | L14 | L15 | L16 | L17 | L18 | L19 | L20 | L21 |
| Value     | 17.7 | 0.9 | 15.4 | 2.6 | 16.3 | 16.0 | 14.6 | 15.6 | 12.4 | 12.6 |

**TABLE 2. The detailed geometry size of the optimized DPA with the method proposed in [21].**

| Parameter | W1   | W2   | W3   | W4   | W5   | W6   | W7   | W8   | W9   | W10  | W11  |
|-----------|------|------|------|------|------|------|------|------|------|------|------|
| Value     | 12.4 | 1.1  | 7.6  | 20.0 | 1.8  | 4.8  | 3.2  | 5.8  | 1.6  | 1.6  | 7.9  |
| Parameter | W12  | W13  | W14  | W15  | W16  | W17  | W18  | W19  | W20  | W21  |
| Value     | 5.0  | 14.5 | 20.0 | 1.8  | 14.4 | 10.0 | 7.6  | 3.6  | 1.7  | 1.54 |
| Parameter | L1   | L2   | L3   | L4   | L5   | L6   | L7   | L8   | L9   | L10  | L11  |
| Value     | 1.3  | 2.5  | 1.9  | 4.9  | 2.6  | 6.9  | 2.5  | 1.2  | 13.2 | 11.9 | 6.4  |
| Parameter | L12  | L13  | L14  | L15  | L16  | L17  | L18  | L19  | L20  | L21  |
| Value     | 14.2 | 1.3  | 15.1 | 2.8  | 17.8 | 20.0 | 10.2 | 12.5 | 13.5 | 13.8 |
load-pull. In addition, the optimal load impedance of the transistor and the optimal performance of the circuit must ensure high consistency. However, this paper directly optimizes the performance of circuit, which reduces the constraint of the theoretical optimal value of the load impedance. Thus, it can greatly improve the optimization efficiency.

D. THE DETAILED OPTIMIZATION PROCEDURE

In this paper, we combine ADS with MATLAB to acquire training data and accomplish model regression and search algorithm. The corresponding paths have been added between them to realize the communication during optimization. The detailed simulation steps are presented as follows. Firstly, the initial input parameters, i.e., the initial length and width values of the transmission lines, are obtained from the initial circuit.

Then, the initial input data are fed into MATLAB and sampled by Latin hypercube sampling (LHS) to obtain input parameters corresponding to the training data and the predicted data.

Subsequently, the input parameters of training data are imported into ADS. The fundamental output power and drain efficiency at saturation and the drain efficiency at 9 dB back-off are simulated, respectively. Therefore, each set of training data includes a set of input parameters and the corresponding three target values $Y_1$, $Y_2$, and $Y_3$. And then the resulting training data are sent back to MATLAB for model training and prediction.

After that, the above three objective functions are modeled separately using the GPR regression model. Then, the root mean square for the predicted mean of each set of parameters corresponding to multiple models is used as the new mean. Similarly, the root mean square for the prediction variance of each set of parameters corresponding to multiple models is used as the new variance.

Later, the model is sampled using the CG-GPUCB algorithm. Furthermore, the input parameters corresponding to the sample point are returned to the ADS for harmonic balance (HB) simulation. Followed by, the simulation data corresponding to the sample point is sent to MATLAB for reconstructing the sub-models for the objective functions of eqs. (10)-(12). The LHS will perform the next iteration again near the new acquisition point and the above iterations are repeated until the optimal point are obtained. The flowchart of the detailed optimization procedure of DPA is illustrated in Fig. 8.

V. SIMULATION AND FABRICATION OF BROADBAND DPA

A. THE SIMULATION PROCESS OF BROADBAND DPAs

For validating the effectiveness of the proposed method, we optimized the DPAs using the ADS optimizers and the BO techniques proposed in this paper and the method proposed
in [21], respectively. The DPAs are designed using the Cree CGH40010F GaN HEMTs which have been verified to be well suited for high power PA design [44], [45], [46], [47].

In the design, the gate bias of the carrier PA and that of the peak PA are set equal to -2.8 V and -7.1 V, respectively. The drain bias of the carrier PA and that of the peak PA are set equal to 20 V and 32 V, respectively. The initial design variables of the DPA are shown in Fig 6. Meanwhile, the initial geometry size of the transmission lines is represented in Table 1. Considering the machining accuracy and cost of fabricate PAs, the bound range for the widths and lengths of transmission lines are restricted as: $1 \text{ mm} \leq W \leq 10 \text{ mm}$, and $L \leq 20 \text{ mm}$, respectively.

In the process of optimizing DPAs with BO algorithm, the number of training data and the iteration is set as 50 and 20, respectively. By sweeping the 50 groups of the input parameters, the $DE_{\text{obo,i}}$, $DE_{\text{sat,i}}$, and $P_{\text{out sat,i}}$ from 2.0-2.6 GHz with a step of 0.1 GHz are simulated by ADS. The BO algorithm is applied to build the sub-models and search the optimum design variables. For comparison, the other DPA is optimized with same number of iterations by applying the method proposed in [21], which set the target function as the root mean square of multiple variables as eq. (10). The geometry size of the initial and optimized design variables by the different BO algorithms is shown in Table 1, Table 2, and Table 3, respectively.

The performance comparison of DPAs is shown in Fig. 9. From the obtained results, we can see that the saturated output power of the initial DPA is greater than 42.8 dBm from 2.2 GHz to 2.6 GHz. The drain efficiency is greater than 48.1% and 35.3% at saturation and 9 dB backoff, respectively. The gain is greater than 3 dB.

The performance of the optimized DPA using the method proposed in [21] achieved a small improvement in terms of the efficiency at backoff. The drain efficiency is greater than 42.5% at 9 dB backoff. However, the performance of the optimized DPA with the proposed method is significantly improved in terms of bandwidth, efficiency, and gain. The optimized DPA achieved the saturated output power greater than 44.1 dBm, the drain efficiency greater than 62.3% and 48.1% at saturation, and 9 dB backoff from 2.0 GHz to 2.6 GHz, respectively. The gain is greater than 9.2 dB in the bandwidth.

For further evaluation of the improved algorithm, the normalized error of the proposed method and the initial algorithm proposed in [21] is shown in Fig. 10. Obviously, the improved algorithm has made a great improvement in model accuracy compared with the original algorithm.

In addition, in order to verify the validity of the proposed algorithm, we optimized another two DPAs by using ADS built-in optimizers with Gradient and Quasi-Newton.
The bias design, optimization variables, and objective functions are all same as those of the DPA that is designed with the method proposed in this paper. The detailed geometry size of the optimized design variables is shown in Table 4 and Table 5. And the performances of DPAs designed with ADS built-in optimizers are shown in Fig. 11.

It can be concluded that the performance of DPA optimized with ADS built-in optimizers has improved compared with the initial DPA. However, the improvement is not significant. The drain efficiency of DPA designed with Quasi-Newton achieved an output power greater than 42.4 dBm from 2.0 GHz to 2.6 GHz. The drain efficiency is greater than 48.2% and 35.3% at saturation and 9 dB backoff in the VOLUME 10, 2022

| Parameter | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 | W10 | W11 |
|-----------|----|----|----|----|----|----|----|----|----|------|------|
| Value (mm)| 11.4 | 1.0 | 5.5 | 15.0 | 2.0 | 3.8 | 2.4 | 5.6 | 1.5 | 1.4 | 10.0 |

| Parameter | W12 | W13 | W14 | W15 | W16 | W17 | W18 | W19 | W20 | W21 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Value (mm)| 5.7 | 11.8 | 17.8 | 2.1 | 13.7 | 7.8 | 4.2 | 2.6 | 1.7 | 1.5 |

| Parameter | L12 | L13 | L14 | L15 | L16 | L17 | L18 | L19 | L20 | L21 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Value (mm)| 1.3 | 3.0 | 2.0 | 5.4 | 2.9 | 6.8 | 0.3 | 1.3 | 13.2 | 12.6 | 0.2 |

FIGURE 11. Performance of optimized DPAs by ADS built-in optimizers: (a) Quasi-Newton and (b) Gradient.

FIGURE 12. Photograph of the fabricated DPA based on the GaN HEMT technology.

FIGURE 13. Photograph of the experimental test bench for characterizing the developed DPA.
TABLE 6. Comparisons of the DPAs designed with different methods.

| Parameter                  | Initial DPA | Quasi-Newton | Gradient | BO [16] | Proposed method |
|----------------------------|-------------|--------------|----------|---------|-----------------|
| Frequency (GHz)            | 2.2-2.6     | 2.0-2.6      | 2.1-2.6  | 2.0-2.6 | 2.0-2.6         |
| $P_{out,sat}$ (dBm)        | 42.8        | 42.4         | 43.2     | 43.3    | 44.1            |
| $DE_{sat}$ (%)             | 48.1        | 48.2         | 49.5     | 53.2    | 62.3            |
| $DE_{9dB OBO}$ (%)         | 35.3        | 35.3         | 36.1     | 42.5    | 48.1            |
| Time (min/iteration)       | /           | $\approx$2.0 | $\approx$3.5 | $\approx$5.8 | $\approx$5.8 |
| Numbers of iteration       | /           | 160          | 80       | 20      | 20              |

bandwidth, respectively. The gain is greater than 3.2 dB in the bandwidth. In addition, the other DPA designed with Gradient achieved an output power greater than 43.2 dBm from 2.1 GHz to 2.6 GHz. The drain efficiency is greater than 49.5% and 36.1%, respectively. The gain is greater than 7.5 dB in the considered bandwidth.

In addition, it needs to be emphasized that the ADS built-in optimizers exhibit some obvious drawbacks during circuit simulation. First of all, the optimizer frequently interrupts automatically. Since the ADS optimizer is a unidirectional optimizer, the optimizer will force an automatic break when the simulation does not converge during optimization. Besides, the single ADS built-in optimizer can easily trap the amplifier design into a local optimal solution and cannot obtain a globally optimal solution when there are many variables. As a result, the above issues will result in a time-consuming automatic optimization process that greatly increases the amplifier design cycle.

To further compare the proposed optimization algorithm and the ADS built-in optimizers, a detailed comparison is given in Table 6. We can draw the conclusion that the proposed BO method provides the best design compared to the other optimizers. This is confirmed by the fact that the drain efficiency at saturation and 9 dB backoff are improved, while the gain and effective bandwidth are maintained at a high level. Moreover, the proposed method achieved desirable results in a shorter optimization time, due to the strong fitting performance of the algorithm and the flexible error degree discrimination ability.

B. FABRICATION AND ANALYSIS OF DPA

To verify the efficiency of the proposed method, the DPA optimized with the proposed algorithm is fabricated with the Rogers RO4350 board, with $\varepsilon_r = 3.66$ and a thickness of 0.762 mm, as shown in Fig. 12. The bias setting during measurements is consistent with those during simulation. The measurement frequency range goes from 2.0 GHz to 2.6 GHz with a step of 0.1 GHz. The test bench used for DPA measurement is shown in Fig. 13.

As shown in Fig.14, the measured output power at saturation is greater than 43.8 dBm from 2.0 GHz to 2.6 GHz. The drain efficiency is greater than 60.5% and 44.6% at saturation and backoff, respectively. The gain is over 8.5 dB in the frequency band. It is worth noticing that the achieved measurement results are roughly consistent with the simulation results.

Finally, Table 7 is added to compare the performance between this work and the latest published works. Compared with [22], the DPA in this paper achieves significant improvements in drain efficiency and output power at saturation. Compared with [20] and [48], the DPA proposed in this paper possesses a higher drain efficiency at saturation with the large backoff, while maintaining the bandwidth at a high level.

VI. CONCLUSION

In this paper, an improved BO algorithm was employed for a DPA design. The DPA designed by the proposed algorithm outperforms the DPAs optimized by ADS built-in optimizers and the initial BO algorithm in [21]. The proposed DPA achieved high efficiency both at saturation and backoff with the broad bandwidth, which needs less optimization time. To further verify the effectiveness of the proposed method, the DPA designed with the developed method is fabricated with the Rogers RO4350 board. The measured results are roughly consistent with the simulation results. The comparison results between the performance of this work and the other state-of-the-art DPAs show that presented DPA promises larger backoff without sacrificing the efficiency performance and the bandwidth.
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