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Particle Swarm Algorithm Based on Homogenized Logistic Mapping and Its Application in Antenna Parameter Optimization

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Abstract: Aiming at the problems of computing complexity, long time-consuming and low accuracy in the process of antenna optimization design, a particle swarm optimization algorithm based on chaotic ergodic search is proposed in this paper. In order to improve the rationality of the selection of the initial population of the traditional particle swarm optimization algorithm and enhance the diversity of particles in the iterative process of the algorithm, this algorithm introduces a uniform Logistic chaotic map into the traditional particle swarm optimization algorithm, so as to improve the convergence speed and optimization performance of the particle swarm optimization more effectively. In this paper, the Logistic map is selected in the chaotic map, and the analysis shows that although it has good long-term periodicity and initial value sensitivity, the data does not obey the uniform distribution, which makes the omission range when the sequence value is small, which reduces the chaos. The efficiency of traversal, in view of this shortcoming, this paper proposes a method of homogenizing Logistic, and deduces and analyzes it. It is concluded that this homogenized Logistic method has better randomness and can better reflect the characteristics of uniform distribution of data. Further, based on the optimization algorithm, the rectangular microstrip antennas with two feeding modes are optimized, and the antenna size obtained by empirical formula is modeled and analyzed in HFSS software. The research results show that the optimization algorithm in this paper can bring faster convergence speed and more accurate optimization results for antenna optimization.

Keywords: Antenna Optimization, Homogenized Chaotic Mapping, Particle Swarm Optimization, Microstrip Antenna

1. Introduction

Wireless mobile communication and antenna have become an important influencing factor in the development and change of communication field [1]. In 1953, the concept of a microstrip microwave antenna was made public. Researchers such as Munson and Howell designed a microstrip antenna that satisfies both low profile antenna and spatial standards [2]. In 1974, R. Munson proposed a transmission line model for rectangular patch antennas to simplify the analysis process. In 1979, W. F. Richards and Y. T. Lo et al. proposed a theoretical cavity model, which greatly simplifies the calculation of the input impedance of a regular thin microstrip antenna [3]. In 1981, the establishment of the IEEE microstrip antenna album marked that the research of microstrip antenna has officially become a unique field of study [4].

In the process of traditional algorithm for antenna optimization, there is a drawback that only local optimal solution can be obtained, which takes a long time. The size parameters of antenna are also very dependent on the design experience of antenna researchers. The combination of the development of chaos and traditional particle swarm optimization can improve the slow convergence of the latter stage. It can successfully solve the shortcomings such as the increase of iteration while the diversity of particles cannot be guaranteed, and it can overcome the shortcomings such as the algorithm cannot effectively jump out of the local optimal solution. Li Bing has introduced a chaos optimization algorithm, and Zhang Tong has also introduced a chaos optimization algorithm with variable scale. Later, a group of scholars intermingled chaotic system with other optimization algorithms to propose a more efficient optimization algorithm. There are optimization algorithms combined with conjugate gradient method, mode search method, intelligent algorithm and so on [5]. These algorithms make better use of the superiority of the chaotic system itself, so as to make up for the deficiency of the original optimization algorithm in the optimization process, but they do not improve the deficiency of the chaotic system properly. Although the chaotic series generated by chaotic system does appear to have very good pseudo-randomness, it is found that the chaotic series cannot guarantee the uniformity of the data. As a result, if chaotic series is used as the initial value of the optimization algorithm in the optimization process, there must be a problem that the optimal solution cannot be found due to the insufficient sequence length. To solve these problems, this paper presents an antenna optimization design method based on chaotic traversal optimization.

2. Microstrip Antenna Base

2.1. Basic Classification and Analysis of Microstrip Antennas

The essence of antenna analysis is to analyze the distribution of electromagnetic field around the antenna under radiation excitation. There are three main analysis methods for microstrip antenna in this paper, transmission line model theory, cavity model theory and full-wave analysis theory [7].

2.2. Feeding Technology of Microstrip Antenna

There are many feeding modes for microstrip antenna. This paper mainly introduces two feeding modes, microstrip line feeding and coaxial feeding. Coaxial feeding usually uses coaxial feeder to pass through and fix on the grounding plate. Conductors in coaxial feeder can pass through the dielectric base to attach patches. This paper mainly chooses coaxial feeding rectangular microstrip antenna and microstrip feeding rectangular microstrip antenna with resonance frequency of 2.45GHz to optimize and design, and compares their gain, radiation characteristics and impedance matching [8].

2.3. Electrical Parameters of Microstrip Antenna

In engineering design, the S parameter of an electromagnetic device is defined by power. In the S parameter, the return loss is S_{11}, and the return loss is between zero and negative infinity. The smaller the value is, the better the match. When S_{11}<-10dB, the antenna impedance matches well, which can meet the basic requirements of design and manufacture. That is, the frequency bandwidth of S_{11}<-10dB is defined as the antenna bandwidth, so this paper uses S_{11} curve to analyze the antenna bandwidth.

3. Rectangular Microstrip Antenna Design

3.1. Rectangular Microstrip Antenna Design with Two Feeding Modes

This paper chooses rectangular patch microstrip antenna for simulation analysis. Width W of metal patch can be calculated by resonance frequency. The empirical formula is as follows.

$$W = \frac{c}{2f_c}\left(\frac{\varepsilon_r+1}{2}\right)^{-\frac{1}{2}} \tag{1}$$

The length of the radiation patch is generally $\lambda_e/2$, λ_e The guided wave length in the medium is shown below.

$$\lambda_e = \frac{c}{f\sqrt{\varepsilon_{eff}}} \tag{2}$$

The length L of the radiated iron sheet can be expressed as follows.

$$L = \frac{c}{2fc\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{3}$$

The effective relative dielectric constant ε_{eff} and its equivalent slot broadband ΔL can be calculated by the following formula.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-\frac{1}{2}} \tag{4}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{w}{h}+0.8)} \tag{5}$$

The matched feed point location L_1 is shown below.

$$L_1 = \frac{L}{2}\left(1-\frac{1}{\sqrt{\xi_{re}}}\right) \tag{6}$$

In the above equation, ξ_{re} is determined by equation (7).

$$\xi_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{L}\right)^{-\frac{1}{2}} \tag{7}$$

A section of 1 / 4 wavelength impedance converter is added to the microstrip fed rectangular microstrip antenna design to ensure that the edge impedance of the microstrip antenna matches the 50Ω impedance. In this paper, we assume that the edge impedance of the antenna is Z_L, the characteristic impedance of the 1 / 4 wavelength impedance converter is Z_1, and the characteristic impedance of the microstrip line is Z_0. The impedance matching criteria are as follows.

$$Z_1 = \sqrt{Z_0 Z_L} \tag{8}$$

The coaxial feed rectangular microstrip antenna has a feed position of 7 mm, the 1 / 4 wavelength impedance conversion length and width of the microstrip feed rectangular patch are 17.9 mm and 1.16 mm, and the 50Ω microstrip line length and width are 15 mm and 2.98 mm, respectively. The two microstrip antenna sizes are designed with the same operating frequency of 2.45 GHz and the rectangular patch has the same relative sword constant of 4.4, the rectangular patch length L_0 is 27.9 mm, the width W_0 is 37.26 mm and the dielectric base thickness is 1.6 mm, respectively [10]. The materials used in their respective media bases and feeding modes are FR4, PEC and coaxial line. Based on the size parameters of coaxial feed rectangular microstrip antenna and microstrip feed rectangular microstrip antenna [14], a top view is designed in HFSS software as follows.

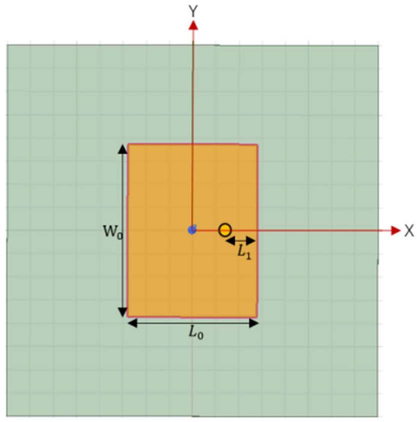

***Figure 1.** Coaxial fed rectangular patch model.*

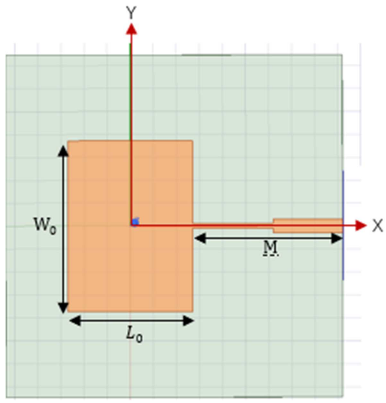

***Figure 2.** Microstrip fed rectangular patch mode.*

3.2. Antenna Simulation Results and Analysis

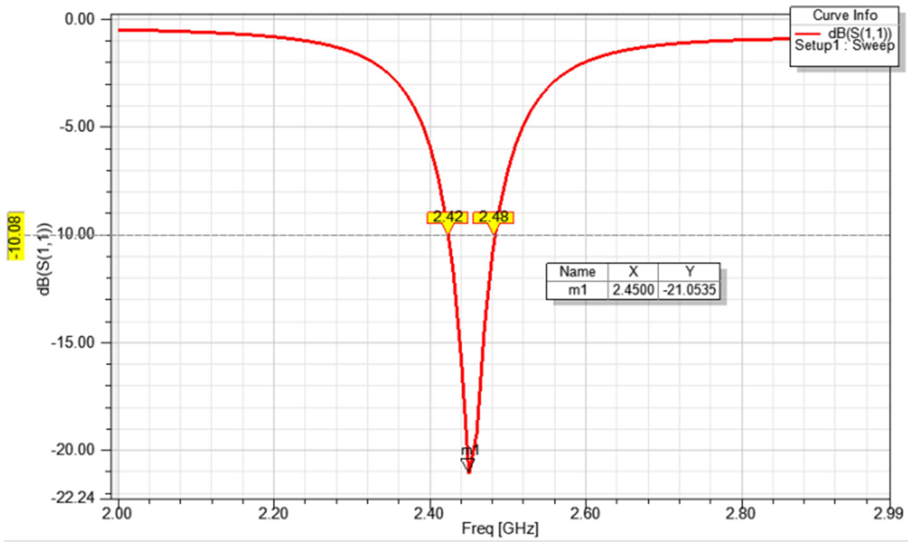

***Figure 3.** Coaxial fed rectangular microstrip antenna s_{11} curve.*

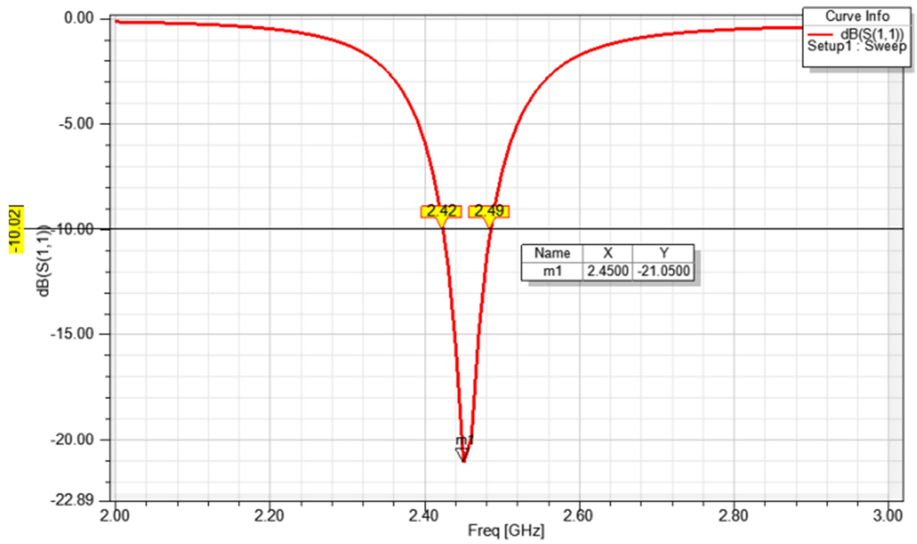

***Figure 4.** s_{11} curve of microstrip fed rectangular microstrip antenna.*

Observe the return loss curve s_{11} and the three-dimensional stereo pattern of two rectangular microstrip antennas. The return loss s_{11} curve can observe the impedance matching degree and relative bandwidth of the antenna. The three-dimensional stereo pattern is used to reflect the radiation characteristics of the antenna. The intensity of the radiation characteristics is marked by different colors. The smoother the image is, the better the directionality is.

From the m1 curves labeled in Figure 3 and Figure 4 above, the resonant center frequencies and the minimum number of echo losses of the two antennas can be seen. The following is a three-dimensional stereo pattern of two antennas.

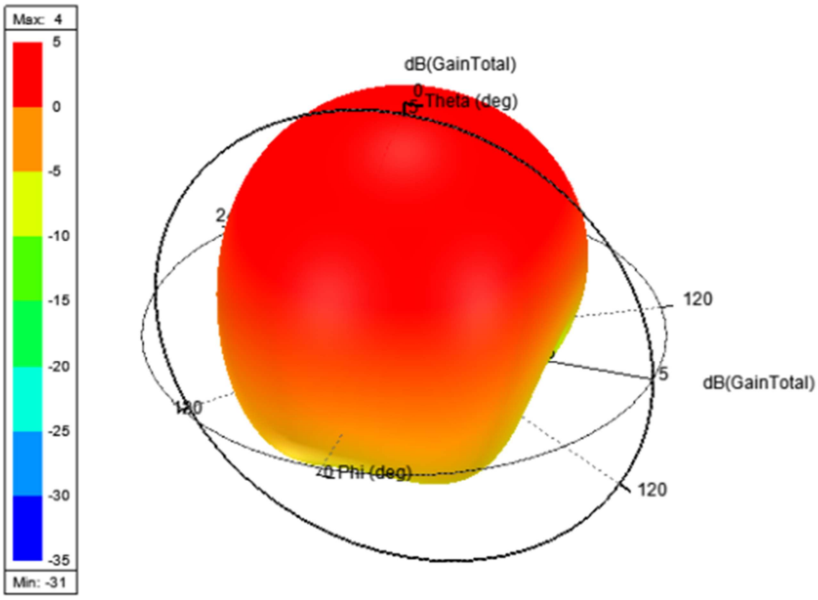

Figure 5. *Three dimensional three-dimensional pattern of coaxial fed rectangular patch antenna.*

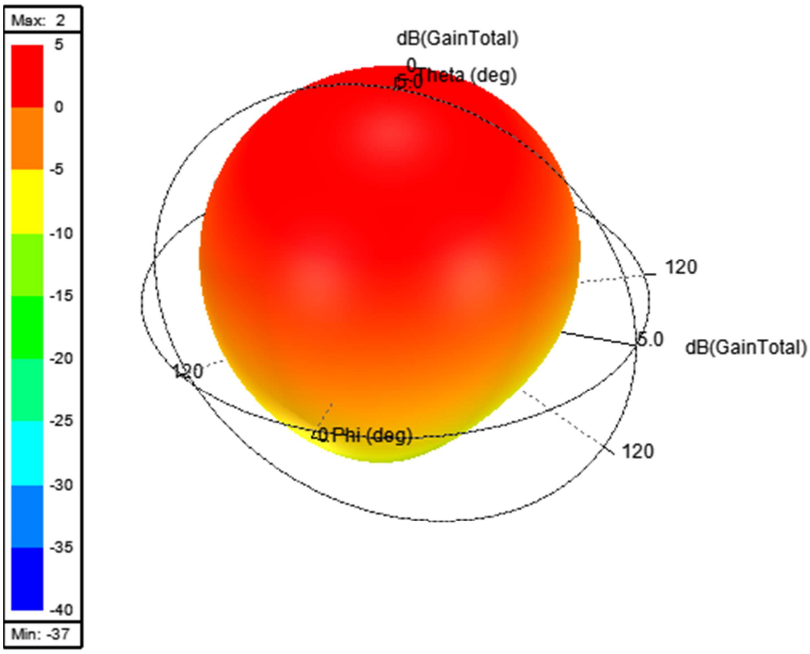

Figure 6. *Three dimensional pattern of microstrip fed rectangular patch antenna.*

From Figure 5 and Figure 6 above, it can be seen that the gain and directionality of the two antennas are good [9].

4. Chaotic Traversal Optimization Algorithm

4.1. Logistic Mapping Related Performance

The Logistic mapping mathematical expression is as follows.

$$x_{n+1} = \mu x_n(1 - x_n) \tag{9}$$

$\mu \in (0,4]$, when $3.5699 < \mu \leq 4$, the system is chaotic. Take $\mu=4$, $x_1=0.2501$, and iterate 100 times to produce sequence diagram and sequence frequency distribution diagram as follows [12].

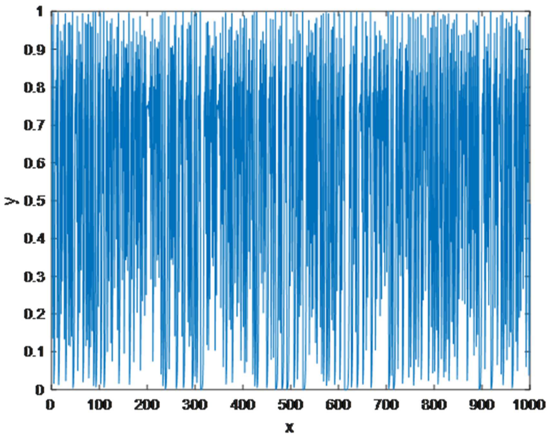

Figure 7. *Sequence of logistic map.*

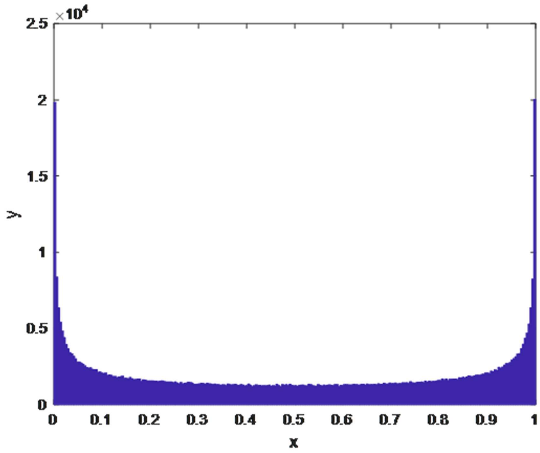

Figure 8. *Sequence frequency distribution of logistic map.*

4.2. Improvement Principle and Process of Logistic Unification

Previously, the homogenization of Logistic maps was segmented into Logistic sequences using power function carriers [15].

$$Z_n' = \begin{cases} z_n^p,\ z_n \in [0,a) \\ z_n,\ z_n \in [a,b) \\ z_n^q,\ z_n \in [b,1] \end{cases} \tag{10}$$

$0 < a < b < 1$, $0 < p < 1$, $0 < p < 1$, Z_n are logistic sequences derived from the formula (10). This method is very good from the results. It can homogenize the sequence from the data level, but it cannot be explained globally that it can homogenize the Logistic sequence with infinite length. The improved method used in this paper is to derive a regulator formula by adding probability density function based on Logistic mapping. The regulator can homogenize the sequence [9]. In formula (9), if μ=4 is made, the Logistic sequence probability density function is as follows.

$$\rho_x = \begin{cases} \frac{1}{\pi\sqrt{x(1-x)}}, x \in (0,1) \\ 0, \text{others} \end{cases} \tag{11}$$

With $x = f(x)$, the probability density function for sequence $\{y_n\}$ can be derived as follows.

$$\rho_y = \begin{cases} \frac{f'(y)}{\pi\sqrt{f(y)(1-f(y))}}, y \in (0,1) \\ 0, \text{others} \end{cases} \tag{12}$$

Since we expect the probability density to be uniformly distributed, we can simplify the derivation of the above equation to solve the differential equation and get the following equation.

$$f(y) = \frac{\sin\left(-\frac{\pi}{2}+\pi y\right)+1}{2} \tag{13}$$

So the equation y for x is as follows.

$$y = \frac{1}{\pi}\arcsin(2x-1) + \frac{1}{2} \tag{14}$$

The improved logical mapping from equation (11) to equation (14) is as follows

$$\begin{cases} x_{n+1} = \mu x_n(1-x_n) \\ y_n = \frac{1}{\pi} arcsin(2x_{n+1}-1) + \frac{1}{2} \end{cases} \tag{15}$$

4.3. Homogeneous Logistic Mapping Related Performance

The frequency and probability distributions of the homogenized Logistic series are as follows:

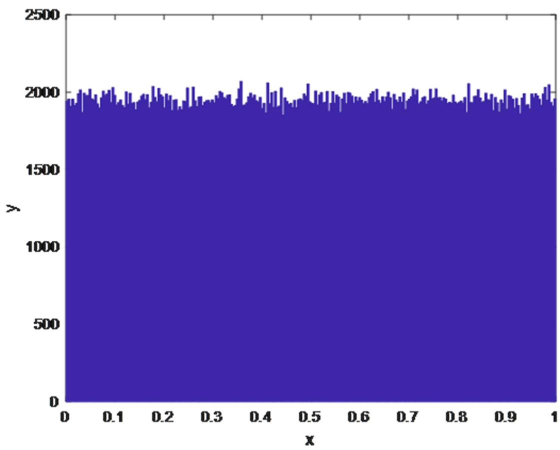

Figure 9. *Sequence spectrum after homogenization.*

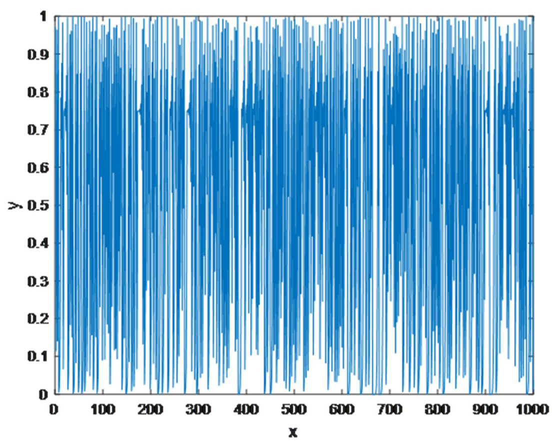

Figure 10. *Homogenized Sequence Probability Density Graph.*

From the two figures above, it is obvious that the distribution of Logistic series with the regulator formula tends to be uniform, but at the same time the distribution of data is still fluctuating, which is caused by the random nature of the chaotic series itself [6].

4.4. Standard Particle Swarm Optimization

Particle swarm optimization (PSO) considers all particles as separate mass-free, volume-free points, and each particle may become a potential solution to the optimization problem. Each particle searches for the optimal solution in the fitness function as an individual extreme Pbest, and all particles in the particle swarm can search for the optimal solution as a global extreme Gbest [11]. The iteration process of particles is shown below.

$$v_{id}^{k+1} = \omega v_{id}^{k} + c_1 \cdot \gamma_1 \cdot (p_{id}^{k} - x_{id}^{k}) + c_2 \cdot \gamma_2 \cdot (p_{gd}^{k} - x_{id}^{k}) \quad (16)$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad (17)$$

v_{id}^{k+1} and x_{id}^{k+1} are the velocities and locations of the i-th particle in the second iteration along the $d(d = 1,2,3,\ldots,D)$-dimensional direction in $(k+1)$. v_{id}^{k}, x_{id}^{k}, p_{id}^{k} and p_{gd}^{k} correspond to the velocities, locations, individual extreme locations and global extreme locations in the kth iteration respectively. γ_1 and γ_2 are random numbers from zero to one. Formula (17) indicates that the future position of a particle is the result of the addition of the previous position of the particle to the next velocity of motion [16].

4.5. Particle Swarm Algorithm for Homogenizing Logistic Maps

The homogenization logistic map is mainly for the initialization of the particle swarm and varies the particle through it. The initial position of the particle at the initialization of the particle swarm is determined by linear transformation of the sequence generated by the homogenization logistic map [13]. Since traversing the optimization process requires an omni-directional search of the entire value space of the variable, the following design is needed to homogenize the Logistic map.

$$\begin{cases} x_{n+1} = 4x_n(1 - x_n) \\ y_n = \frac{1}{\pi} arcsin(2x_{n+1} - 1) + \frac{1}{2} \end{cases} \quad (18)$$

$$Z_i = a_i + (b_i - a_i)x_n \quad (19)$$

First, the homogenized Logistic sequence $[y_n]$ is obtained by Formula (18), and then the initial position of the particles is obtained by using the resulting sequence in Formula (19). When the initial position of each particle is obtained by the particle population, the initial particle population is substituted into the fitness function, based on which the uniform Logistic mapping changes mentioned above are made, and the search interval is iterated and searched [17]. In this process, a particle in the original particle needs to be replaced by a mutant particle to ensure the efficiency of optimization.

5. Antenna Optimization Based on Chaotic Traversal Algorithm

5.1. Establishment of Optimized Model for Microstrip Antenna

Because rectangular patch is the most widely used patch shape, coaxial and microstrip feeds have been selected in the previous design. Considering the optimum return loss S_{11} of the antenna [18], the target function is designed at the resonance frequency $f = 2.45\text{GHz}$ as follows.

$$fit(L_1, L_2) = S_{11}(f) \quad (20)$$

For coaxially fed rectangular microstrip antennas, the input impedance is as follows.

$$Z_{in} = \frac{1}{Y_1} + jX_L \quad (21)$$

In the formula (21), Z_{in} is the input impedance of the antenna; Y_1 inputs the admittance for the feed point, X_L the antenna reactance, and the formula for calculating the input admittance is as follows.

$$Y_1 = Y_0 \left[\frac{z_0 \cos\beta L_1 + jz_w \sin\beta L_1}{z_w \cos\beta L_1 + jz_0 \sin\beta L_1} + \frac{z_0 \cos\beta L_2 + jz_w \sin\beta L_2}{z_0 \cos\beta L_2 + jz_w \sin\beta L_2}\right] \quad (22)$$

In formula (22), Y_0, Z_0 are the characteristic admittance and impedance when the antenna is considered as a transmission line, β is the phase constant of the medium, L_1 and L_2 are the feed potential locations and L_1+L_2=L_0, Y_w and Z_w are the wall admittance and impedance respectively. The calculation formulas are as follows.

$$Y_w = 0.00836\frac{w}{\lambda} + j0.01668\frac{\Delta L}{h}\varepsilon_{eff} \quad (23)$$

In formula (23), $w = 2\pi f$ is the angular frequency, ΔL is the equivalent slot width, h is the thickness of the media base, λ is the wavelength, ε_{eff} is the effective dielectric constant. The formula for calculating the reactance part is as follows.

$$X_L = \frac{377}{\sqrt{\varepsilon_r}} tan(kh) \quad (24)$$

In formula (24), $k = w\sqrt{u_0\varepsilon_0}$ is the free space phase constant and X_L is the reactance of the antenna. When the impedance is obtained from the upper formula (24), the return loss S_{11} is calculated from the impedance as follows.

$$S_{11}(L_1, L_2, f_i) = 20lg\left(\left|\frac{Z_{in} - Z_0}{Z_{in} + Z_0}\right|\right) \quad (25)$$

In formula (25), the value of Z_0 is usually 50Ω, from which return loss S_{11} can be obtained. The expression that ultimately leads to the optimization model is as follows.

$$\min_{L_1, L_2} fit(L_1, L_2) \quad (26)$$

For rectangular side-fed microstrip antennas, the input admittance is calculated by the following formula (27).

$$Y_{in}(z) = 2G\left[cos^2(Y^2) + \frac{G^2 + B^2}{Y_0^2} sin^2(\beta M) - \frac{B}{Y_0} sin(2\beta M)\right]^{-1} \quad (27)$$

In formula (27), M is the distance from the feed point to the corner of the edge of the radiation patch, Y_0 is the characteristic admittance of an antenna as a transmission line, β is the phase constant in the medium, G is the radiated conductance, B is the equivalent admittance, and it is shown as follows.

$$G = \frac{I}{120\pi^2} \tag{28}$$

In the formula above.

$$I = \int_0^{\pi} sin^2\left(\frac{kW}{2} cos\,\theta\right) tan^2\theta\, sin\,\theta\, d\theta \tag{29}$$

$$B = \frac{k\Delta L\sqrt{\varepsilon_{eff}}}{Z_0} \tag{30}$$

In formula (30), Z_0 is the characteristic impedance when an antenna is considered a transmission line. In general, $G/Y_0 \ll 1$, $B/Y_0 \ll 1$. Thus, the upper formula (27) can be reduced to the following.

$$Y_{in}(z) = \frac{2G}{cos^2(\beta z)} \tag{31}$$

In the upper formula (31), all formulas are true except $\beta z = \pi/2$. Because $Z_{in} = 1/Y_{in}$ is the same as S_{11} for coaxial feed antenna, the following formula can be obtained

$$S_{11}(M, f_i) = 20lg\left(\left|\frac{Z_{in}-Z_0}{Z_{in}+Z_0}\right|\right) \tag{32}$$

Similarly, the expression that ultimately leads to the optimization model can be simplified (33).

$$\min_{M} fit(M) \tag{33}$$

5.2. Optimized Parameter Analysis and Simulation Results of Microstrip Antenna

Formula (20) optimizes the objective function of return loss for this microstrip antenna. Parameters L_1 = 6mm~7mm, L_2=21mm~22mm, and Design L_1 have precision 4 digits after the decimal point. The learning factor is set to 2; The population number is 5, and the number of cycles stops after 50 times, resulting in an iteration chart shown in Figure 11 below. From Figure 11, it can be seen that the uniformized Logistic particle swarm algorithm has completed convergence within ten iterations, but the traditional particle swarm algorithm has a large number of iterations in the optimization process for coaxial fed rectangular microstrip antenna, and cannot converge efficiently. Finally, $L_1 = 6.5mm$, $L_2 = 21.7mm$ are obtained. The dimension parameters obtained by this optimization algorithm are re-simulated in HFSS and the echo loss curves are compared as shown in Figure 12 below and the optimized three-dimensional stereo pattern as shown in Figure 13 below.

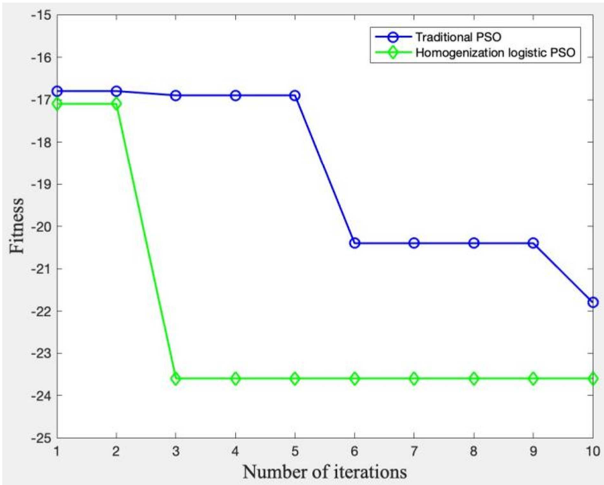

Figure 11. *Coaxial feeding fitness iteration.*

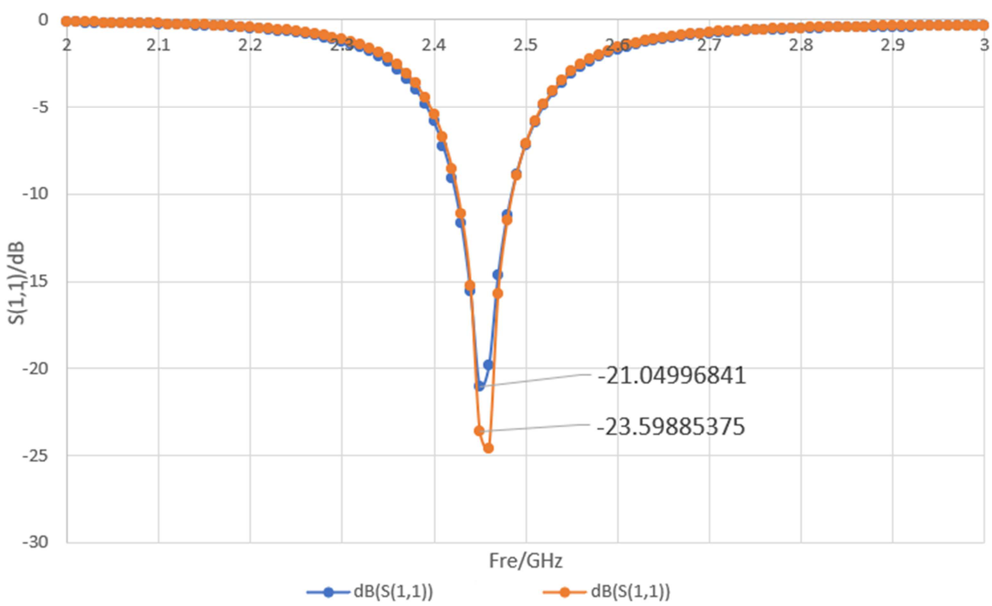

Figure 12. *Comparison Chart of Return Loss Curve of Coaxial Feed.*

Figure 12 shows that at 2.45GHz, the return loss is -21.05dB using empirical formula, and -23.59dB using particle swarm algorithm. As a result, using particle swarm algorithm with uniform Logistic mapping, the return loss at the frequency spectrum of the resonance center is lower, the impedance matching is better, and it is more suitable for engineering needs.

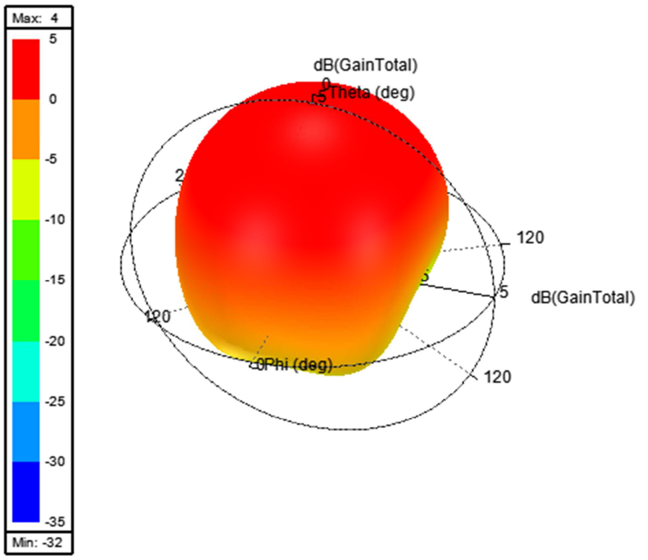

Figure 13. *Three dimensional three-dimensional pattern after coaxial feeding optimization.*

As shown in Figure 13, the gain and directivity after optimization have not been significantly improved. Compared with the size model of coaxial fed microstrip antenna calculated by empirical formula, it has 70MHz bandwidth, and it has not significantly achieved higher bandwidth after optimization. The fitness function formula (33) is the objective function of this microstrip antenna to optimize the return loss. Parameter $M = 30mm \sim 35mm$, set the algorithm parameters in the same way as the coaxial fed rectangular microstrip antenna, and finally get the iterative results as shown in Figure 14 below.

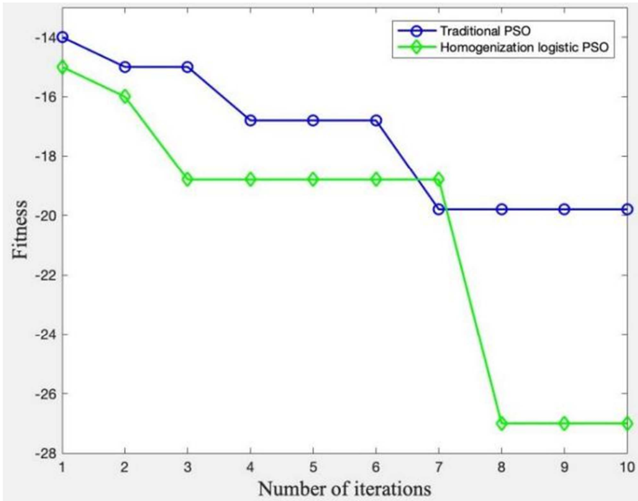

Figure 14. *Microstrip feeding fitness iteration.*

Finally, $M = 32.5mm$ is obtained, where $M_1 = 17.5mm$ and $M_2 = 15mm$. Figure 15 shows the comparison of the return loss curve of the antenna based on the size parameters obtained by this optimization algorithm, and Figure 16 shows the optimized three-dimensional pattern.

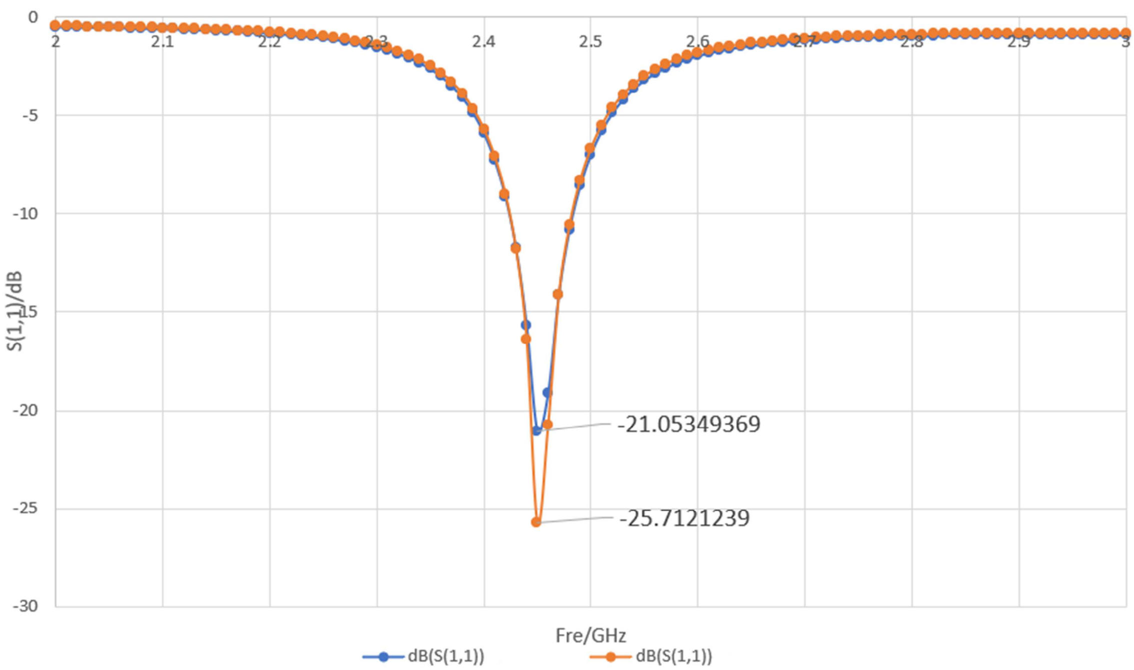

Figure 15. *Comparison Chart of Microstrip Feed Return Loss Curve.*

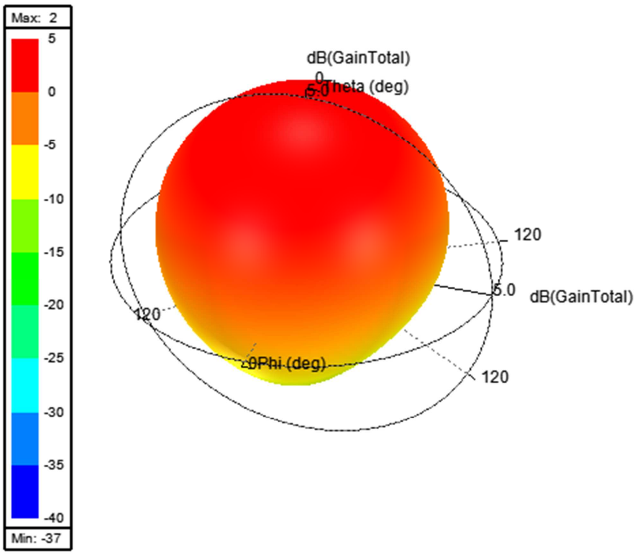

Figure 16. *3D Stereo Pattern after Microstrip Feeding Optimization.*

Figure 15 shows that at the resonant frequency of 2.45GHz, the return loss obtained by empirical formula is -21.05dB, while the return loss obtained by particle swarm optimization algorithm is -25.71dB, instead of - 27.15dB obtained by algorithm iteration. This is because the input admittance function selected for microstrip fed rectangular microstrip antenna in this paper is simplified, so the iteration result is slightly different from the HFSS simulation result. Therefore, the results obtained by using the particle swarm optimization algorithm with homogenized logistic mapping can not only accurately search the central resonant frequency, but also ensure lower return loss value, which can better meet the design requirements and engineering needs of the antenna.

Figure 16 shows that the performance of the optimized gain, directivity and bandwidth has not been greatly improved. It can be seen that the particle swarm optimization algorithm with homogenized logistic mapping has significantly improved the optimization of the antenna in terms of return loss, but has not significantly improved the performance not involved in the fitness function.

6. Conclusion

In this paper, in view of the shortcomings of the current empirical methods of antenna design, such as unsatisfactory return loss, long time consumption and low efficiency, a particle swarm optimization algorithm based on uniform logistic mapping is proposed to study the design of rectangular microstrip broadband antenna under two feeding modes. This algorithm can effectively improve the efficiency of antenna optimization. In this paper, the Logistic map is selected in the chaotic map, and a homogenized Logistic method is proposed for derivation and analysis. It is concluded that this homogenized Logistic method can reflect the characteristics of uniform distribution of data. Then we combine this chaotic map with the traditional particle swarm optimization algorithm, and get a particle swarm optimization algorithm based on the uniform logistic map, and design and implement this algorithm. The simulation results show that the particle swarm optimization algorithm based on homogenized chaotic map can obtain better impedance matching degree than the traditional antenna model, and can converge more efficiently during optimization, greatly reducing the time consumption of the optimization process, and significantly improving the optimization efficiency.

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