Design of coding metasurface based on particle swarm optimization algorithm

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Abstract

In this paper, a convenient method called particle swarm optimization algorithm (PSO) is proposed for achieving the diffusion reflection of electromagnetic waves for the metasurface, which can redirect electromagnetic energies to more directions through optimizing the reflected phase arrangement. Far field scattering pattern of the metasurface can be quickly and accurately synthetized by Array Pattern Synthesis(APS) together with Matlab software. As a comparison and verification, full-wave simulation of the metasurface is also inducted in CST. The far field result of this method is in good agreement with the corresponding CST simulation result. The research results has certain engineering value in radar cross section(RCS) reduction of coding metasurface.

Keywords

PSO,Coding,Metasurface,RCS.

1. Introduction

A Metamaterials are composite materials with periodic or unperiodic structures and specific electromagnetic properties that are processed or synthesized by artificial way. In 2014, the team of the National Key Laboratory of Millimeter Waves of Southeast University first proposed the concept of “coding metasurface”, which was composed of a meta-material unit structure with stable phase difference in a certain arrangement. The proposed metasurface design makes the design process of the metasurface simpler. The 1 bit coded metasurface consists of two cell structures with reflection phases of 0° and 180°, representing the digital states "0" and "1" respectively. The phases of the 2-bit unit structure are 0°, 90°, 180°, and 270° respectively, and the corresponding digital states are “00”, “01”, “10”, and “11” respectively. Furthermore, the coding metasurface can be expanded to 3 bits and multiple bits.

In 2014， Southeast University designed 1bit and 2bit coding metasurface based on the patch structure, and achieved RCS reduction during the 7.8~12GHz and 7.5~15GHz respectively[1]. The literature [2-7] focus on the coding metasurface design with polarization insensitivity and wide incident angle characteristics, and achieves broadband RCS reduction more than 10dB .

2. Concept of Coding Metasurface

It is assumed that the surface is composed of N×N array elements, the period of the array elements is D, each array element is composed of a basic unit structure of “0” or “1”, and the distribution of “0” and “1” on the surface is random. We assume that the reflection phase of the (m, n)th array element is φ(m,n), then the phase value is 0° or 180° according to the principle of the 1-bit coding metasurface.

When a plane wave is incident perpendicularly, the far-field scattering of the metasurface can be expressed as[1]:

$$f(\theta,\varphi) = f_e(\theta,\varphi)\sum_{m=1}^{N}\sum_{n=1}^{N}\exp\{-i\{\varphi(\mathrm{m,n}) + KD\sin\theta[(m-\frac{1}{2})\cos\varphi + (\mathrm{n}-\frac{1}{2})\sin\varphi]\}\} \quad (1)$$

Where θ and φ are the elevation and azimuth angles repectively, and $f_e(\theta, \varphi)$ is the scattering pattern of the array elements. As shown in Fig.1, there are 4 different far-field pattern with 4 different phase arrangements, which means that the EM waves of metasurface can be controlled by changing the distribution of phase.

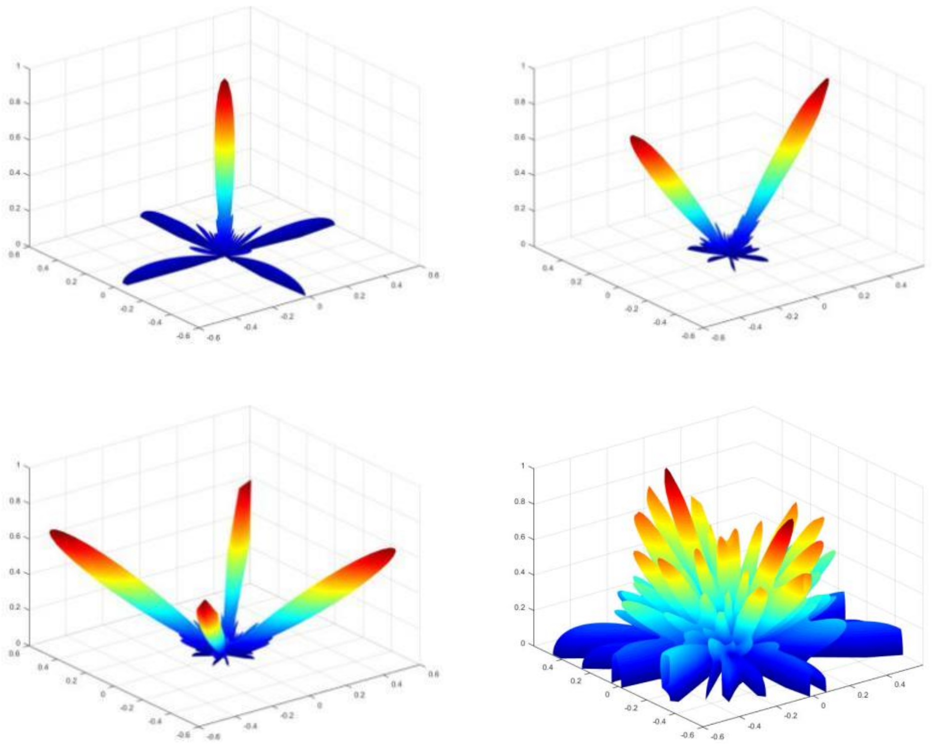

Fig.1 Far-field pattern of 4 different coding sequences

3. Particle Swarm Optimization

The PSO algorithm is an intelligent optimization algorithm proposed by Kenndey and Eberhart in 1995[8]. The algorithm simulates the process of the bird group searching for surrounding food. In the PSO algorithm, each particle can be regarded as an individual, and the optimal solution is found through cooperation between individuals and sharing information. As a global search method, PSO is widely used in the optimization of various electromagnetic problems due to its simple principle, few parameters and fast convergence. A potential solution can be thought as a particle whose mathematical fomula of the velocity and location of next-generation particle can be described as[8] :

$$v_j^i = w * v_j^i + c_1 * rand(0,1) * (pbest_j^i - x_j^i) + \mathrm{c}_2 * rand(0,1) * (gbest_j^i - x_j^i) \quad (2)$$

Where $pbest_j^i$ and $gbest_j^i$ represent the optimal location of the individual particle and the global optimal location respectively. The function $rand(0,1)$ is a random number between 0 and 1, c_1 and c_2 are called learning factors or acceleration factors, usually taking a value of 2 according to past experience. And w means the inertia weight.Previous studies have proved that the result of algorithm obtained by using the time-dependent weight factor is ordinarily better than the weight factor of the fixed value. The commonly used weight factor mathematical expression is:

$$w(k) = w_{\max} - (w_{\max} - w_{\min})k / N_{iter} \quad (3)$$

Where N_{iter} is the maximum number of iterations of the algorithm, and $w_{\max}$ and $w_{\min}$ are usually set to 0.9 and 0.4 respectively.

4. Algorithm Analysis

In order to achieve the best performance of the metasurface, the Particle Swarm Optimization (PSO) algorithm is combined with Array Pattern Synthesis (APS) to obtain the best phase arrangement. The flow chart of the APS-PSO algorithm is shown in Figure 2, in which two modules have been utilized together to design the phase arrangement of the metasurface. The PSO module evaluates the fitness in each iteration, updates the particle velocity and population location which is the desired phase arrangement, and then sends the information to the APS module. We use Matlab to complete the design of the algorithm. The population particle position(i.e. our phase arrangement)can be regarded as a random matrix (only 0 and 1), and the speed is also the same. The fitness function can be set to:

$$fitness = f(\theta, \varphi) \quad (4)$$

The APS module calculates the current RCS value according to the current phase arrangement, then calculates the fitness function value and returns to the PSO module. After a number of iterations, we can get the best phase arrangement of the minimum RCS required for the meta surface. The core of this flow chart is that the PSO module generates various phase arrangement combinations of coding metasurfaces, and its performance is judged by the APS module to find the best solution.

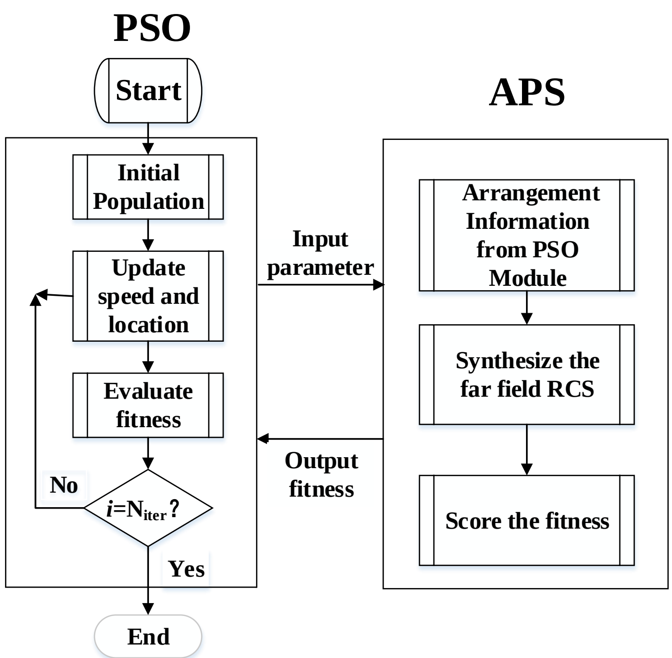

Fig.2 The flowchart of algorithem

The population used in the PSO module and the number of iterations are set to 100 and 500 respectively. The metasurface cell structure has an initial value of 0 or 1 corresponding to 0 or π. The fitness function curve obtained by using Matlab for numerical optimization is shown in Figure 3. It can be seen that the curve decreases rapidly in the initial stage and then tends to be stable, indicating that the APS-PSO algorithm has high efficiency. The optimization result is shown in Fig.4. The theoretical prediction of the far field pattern of the RCS is shown in Fig. 5. The diffusion scattering pattern means that scattered fields are suppressed in all directions, so that bistatic RCS can be greatly reduced. This result provides a feasible way for wideband diffusion of EM waves.

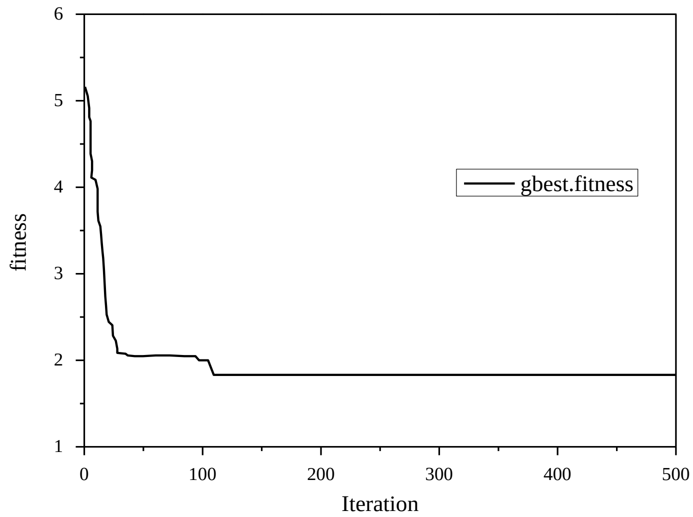

Fig.3 Adaptive evolution curve

0	1	1	1	0	1	0	0	1	0
0	1	0	1	0	0	1	1	1	1
1	0	0	1	1	0	0	0	1	1
0	1	0	1	1	0	0	0	1	1
1	1	0	0	0	0	0	0	0	1
1	1	0	1	1	1	1	1	1	0
1	1	0	0	1	0	0	1	0	1
0	0	1	1	0	1	1	1	0	1
0	0	0	1	1	0	0	0	1	0
0	1	1	0	0	0	1	1	0	1

Fig.4 Optimal coding consequence

5. Conclusion

Firstly, based on the basic principle of coding metasurface, it is proved that different coding sequences can obtain different far-field characteristics. Then, particle swarm optimization algorithm is proposed to optimize the reflection phase distribution of metasurface, so as to complete the construction of coding metasurface. Furthermore, the far-field scattering pattern of metasurface is obtained by theoretical numerical calculation with Matlab. In order to verify the reliability of the algorithm, full-wave simulation of the metasurface is carried out in CST, and the results are basically consistent with those in matlab.

Acknowledgements

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