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A NOVEL CONFORMAL END-FIRE ANTENNA DESIGN USING THE COMPETITIVE ALGORITHM OF SIMULATING NATURAL TREE GROWTH

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Abstract—This paper presents a novel conformal end-fire antenna whose design employs the Competitive Algorithm of Simulating Natural Tree Growth. This algorithm is based on the idea of simulating the processes of growth and wilting of natural trees and can search from simple to complicated structures with rapid convergence. Four optimized radiation elements were designed on a cross structure to verify the performance of the algorithm. A prototype of the designed antenna was also fabricated and tested. The antenna resonates at the center frequency of 2.45 GHz, exhibiting an ideal end-fire property. In addition, the measured and simulated results are in good agreement. Finally, we propose a novel end-fire antenna array based on the cross structure, with a radiation gain reaching 17.6 dBi.

1. INTRODUCTION

In recent years, conformal antennas have found good potential for applications in aircrafts, satellites, and land vehicles due to their advantages of light weight, low profile, low cost, excellent aerodynamic characteristics, and simple manufacturing process requirements [1–6]. Meanwhile, end-fire antennas also play important parts in the domains mentioned above [7–9]. As separate applications, conformal antennas [10–12] and end-fire antennas [13, 14] have been discussed frequently; however, studies on conformal end-fire antennas are rare.

In this paper, we adopt a new Competitive Algorithm of Simulating Natural Tree Growth to design a conformal end-fire antenna confined to a cross structure, which usually appears in aerospace vehicles. Nowadays, there are many optimization algorithms used in

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antenna design, such as Genetic Algorithm [10, 15, 16], Particle Swarm Optimization Algorithm [11, 17], Differential Evolution Algorithm [18], and so on. However, these algorithms can only optimize some antenna structure parameters given by designers in advance. In comparison, the algorithm in the current paper can generate antenna structures by itself, which is more convenient to designers, and it has shown advantages in terms of mathematical curve fitting [19], ability to solve transcendental equations [20] and the use of automated line antenna design [21–23]. A novel antenna based on the Competitive Algorithm of Simulating Natural Tree Growth is presented in this paper. The proposed design can satisfy the end-fire property without using any other measures, such as phased array, using stereo reflex plate [23], and so on. In addition, it is confined to the ideal cross structure, thus having the advantages of being easy to assemble and having a light weight.

2. THE COMPETITIVE ALGORITHM OF SIMULATING NATURAL TREE GROWTH

Simulating the growth of a natural tree is a complicated process. To simplify the procedure, the algorithm only considers the growth and wilting of the branches. In order to grow, a natural tree must absorb sunlight and obtain nutrition from the soil. The branches located in the top of a natural tree can absorb sunlight well, but they cannot obtain nutrition properly due to their distance from the roots of the tree. On the contrary, the branches located at the bottom of a natural tree can obtain nutrition properly, but they cannot absorb sunlight that well because of the shading provided by other branches. Thus, the final shape of a natural tree is a result of how the tree has adapted to its environment. The processes of growth and wilting embody conflict and reunification. A natural tree can be considered as an antenna that receives enough electromagnetic waves to perform photosynthesis. Thus, the Competitive Algorithm of Simulating Natural Tree Growth can be naturally extended to design antennas. In consideration of the above description, the growth of a tree is controlled by three factors, namely, sunlight fitness, nutrition factor, and shading factor.

2.1. Definition 1 Sunlight Fitness

Sunlight fitness can be expressed as:

$$\eta = A_1 \cdot Abs(180 - \theta)/9 + A_2 \cdot Gain + A_3 \cdot BW + A_4 \cdot Ratio \qquad (1)$$

where θ is the angle of the main lobe of the antenna, which is expected to be zero because of the required end-fire property; *Gain* is the end-fire gain when the antenna works at the frequency of 2.45 GHz; BW and $Ratio$ are the relative impedance bandwidth and front-to-back ratio, respectively. The value of θ is in degree and those of $Gain$ and $Ratio$ are in dBi. In addition, A_1, A_2, A_3 and A_4 are weights, because an ideal end-fire property is required, and of these, A_1 is the most important. In this paper, they were set to 0.15, 0.05, 0.02 and 0.05, respectively.

2.2. Definition 2 Nutrition Factor

Nutrition factor can be expressed as:

$$\alpha_i = \exp\left(-c \cdot \sum_{i=0}^{n} l_i\right) \tag{2}$$

where n is the total amount of branches connecting the ith branches to the trunk; l_i is the length of the ith branch; $i = 0$ responds to the trunk; and c is a coefficient chosen by experience, which can adjust the nutrition factor α_i. This was set to 0.95 in this paper.

2.3. Definition 3 Shading Factor

Shading factor can be expressed as:

$$\beta_i = \left(1 - \frac{R_i}{R_{\max}}\right) \cdot \left(1 - \frac{Z_i}{Z_{\max}}\right) \tag{3}$$

where β_i is the shading factor of the ith branch; R_i is the horizontal distance from the ith branch to the trunk; Z_i is the height of the ith branch; and $R_{\max}$ and $Z_{\max}$ are the maximum distance and maximum height, respectively, for all branches of a natural tree. The smaller values of R_i and Z_i, the bigger the value of β_i, which is in accordance with the natural law. Specifically, the branches in the inner layers are easily shaded compared with those in the outer layers; thus, the outermost branches grow more easily.

The sunlight fitness may increase by adjusting the structural parameters of the branches, such as the angle of growth and the length, among others. For a branch, the angle of growth may be chosen by the program, and the length is controlled by nutrition factor and shading factor. Thus, the growth formula of the ith branch can be described as:

$$b_i^{t+1} = b_i^t + D \cdot \alpha_i \cdot (1 - \beta_i) \cdot \lambda \tag{4}$$

where α_i and β_i are the nutrition and shading factors, respectively; t is the generation of the tree, and the total generations are given by program; λ is a coefficient chosen by experience and set to 0.9 in this paper; b_i^t is the length of the ith branch; and η^t is the sunlight fitness of the tth generation. If $\eta^{t+1} > \eta^t$, the branch has an increment, meanwhile, $D = 1$. On the contrary, it explores in the reverse direction and $D = -1$.

The branches may wilt because of the lack of sunlight and nutrition. The condition of wilting can be described as:

$$\alpha_i < k_1 \quad \text{or} \quad \beta_i > k_2 \tag{5}$$

where k_1 and k_2 are the nutrition and shading threshold, respectively. Their values can be chosen by experience. In this paper, they were set to 0.05 and 0.95, respectively. Although the wilting of branches may reduce the sunlight fitness temporarily, as a whole, it is favorable for growth instead of sinking into local maximum.

The whole flow chart of the Competitive Algorithm of Simulating Natural Tree Growth is shown in Figure 1.

3. AUTOMATED DESIGN OF CONFORMAL END-FIRE ANTENNA

3.1. Design Procedure

The system of the automated design of conformal end-fire antenna consists of the master and slave processes. The master process realized

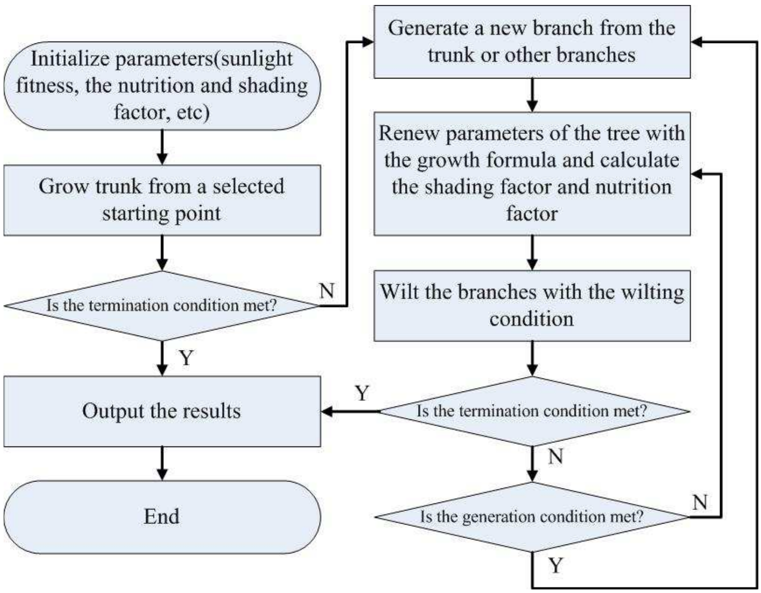


Figure 1. The flow chart of the Competitive Algorithm of Simulating Natural Tree Growth.

by Visual C++ accomplishes the growth and wilting of the tree using the Competitive Algorithm of Simulating Natural Tree Growth. The slave process realized by Visual Basic calls the numerical calculation program of Finite Difference Time Domain (FDTD) and calculates the sunlight fitness to be returned to the master process.

3.2. Antenna Configuration

The optimized tree configuration is shown in Figure 2. There were 7 branches in all, and the width of the branch W_2 was 1.3 mm. Since the antenna was fed by a 50 Ω coaxial line, the value of W_1 was set to 2.7 mm. The trunk was considered a microstrip transmission line and consisted of two segments, i.e., one with length of L_2 and width of W_1, and another with length of L_1 and width tapered from W_1 to W_2. L_1 and L_2 were set to 15 and 5 mm, respectively. As shown in Figure 2, the radiation elements were placed on a substrate with a size of $W \times L$, and the size of ground was $(L_1 + L_2) \times L$. L and W were set at 175 and

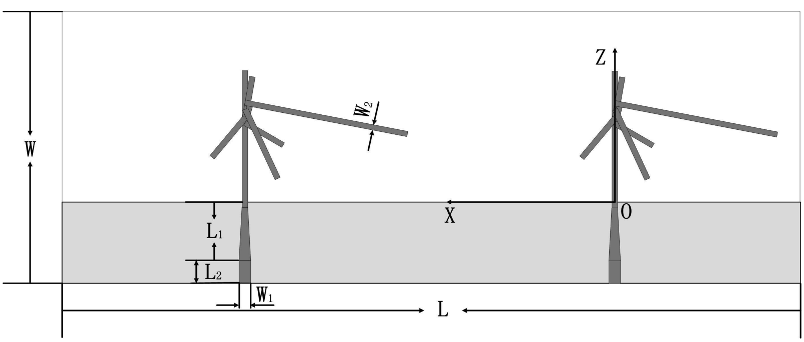


Figure 2. The geometry of the tree antenna.

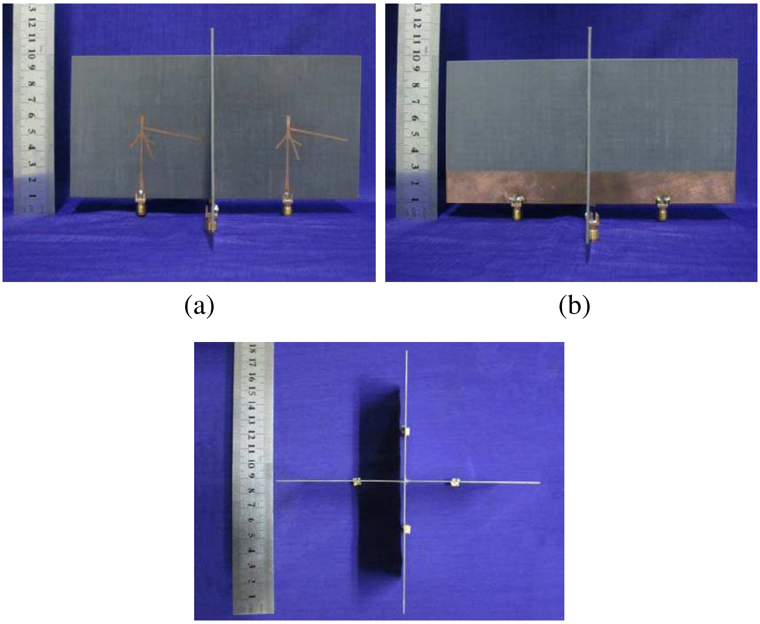
Table 1. The coordinate values of branches (unit: mm).

No.	Start Point (x, z)	End Point (x, z)
1	(0.0, 0.0)	(0.0, 30.94)
2	(0.0, 18.23)	(−0.84, 30.17)
3	(0.0, 18.12)	(−0.46, 21.86)
4	(−0.02, 18.52)	(−8.37, 12.8)
5	(0.0, 23.24)	(−36.73, 16.12)
6	(0.0, 19.79)	(6.76, 10.9)
7	(−0.41, 21.43)	(−6.86, 4.26)

87.5 mm, respectively. Since a cross structure is required, four of the same elements were printed on a cross printed circuit board (PCB). As shown in Figure 2, in order to make resultant field of end-fire maximum and shorten the runtime of the program, both radiation elements have the same planar orientation and the same shape. The whole antenna configuration can be described as having two parts, namely, the part shown in Figure 2 and its replica, which rotates 90 degrees around the central axis of itself. The coordinate values of branches are shown in Table 1.

4. RESULTS AND DISCUSSION

To validate the theoretical design, a prototype of the antenna was fabricated. Its structure is shown in Figure 3. The radiation elements were printed on a PCB whose relative dielectric constant and thickness were 2.65 and 1 mm, respectively. In addition, a four-way microstrip Wilkinson power divider (MWPD), as shown in Figure 4, was designed and fabricated to excite four ports of the whole antenna.



(a) (b)

(c)

Figure 3. Photographs of the antenna: (a) front view of the antenna, (b) left view of the antenna, (c) top view of the antenna.

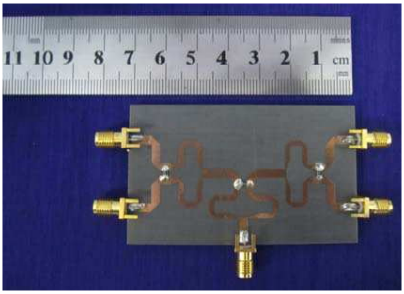


Figure 4. A four-way MWPD.

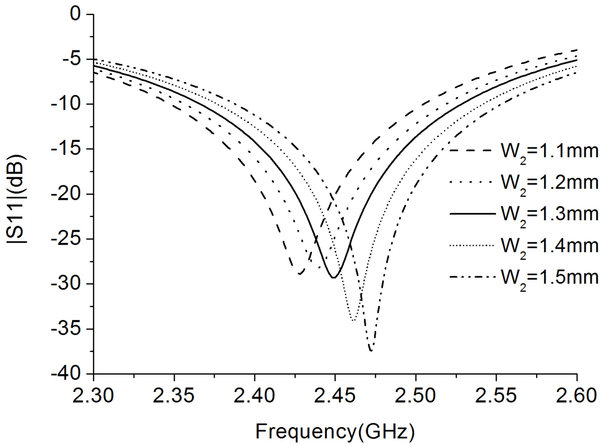


Figure 5. Simulated $|S_{11}|$ with different values of W_2.

The resonant frequency of the proposed antenna changes slightly with the alteration of the width of W_2, hence, we considered W_2 as a parameter to be optimized in the algorithm. The optimization process is shown in Figure 5. As W_2 changes from 1.1 to 1.5 mm, the resonant frequency increases from 2.43 to 2.47 GHz. Since the proposed antenna must resonate at the center frequency of 2.45 GHz, the optimized value of W_2 set to 1.3 mm.

The input reflection coefficient of the fabricated conformal end-fire antenna was measured using an Agilent E8362B Network Analyzer. Figure 6 compares the simulated and measured results. The measured result shows that the proposed antenna resonates at the center frequency of 2.45 GHz, which is same as the simulated result. The

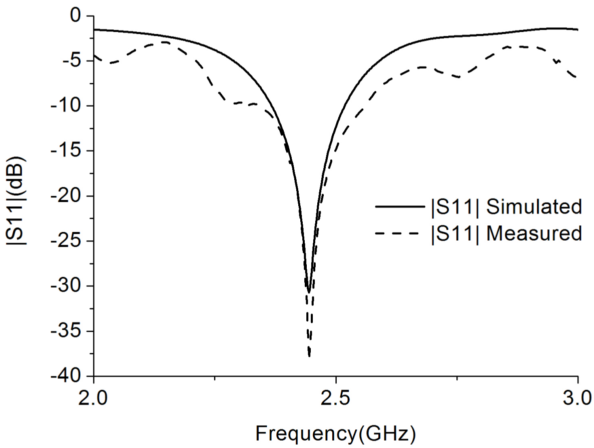


Figure 6. Simulated and measured $|S_{11}|$ of the proposed antenna.

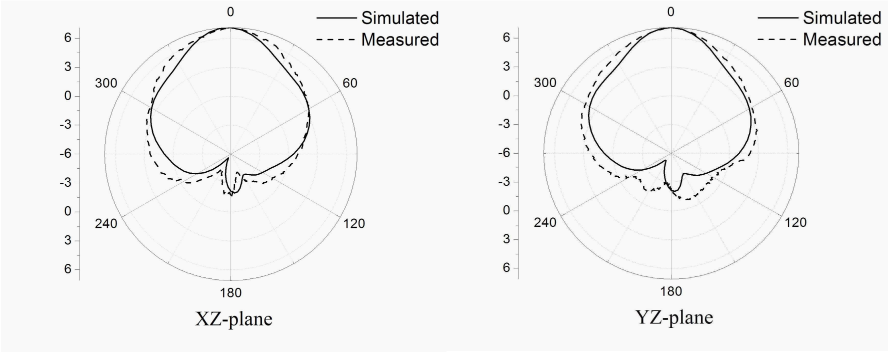


Figure 7. Radiation patterns of the proposed antenna at 2.45 GHz.

measured relative impedance bandwidth for $|S_{11}| < -10\,\text{dB}$ is about 10.2%, covering a frequency range from 2.31 to 2.56 GHz. Meanwhile, the corresponding simulated relative impedance bandwidth for $|S_{11}| < -10\,\text{dB}$ is about 6.1%, covering a frequency range from 2.37 to 2.52 GHz. As can be seen, the measured result agrees well with the simulated one.

Figure 7 shows the simulated and measured radiation patterns at the frequency of 2.45 GHz for the proposed antenna. As can be seen, both sets of patterns are in good agreement with each other.

The proposed antenna exhibits a typical end-fire property without any shifting of the direction of main lobe, which can be attributed to the effect of the Competitive Algorithm of Simulating Natural Tree Growth. The radiation gain of the antenna reaches 7.11 dBi (with efficiency greater than 95%), and the front-to-back ratio is better than 10 dBi at the resonant frequency. As shown in Figure 7, the measured −3 dB bandwidth is broader than the simulated one, which may be caused by slight bending of the fabricated cross structure.

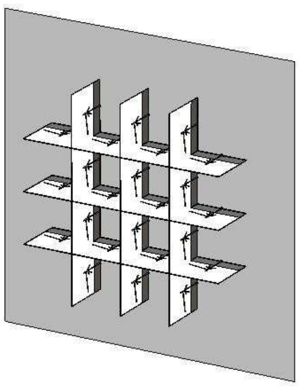


Figure 8. Structure of the antenna array.

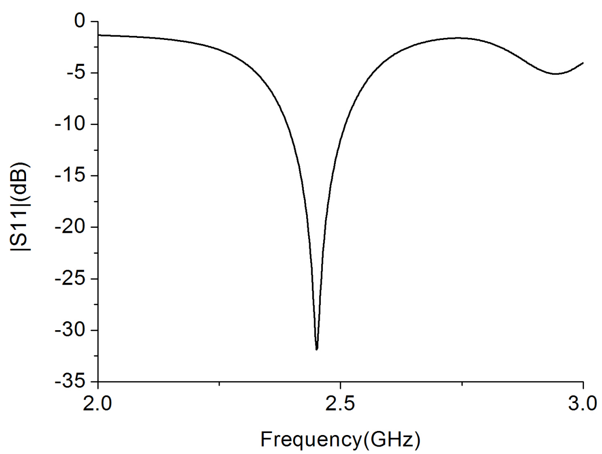


Figure 9. Simulated $|S_{11}|$ of the antenna array.

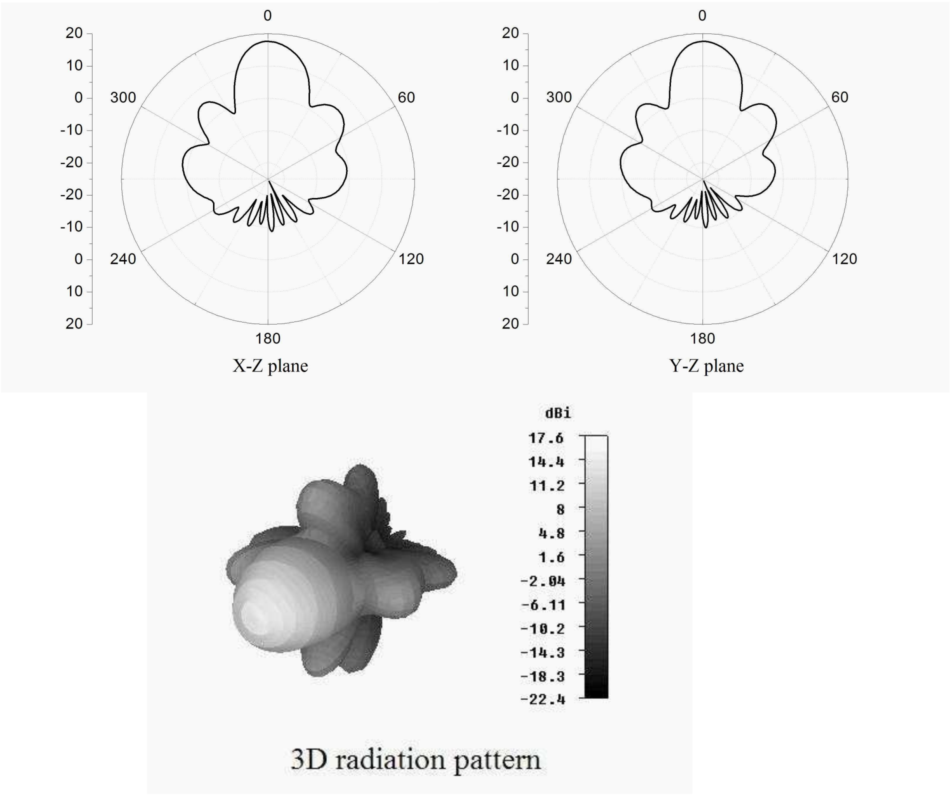


Figure 10. Radiation patterns of the antenna array at 2.45 GHz.

Considering the limited radiation gain of the antenna, which consists of four radiating elements, we propose a novel array structure shown in Figure 8. The antenna array consists of 24 radiating elements and utilizes uniform excitation feed. The simulated input reflection coefficient is presented in Figure 9. The antenna array resonates at the center frequency of 2.45 GHz and has a relative impedance bandwidth of 4.9% ranging from 2.39 to 2.51 GHz for $|S_{11}| < -10\,\mathrm{dB}$. In order to lower back lobe, we adopted a square metal reflector. Figure 10 shows the radiation pattern. The radiation gain of the antenna array reaches 17.6 dBi, and the front-to-back ratio is better than 27 dBi. The simulated $-3\,\mathrm{dB}$ beamwidth of the antenna array is less than that of the antenna with cross structure; moreover, the antenna array also shows a typical end-fire property.

5. CONCLUSION

A novel conformal end-fire antenna based on the Competitive Algorithm of Simulating Natural Tree Growth is proposed in this paper. The algorithm is adopted to design conformal antenna for the first time. The proposed antenna resonates at the center frequency of 2.45 GHz and has a relative impedance bandwidth of 10.2% ranging from 2.31 to 2.56 GHz for $|S_{11}| < -10$ dB. The antenna also shows a typical end-fire property, with radiation gain reaching 7.11 dBi. With relatively small quantities of antenna simulations, the proposed antenna satisfies the design requirements, demonstrating the high efficiency of the algorithm in designing antennas. We also propose a novel antenna array with the end-fire property, which is based on the cross structure. The radiation gain of the array can reach 17.6 dBi, and the front-to-back ratio is better than 27 dBi.

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