



Adaptive Particle Swarm Optimization for Harmonic Impedance Matching in 5G Power Amplifier Design

Chengxi Bian, Weiqing Dong, Wa Kong, and Jing Xia^(✉)

School of Computer Science and Communication Engineering, Jiangsu University,
Zhenjiang 212013, China

2221908005@stmail.ujs.edu.cn, Jingxia@ujs.edu.cn

Abstract. This paper proposes an optimization-oriented design method for harmonic tuned power amplifier (PA) using particle swarm optimization (PSO). Optimal source and load impedances for achieving high efficiency are obtained at the package plane of a Wolfspeed CGH40010 transistor. PSO is employed to optimize matching networks for fitting the desired trajectories of impedances. The designed PA with optimized matching networks was simulated in Keysight's advanced design system for verification. The results showed that the saturation efficiency of the PA reaches 75% at 3.5 GHz with associated output power of 42 dBm, which verified that the method can be used to design high efficiency PA for 5G mobile communication systems.

Keywords: 5G · Class-F · Particle swarm optimization · Harmonic impedance · High efficiency · Power amplifier

1 Introduction

Future wireless communication systems require higher data rates and efficient energy consumption, which will increase the requirements for power amplifiers (PAs). How to achieve highly efficient operation of the power amplifier is an important issue in wireless communication system design. In the past few decades, many different types of power amplifiers have been developed to meet these requirements, such as Class E, Class F and Class F-1. Class F power amplifiers achieve high efficiency due to their non-overlapping drain voltage and current waveforms [1]. However, achieving good control of harmonic waveforms has higher requirements on the design of matching networks [2]. Although there are multiple technologies used in the design of high-efficiency power amplifiers [3, 4], it is necessary to further optimize the matching network to control harmonic impedance. Therefore, it is useful to use excellent optimization algorithms to design and optimize the matching network.

Particle swarm optimization (PSO) algorithm is a simple and powerful optimization algorithm, which has a strong applicability when solving continuous function optimization problems [5, 6]. If there is a definite matching network structure and a clear

optimization goal, the optimization can be completely handed over to the intelligent algorithm.

This paper proposes an optimization-oriented design method for harmonic tuned power amplifier using PSO. The theoretical basis of the adaptive particle swarm optimization algorithm was given and then used to analyze the input and output matching network of the power amplifier to obtain the corresponding fitness function. A 3.5 GHz high-efficiency power amplifier is optimally designed with the load impedance value obtained by using load-pull as the goal. The optimization result was evaluated and the best matching network was selected for the design. The feasibility of the proposed method provides a useful design for high efficiency power amplifiers.

2 Theoretical Analysis of Adaptive Particle Swarm Optimization

The particle swarm optimization algorithm is an evolution algorithm based on swarms, which is developed by the bird's foraging behavior [7]. Each particle in the particle swarm represents a possible solution to a problem. All particles have a position attribute and a velocity attribute. The position attribute is the position of the particle in the solution space, and the velocity attribute is used to determine the direction of the next movement of the particle and speed. In each iteration, the particles in the population change their own speed attributes by sharing their own information, and eventually all particles in the population will approach the optimal solution.

The algorithm used in this paper is an adaptive particle swarm optimization (APSO) algorithm. The following will introduce some necessary formulas in this algorithm in order to understand the adaptive particle swarm optimization algorithm.

Suppose that in an S -dimensional target search space, m particles form a group, and the i -th particle is represented as an S -dimensional vector $\vec{x}_i = (x_{i1}, x_{i2}, \dots, x_{iS})$, $i = 1, 2, \dots, m$, and the position of each particle is a potential solution. The fitness value can be calculated by substituting \vec{x}_i into an objective function, and the merits of the solution can be measured according to the fitness value. The speed of the i -th particle is an S -dimensional vector, denoted as $\vec{V} = (V_{i1}, V_{i2}, \dots, V_{iS})$. The best position searched so far for the i -th particle is the best position $\vec{P}_{gS} = (P_{gS}, P_{gS}, \dots, P_{gS})$.

Assuming $f(x)$ is the objective function of minimization, the current best position of particle i is determined by the followings:

$$P_i(t+1) = \begin{cases} P_i(t) \rightarrow f(x_i(t+1)) \geq f(P_i(t)) \\ X_i(t+1) \rightarrow f(x_i(t+1)) < f(P_i(t)) \end{cases} \quad (1)$$

The particle can be operated by

$$v_{is}(t+1) = v_{is}(t) + c_1 r_{1s}(t)(p_{is}(t) - x_{is}(t)) + c_2 r_{2s}(t)(p_{gs}(t) - x_{is}(t)) \quad (2)$$

$$x_{is}(t+1) = x_{is}(t) + v_{is}(t+1) \quad (3)$$

where $i = [1, m]$, $s = [1, S]$, and learning factors c_1 and c_2 are non-negative constants. And, r_1 and r_2 are independent pseudo-random numbers, which subject to uniform distribution on $[0, 1]$. $v_{is} \in [-v_{\max}, v_{\max}]$, and v_{\max} is a constant, set by the user.

It can be seen from above equations that c_1 regulates the step size of particles flying towards their best position, and c_2 regulates the step size of particles flying towards their global best position. In order to reduce the possibility of particles leaving the search space during evolution, v_{is} is usually limited to a range, that is $v_{is} \in [-v_{\max}, v_{\max}]$. If the search space is in the middle of $[-x_{\max}, x_{\max}]$, $v_{\max} = kx_{\max}$ can be set, where $0.1 \leq k \leq 1.0$.

To improve the optimization performance, (2) can be improved as

$$v_{is}(t + 1) = \omega v_{is}(t) + c_1 r_{1s}(P_{is}(t) - x_{is}(t)) + c_2 r_{2s}(t)(P_{gs}(t) - x_{gs}(t)) \quad (4)$$

where ω is a non-negative number (called a dynamic constant), which controls the effect of the previous speed on the current speed. When ω is larger, the previous speed has a greater impact and the global search ability is stronger. When ω is smaller, the previous speed has a smaller effect, the local search ability is stronger. By adjusting the size of ω , the local minimum can be jumped out.

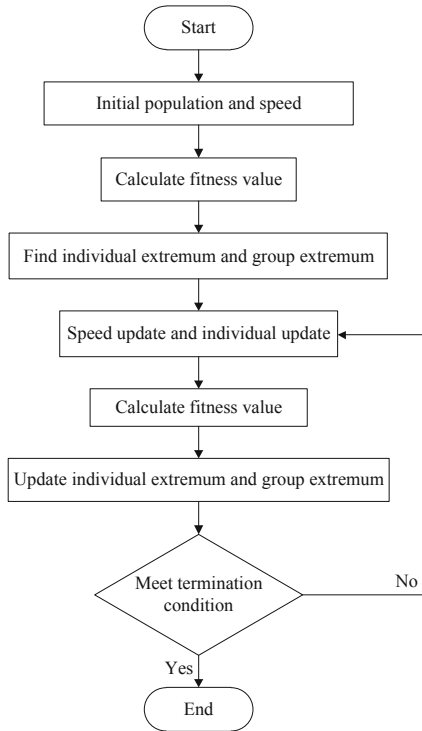


Fig. 1. Flow chart of adaptive particle swarm optimization.

In order to balance the global search ability and local improvement ability of the PSO algorithm, a nonlinear dynamic inertia weight coefficient formula can be given as follows:

$$\omega = \begin{cases} \omega_{\max} - \frac{(\omega_{\max} - \omega_{\min}) * (f - f_{\min})}{f_{avg} - f_{\min}}, & f \leq f_{avg} \\ \omega_{\max}, & f > f_{avg} \end{cases} \quad (5)$$

where ω_{\max} and ω_{\min} represent the maximum and minimum values of ω , f represents the current target function value of the particles, and f_{avg} and f_{\min} represent the current average target value and minimum target value of all particles, respectively. In this algorithm, ω is called adaptive weight because the inertia weight changes automatically with the target function value of particles. So, the improved PSO algorithm is called APSO.

The termination condition of the adaptive particle swarm optimization algorithm takes the maximum number of iterations or the predetermined minimum threshold value satisfied by the optimal position searched by the particle swarm according to the specific problem. The algorithm flow is shown in the Fig. 1.

3 Matching Network Design and Optimization

3.1 Input Matching Network Design and Optimization

The input matching network is an important part of the PA, and its purpose is to achieve the impedance matching of the external load impedance of 50Ω and the power amplifier tube source impedance Z_S . Figure 2 is a circuit diagram of input matching network, which consists of parallel open circuit lines (Z_2, θ_2) and series transmission lines (Z_1, θ_1). The following is the derivation of the source impedance.

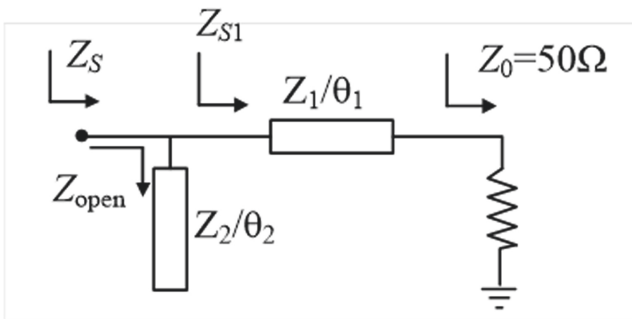


Fig. 2. Circuit diagram of input matching network.

The target source impedance of the Wolfspeed CGH40010 transistor at 3.5 GHz can be determined to be $7-j16 \Omega$ by using source-pull simulation in Keysight’s advanced design system (ADS).

Normalized frequency is used for source impedance calculation in fitness function. According to the transmission line impedance transformation formula, Z_{S1} can be obtained, as follows:

$$Z_{S1} = Z_1 \frac{(Z_0 + jZ_1 \tan(\theta_1 \frac{\pi}{180}))}{(Z_1 + jZ_0 \tan(\theta_1 \frac{\pi}{180}))} \quad (6)$$

Similarly, the impedance Z_{open} of the open transmission line can be calculated

$$Z_{open} = Z_2 \frac{(\infty + jZ_2 \tan(\theta_2 \frac{\pi}{180}))}{(Z_2 + j\infty \tan(\theta_2 \frac{\pi}{180}))} = Z_2 \frac{1}{j \tan(\theta_2 \frac{\pi}{180})} \quad (7)$$

It can be obtained from the circuit schematic diagram in Fig. 2 that Z_S is the parallel connection of Z_{S1} and Z_{open} , which can be expressed as:

$$Z_S = Z_{S1} // Z_{open} = \frac{Z_{S1} \cdot Z_{open}}{Z_{S1} + Z_{open}} \quad (8)$$

When the target source impedance Z_{s_target} is $7-j16 \Omega$, the fitness function can be expressed as the sum of the absolute values of the impedance difference between the real and imaginary parts:

$$F = |9 - \text{real}(Z_S)| + |16 + \text{imag}(Z_S)| \quad (9)$$

The variables in APSO optimization are Z_1 , θ_1 , Z_2 and θ_2 . The APSO optimizes the source impedance that meets the requirements according to the fitness function above.

In the optimization algorithm, the population size is 10 individuals, and the evolutionary generation is 60 generations. In order to observe the change trend of fitness, the optimization program was run 10 times. Figure 3 shows the relationship between the value of the objective function (fitness value) and the evolutionary generation during optimization operation. It can be seen from Fig. 3 that the blue line in the figure represents the fitness value of the best individual, and the red dotted line represents the average fitness value optimized 100 times. As the number of iterations increases, the fitness value of the best individual keeps decreasing from around 1 and finally stabilizes at around 0; and the average fitness value also shows a downward trend, which is stable at around 0 between 30 and 40 generations.

Figure 4(a) and Fig. 4(b) give the changes of various parameters (Z_1 , Z_2 , θ_1 and θ_2) and $\text{real}(Z_{L1})$ and $\text{imag}(Z_{L1})$ in the optimal optimization. The results show that these parameters and results are deviate greatly from the expected value in the early stage, but with the increase of the number of iterations, they quickly turn to the optimal value. The optimal solution is $Z_1 = 43.7 \Omega$, $\theta_1 = 47.4^\circ$, $Z_2 = 57.7 \Omega$, $\theta_2 = 70.6^\circ$. The fitness data is close to 0, indicating that the difference between the current impedance and the target impedance can be minimized, which means that the input matching network is optimized.

3.2 Output Matching Network Design and Optimization

The output matching network is an important part of the PA, which achieves the impedance matching of the external load impedance 50Ω and the optimal load

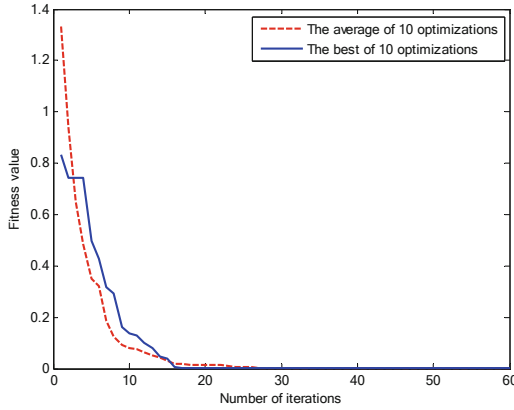


Fig. 3. The fitness value changes with the number of iterations.

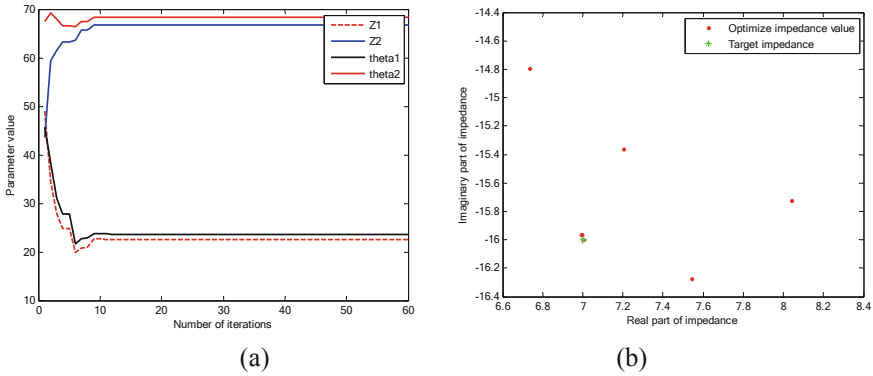


Fig. 4. (a) The values of Z_1 , Z_2 , θ_1 and θ_2 with algebra (b) Changes in impedance during optimization.

impedance Z_L of the power amplifier tube. Figure 5 is the circuit diagram of the output matching network, which consists of two-stage parallel open-circuit transmission line and 4-stage series transmission line. The parameters of the output matching network are (Z_1, θ_1) , (Z_2, θ_2) , (Z_3, θ_3) , (Z_4, θ_4) , (Z_5, θ_5) and (Z_6, θ_6) . The target load impedance value can be obtained from the load-pull simulation results. The target fundamental frequency $Z_{L_target_1}$ is $16.2-j0.4 \Omega$, the 2nd harmonic frequency $Z_{L_target_2}$ is $j36 \Omega$ and the 3rd harmonic frequency $Z_{L_target_3}$ is $-j293 \Omega$.

According to the transmission line impedance transformation formula, Z_{L1} can be calculated as follows:

$$Z_{L1} = Z_6 \frac{(z_0 + jz_6 \tan(\theta_6 \frac{\pi}{180}))}{(z_6 + jz_0 \tan(\theta_6 \frac{\pi}{180}))} \tag{10}$$

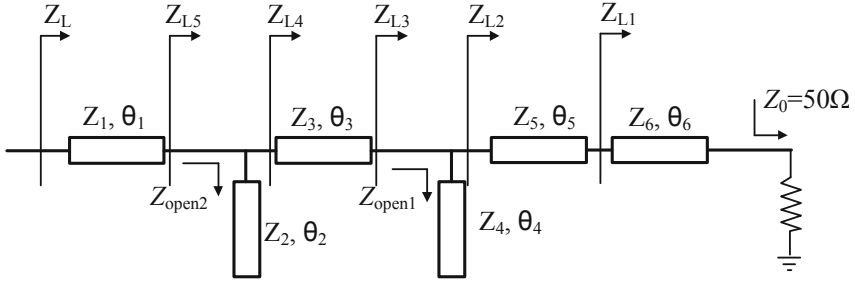


Fig. 5. Circuit diagram of output matching network

Taking into account (10), Z_{L2} are expressed as

$$Z_{L2} = Z_{L5} \frac{(z_{L1} + jz_5 \tan(\theta_5 \frac{\pi}{180}))}{(z_5 + jz_{L1} \tan(\theta_5 \frac{\pi}{180}))} \quad (11)$$

Similarly, the input impedance of the open line Z_{open1} , Z_{open2} can be given by

$$Z_{open1} = Z_4 \frac{1}{j \tan(\theta_4 \frac{\pi}{180})} \quad (12)$$

$$Z_{open2} = Z_2 \frac{1}{j \tan(\theta_2 \frac{\pi}{180})} \quad (13)$$

According to (10) and (11) and combined with the circuit schematic, Z_{L3} can be calculated as follows:

$$Z_{L3} = Z_{L2} // Z_{L_open1} = \frac{(z_{L2} \cdot z_{L_open1})}{(z_{L2} + z_{L_open1})} \quad (14)$$

Therefore, Z_{L4} can be retrieved:

$$Z_{L4} = Z_3 \frac{(z_{L3} + jz_3 \tan(\theta_3 \frac{\pi}{180}))}{(z_3 + jz_{L3} \tan(\theta_3 \frac{\pi}{180}))} \quad (15)$$

From (14), Z_{L5} can be obtained:

$$Z_{L5} = Z_{L4} // Z_{L_open2} = \frac{(z_{L4} \cdot z_{L_open2})}{(z_{L4} + z_{L_open2})} \quad (16)$$

Z_L can finally be calculated:

$$Z_L = Z_1 \frac{(z_{L5} + jz_1 \tan(\theta_1 \frac{\pi}{180}))}{(z_1 + jz_{L5} \tan(\theta_1 \frac{\pi}{180}))} \quad (17)$$

When the target fundamental load impedance $Z_{L_target_1}$ is $16.2 - j0.4 \Omega$, the fitness function can be expressed as the sum of the absolute values of the impedance difference between the real and imaginary parts:

$$F_{1st} = |16.2 - \text{real}(Z_L)| + |0.4 + \text{imag}(Z_L)| \quad (18)$$

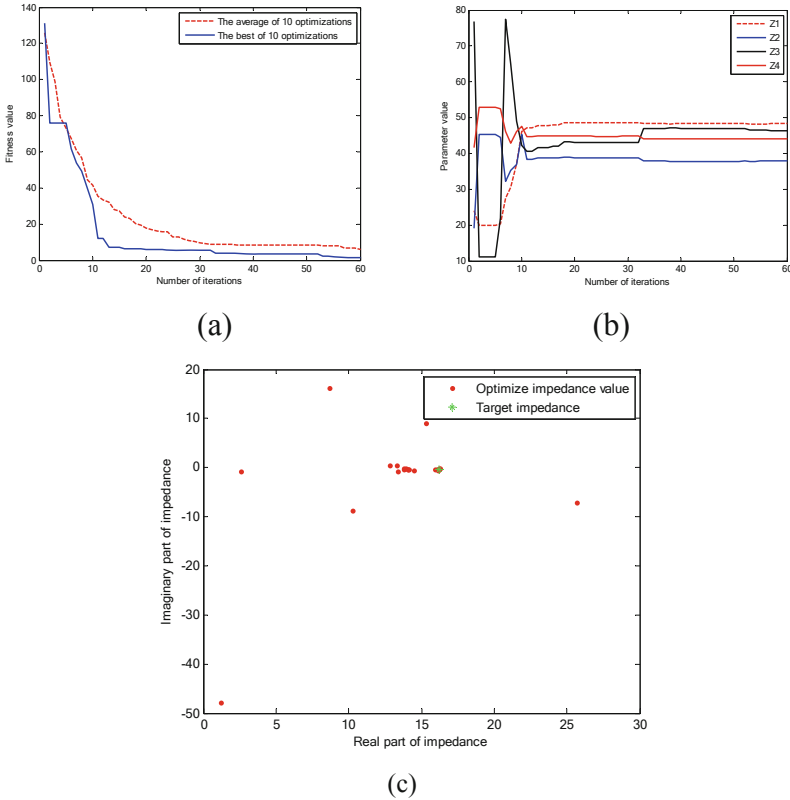


Fig. 6. (a) The fitness value changes with the number of iterations. (b) The values of Z_1 , Z_2 , Z_3 and Z_4 with algebra (c) Changes in impedance during optimization.

The calculation of the target 2nd and 3rd load impedance is similar to the above fundamental wave calculation, and can be calculated as follows:

$$F_{2nd} = |0 - \text{real}(Z_L)| + |36 + \text{imag}(Z_L)| \tag{19}$$

$$F_{3rd} = |0 - \text{real}(Z_L)| + |293 - \text{imag}(Z_L)| \tag{20}$$

After the impedance at three frequencies is used as the optimization target, the optimization output results are shown in Fig. 6. The results show that the values of the parameters sought are $Z_1 = 39.9 \Omega$, $Z_2 = 33.5 \Omega$, $Z_3 = 45.3 \Omega$, $Z_4 = 32.0 \Omega$, $Z_5 = 27.4 \Omega$, $Z_6 = 25.0 \Omega$, $\theta_1 = 32.1^\circ$, $\theta_2 = 30.6^\circ$, $\theta_3 = 59.3^\circ$, $\theta_4 = 35.8^\circ$, $\theta_5 = 48.9^\circ$, $\theta_6 = 80.2^\circ$. The fitness is at least 1.6, which is approximately the goal.

4 Power Amplifier Simulation

After using the above-mentioned adaptive particle swarm optimization to design the input and output filter matching network, the power amplifier can be designed and simulated

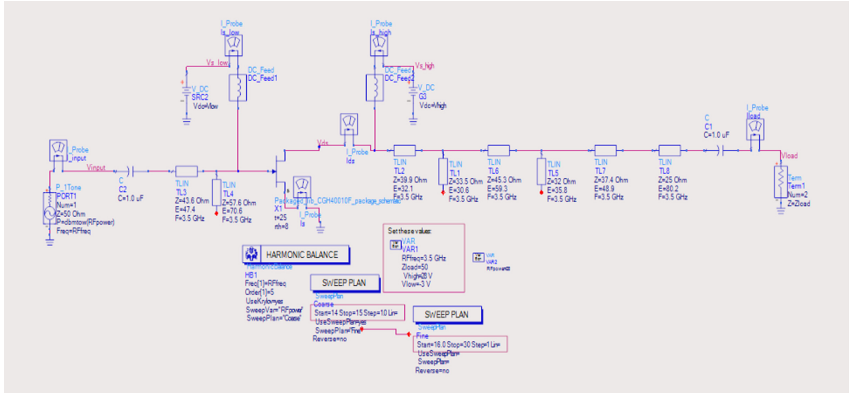


Fig. 7. Power amplifier simulation schematic

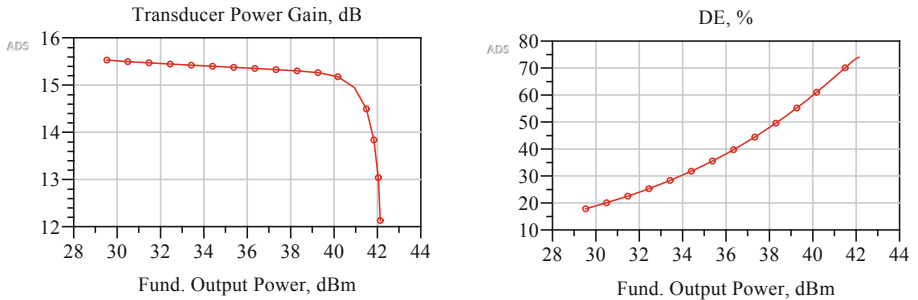


Fig. 8. Gain and efficiency of power amplifier simulation at 3.5 GHz

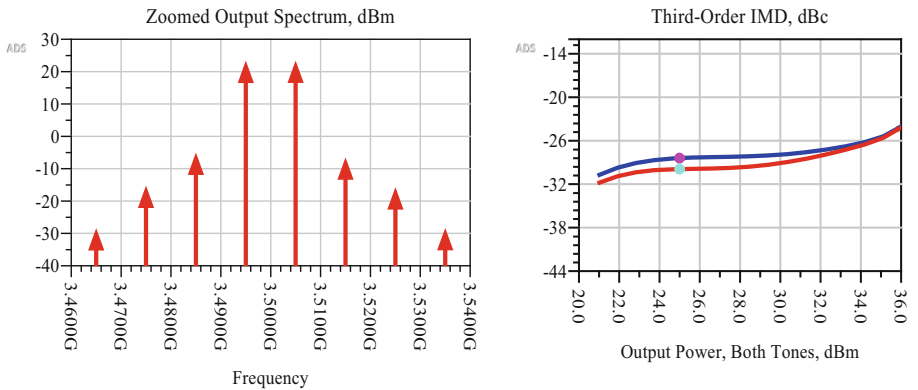


Fig. 9. Third-order intermodulation diagram of power amplifier

in ADS, which is shown in Fig. 7. The simulated gain and efficiency versus output power are shown in Fig. 8. It can be seen from the results that the saturation power of the amplifier is about 42 dBm at 3.5 GHz, and the maximum efficiency reaches 75%, reaching a higher power and efficiency level. Figure 9 is the third-order intermodulation diagram of the designed power amplifier, which illustrates the good linear characteristics of the amplifier.

5 Conclusion

This paper proposes an optimization algorithm to design and optimize the input and output matching circuits of the power amplifier. Using the particle swarm optimization algorithm to match the impedance value of the network, a high-efficiency power amplifier is designed and optimized. Simulation results show that the amplifier can achieve higher efficiency, indicating that the method has practical reference value for the design of PAs.

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