Research on structural design of digital coding metasurfaces based on FDTD and genetic optimization algorithm

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ABSTRACT

The digital coding metasurfaces has the advantages of powerful Manipulations of electromagnetic wave and easy to machine. It has good application prospects in high-performance antennas and reducing radar cross section. However, there are very few studies on the design method of the structure of digital coding metasurface. A method combining Finite-Difference Time-Domain (FDTD) and genetic optimization algorithm (GA) is proposed in this paper, which can automatically realize the structure design of the coding metasurface through programming. Based on the phase response of periodic unit of the digital coding metasurface, a digital coding metasurface with periodic coding sequence 0101…./1010…. is produced. The correctness of the optimized design method proposed in this paper is verified by Computer Simulation Technology (CST) simulation and experiment. It provides important theoretical support for the design of digital coding metasurfaces in the future.

Keywords: FDTD, GA, optimal design, digital coding metasurfaces, manipulations of electromagnetic waves

1. INTRODUCTION

Digitally coding metasurfaces are first proposed by Professor Cui Tiejun of Southeast University in 2014[1], and the main idea of digitally coding metasurfaces is to use the logical numbers “0” and “1” to represent units with phases of 00 and 1800, respectively. By arranging the sequence of “0” and “1” cells, two- beam and four-beam as well as multi-beam reflection or transmission are realized, then the control of electromagnetic waves is realized. Later, Professor Cui’s research group proposed to use Field-Programmable Gate Array to control the coding sequence of the digital coding metasurface in real time, and then change the regulation function of the metasurface. For the phased array antenna, the phase-shifting network is avoided, which greatly reduces the complexity and cost of the system[2,3]. At the same time, Professor Cui’s research group also introduced the discrete convolution theorem and information entropy, and proposed the concept of spatiotemporal coding[4-12]. Professor Li of Peking University has realized dynamic holographic imaging of metasurfaces using loaded diodes[13].

At present, the research on digitally coding metasurfaces has been extended from the microwave band to the terahertz band[14], from isotropic to anisotropic[15], and from reflective to transmissive[16], all of which imply that coding metasurfaces have a good development prospect in regulating electromagnetic waves.

With the continuous promotion of digitally encoding metasurfaces, the research on the optimal design methods of their structural elements is particularly important. At present, there is very little literature on the design methods of coding metasurface structural elements. In this paper, the phase difference of the two structural units is 180° as the optimization goal, and the hybrid method of FDTD and GA optimization algorithm is used to automatically realize the structural design of the encoding metasurface through programming. At the same time, the encoding metasurfaces of 0101....and 1010.... periodic units are fabricated to realize two-beam and four-beam reflection, and the effectiveness and correctness of the proposed design method are verified by CST simulation and experiments.

2. HYBRID OPTIMIZATION ALGORITHMS OF FDTD AND GA

In this paper, a 1-bit digitally coding metasurface unit is taken as an example. The logical number “0” is used to

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International Conference on Optics, Electronics, and Communication Engineering (OECE 2024), edited by Yang Yue, Proc. of SPIE Vol. 13395, 1339544 · © 2024 SPIE · 0277-786X · Published under a Creative Commons Attribution CC-BY 3.0 License · doi: 10.1117/12.3048547

represent the unit with phase response of 0°, and the logical number "1" is used to represent the unit with phase response of 180°. The main idea of the design of the 1-bit digitally coding metasurface element structure is to optimize the phase difference of the two elements with a phase difference of 180°. Therefore, the calculation of the phase of the periodic element is a key step in the optimal design of the structure of the digital coding element.

For the calculation of the phase of the periodic unit, the FDTD algorithm with fast calculation speed and less computer memory is used to calculate the phase. The FDTD algorithm is first proposed in 1966 by K.S. Yee. The basic principle is to use the idea of central difference to discretize Maxwell's equations in space and time.

To calculate the phase of the periodic element, the first step is to establish the calculation model of the periodic element.

2.1 The phase calculation by FDTD

2.1.1 Establishment of a calculation model of period unit. Due to the infinite size of the periodic unit, computation of an entire area can take up a lot of the computer's memory, slowing down the calculation speed. In order to deal with this problem, Floquet's theorem is introduced, that is, the electromagsnetic property distribution of the entire array structure can be obtained by calculating the electromagnetic properties of only one element. Therefore, for a single calculation model, it is only necessary to add periodic boundary conditions to a single computational model and add absorption boundary conditions on the upper and lower bottom surfaces, as shown in Figure 1, which is a 3D structural calculation model of periodic element.

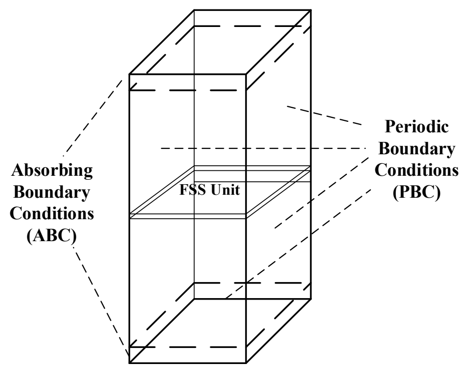

Figure 1. Calculation model of 3-D periodic structure.

If the period of FSS along the x-axis and y-axis are P_x and P_y respectively, then taking the electric field E as an example, it satisfies the following equation in the frequency domain.

$$E(x=0, y, z, w) = E(x=P_x, y, z, w) \times e^{jk_x P_x} \tag{1}$$

where, K_x is the propagation constant in the x-direction.

At present, the commonly used methods to achieve absorption boundary conditions mainly include perfectly matched absorption layer (PML), convolutional perfectly matched layer (CPML) and anisotropic perfectly matched layer (UPML). CPML is an improved method based on PML, and whether the calculation result converges is closely related to the set parameters, in addition, the above parameter range is only applicable to individual special cases, and a larger range of adjustment coefficients is required to meet the boundary absorption condition in the actual calculation process, which is not conducive to the rapid calculation of the results. Therefore, the UPML absorption boundary condition is used in this paper.

2.1.2 Calculation of electromagnetic characteristics. Since the electromagnetic wave propagates along the excitation loading surface and the upper and lower sides, in order to calculate the phase of the periodic element, it is necessary to set the reflection sampling surface and the transmission sampling surface respectively above and below the periodic element structure, and the schematic diagram of the calculation model is shown in Figure 2.

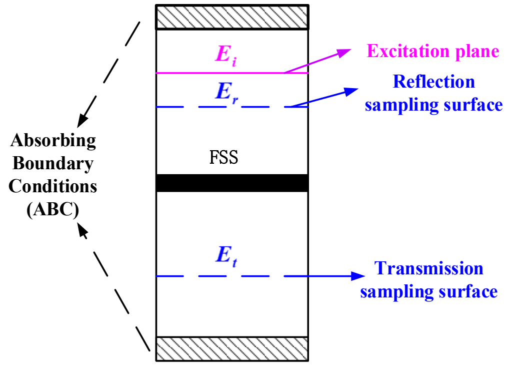

Figure 2. Calculation model.

Therefore, the phase expression for the periodic element is shown in equation (2).

$$Phase = \frac{180}{\pi} \times angle(\frac{R\_Et}{Inc\_Et}) \quad (2)$$

where, R_Et is the total field calculated by the reflection sampling surface; Inc_Et is the incident electric field.

2.2 Optimization algorithm of FDTD and GA

The phase of a single periodic element can be calculated by the FDTD algorithm, and on this basis, the structural size of the periodic element can be optimized by using GA. Genetic algorithm is a population search technology, which regards the population as a set of problem solutions, generates a new population through selection, crossover and mutation of the current population, and gradually evolves the population to a state containing the optimal solution. The crossover probability p_c of the genetic algorithm is generally 0.25-1.00, the mutation probability P_m is 0.001-0.1, and the number of iterations G is between 100-1000.

The optimization objectives in design are:

$$Fitness = \min \left| |P_1 - P_2| - 180 \right| \quad (3)$$

where P_1 is the phase of the first element structure; P_2 is the phase of the second cell structure. The flowchart of hybrid algorithm of the FDTD and GA is shown in Figure 3:

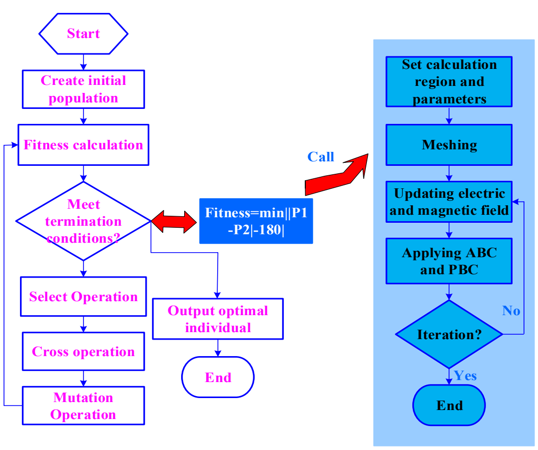

Figure 3. Calculation flow chart of hybrid algorithm.

3. OPTIMIZED DESIGN OF DIGITALLY CODING METASURFACE ELEMENTS

In this paper, a hybrid algorithm of FDTD and GA optimization is used to automatically realize the optimal design of the digitally coding metasurface element structure through MATLAB programming.

In the design process, two structural units with different metal patch phase difference of 180° are represented by "0" and "1", the thickness *h* of the dielectric plate of the two structural units is 1.964 mm, the dielectric constant is 2.65, and the tangent value of the loss angle is 0.001, and the metal patch is square and round, and the structural unit is shown in Figure 4, and the cycle length of the element is 5 mm.

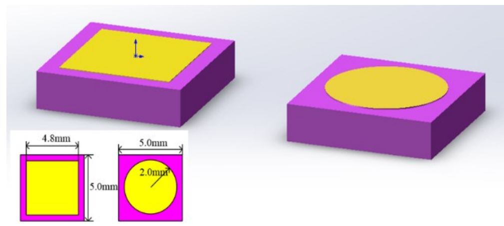

Figure 4. Structure of element.

The fitness evolution curve after 100 iterations is shown in Figure 5. After the iterative calculation, the width of the square patch *W*=4.8 mm and the radius of the circular patch are 2 mm. The phase results of the two structural elements after automatic optimization are shown in Figure 6.

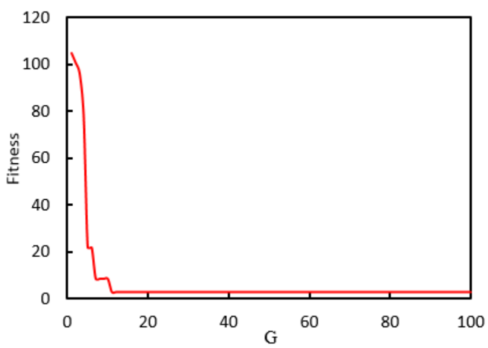

Figure 5. Evolution curve of fitness.

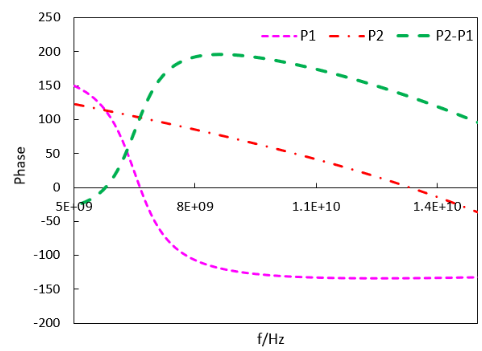

Figure 6. Frequency response curve.

As can be seen from Figure 6, the phase difference between the two structural units is 150°-200° in the frequency range from *f*=7 GHz to *f*=12 GHz, which satisfies the function of digital coding metasurfaces.

4. DIGITALLY ENCODING METASURFACES FOR BEAMFORMING

Digitally encoding metasurfaces, each raster consists of a "0" element and a "1" element with a phase difference of 180°. From the expression of the vertical far-field, the far-field expressions in the sequence of 01010101 and 01100110 can be obtained[2]:

$$|f_1(\theta,\varphi)| = C_2 |\sin\phi_1 + \sin\phi_2| = 2C_2 \left|\sin\frac{\phi_1+\phi_2}{2}\cos\frac{\phi_1-\phi_2}{2}\right| \tag{4}$$

$$|f_2(\theta,\varphi)| = C_3 |\sin\phi_1 + \sin\phi_2| = 2C_3 \left|\sin\frac{\phi_1+\phi_2}{2}\cos\frac{\phi_1-\phi_2}{2}\right| \tag{5}$$

where,

$$\begin{cases} \phi_1 = 0.5kD(\sin\theta\cos\varphi + \sin\theta\sin\varphi) \\ \phi_2 = 0.5kD(-\sin\theta\cos\varphi + \sin\theta\sin\varphi) \end{cases}$$

when the coding sequence is 010101, there are:

$$\begin{cases} \sin\dfrac{\phi_1+\phi_2}{2}=1 \\ \cos\dfrac{\phi_1-\phi_2}{2}=1 \end{cases} \tag{6}$$

It is calculated that φ is 90° and 270°, i.e. two beams are generated.

when the coding sequence is 01100110, there are:

$$\begin{cases} \sin\dfrac{\phi_1+\phi_2}{2}=1 \\ \sin\dfrac{\phi_1-\phi_2}{2}=1 \end{cases} \tag{7}$$

φ is calculated to be 45°, 135°, 225°, and 315°, which produces four beams.

On the basis of the above theory, this paper carries out simulation verification, firstly, a three-dimensional digitally coding metasurface model is established in CST, and then the scattering lobe results at f=7 GHz are simulated and calculated, as shown in Figures 7 and 8.

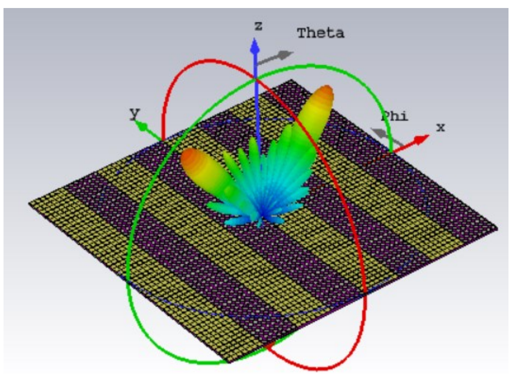

Figure 7. Scattering patterns (010101).

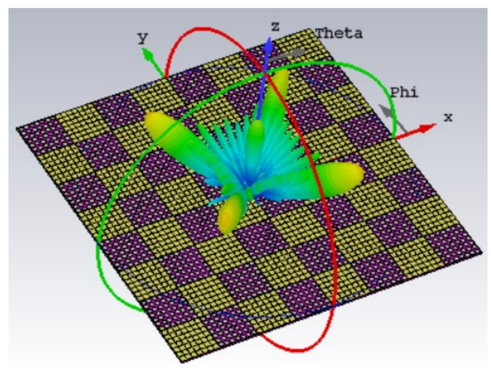

Figure 8. Scattering patterns (01100110).

5. EXPERIMENTAL VALIDATION

In order to verify the correctness of the proposed optimization design method, experimental verification is carried out on the digital coding metasurface encoding for 010101.

As shown in Figure 9, the radiation pattern of the digital metasurface is tested with a vector network analyzer, and the two interfaces of the network analyzer are connected to the transmitting and receiving antennas, respectively. Due to the limitations of the experimental conditions, the horn antenna is used as the feed, and the distance between the antenna and the sample is kept long enough.

In addition, because there is no movable device in the experimental environment, the reflection level measured by the receiving antenna needs to be continuously moved, so the data measured in this paper are not continuous, and there are only discrete results at certain angles. The green data points are experimental result in Figure 10. The red curve in Figure 10 shows the simulation results.

It can be seen from Figure 10 that the main beam is located on both sides of the normal, and the comparison of the simulation results and the test results shows that there are errors between the simulation and experimental results and the maximum level of the test results is low, which is mainly due to the processing technology and test environment. However, within the allowable error range, the digitally coding metasurface structure designed in this paper is reasonable and correct.

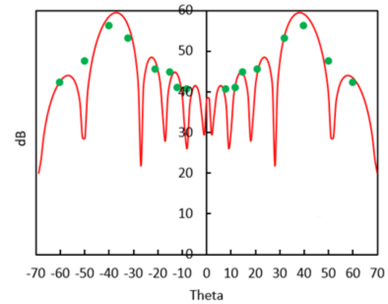

Figure 9. Testing sample. Figure 10. Comparative results.

6. CONCLUSION

In this paper, A method combining FDTD and Genetic Optimization Algorithm (GA) is proposed to automatically realize the design of the encoding metasurface unit structure through programming. Based on this method, the structure of the 1-bit digital coding unit is automatically designed. That is, the square metal patch unit with a side length of W=4.8 mm represents the logical “0” unit, and the circular metal patch unit with a radius of r=2.0 mm represents the logical “1” unit. Based on the beamforming mechanism, two-beam and four-beam beam reflections of the periodic sequence 0101.../1010 are realized. Digitally encoding metasurface with periodically encoding sequence 0101... was produced, and the far-field radiation pattern was measured, and the measurement results were consistent with the simulation results.

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 62203151.

REFERENCES

[1] Cui, T. J., Qi, M. Q., Wan, X., et al., “Coding metamaterials, digital metamaterials and programmable metamaterials,” Light: Science & Applications 3(10), e218 (2014).
[2] Liu, S., [Digitalized Coding Metasurface and Its Applications], Chongqing: Southeast University, Master’s Thesis, (2017).
[3] Luo, J., [Manipulations of Electromagnetic Waves by Coding Metamaterials and Their Applications], Southeast University, Master’s Thesis, (2019).
[4] Liu, S., Cui, T. J., Xu, Q., et al., “Anisotropic coding metamaterials and their powerful manipulation of differently polarized terahertz waves,” Light: Science & Applications 5(5), e16076 (2016).
[5] Liu, S., Cui, T. J., Zhang, L., et al., “Convolution operations on coding metasurfaces to reach flexible and continuous controls of terahertz beams,” Advanced Science 3(10), 1600156 (2016).
[6] Liu, S., Zhang, H. C., Zhang, L., et al., “Full-state controls of terahertz waves using tensor coding metasurfaces,” ACS Applied Materials & Interfaces 9(25), 21503-21514 (2017).
[7] Liu, S., Zhang, L., Yang, Q. L., et al., “Frequency-dependent dual-functional coding metasurfaces at terahertz frequencies,” Advanced Optical Materials 4(12), 1965-1973 (2016).
[8] Cui, T. J., Liu, S. and Li, L. L., “Information entropy of coding metasurface,” Light: Science & Applications 5(11), e16172 (2016).
[9] Zhang, L., Chen, X. Q., Liu, S., et al., “Space-time-coding digital metasurfaces,” Nature Communications 9(1), 4334 (2018).
[10] Zhang, X. G., Tang, W. X., Jiang, W. X., et al., “Light-controllable digital coding metasurfaces,” Advanced Science 5(11), 1801028 (2018).
[11] Zhang, X. G., Jiang, W. X. and Cui, T. J., “Frequency-dependent transmission-type digital coding metasurface controlled by light intensity,” Applied Physics Letters 113(9), 091601 (2018).
[12] Zhang, L., Wu, R. Y., Bai, G. D., et al., “Transmission-reflection-integrated multifunctional coding metasurface

for full-space controls of electromagnetic waves," Advanced Functional Materials, 28(33), 1802205.1-1802205.9 (2018).

[13] Li, L., Cui, T. J., Ji, W., et al., "Electromagnetic reprogrammable coding-metasurface holograms," Nature Communications 8(1), 197 (2017).

[14] Ma, Q., Xiao, Q., Hong, Q. R., Gao, X., Galdi, V. and Cui, T. J., "Digital coding metasurfaces: from theory to applications," IEEE Antennas and Propagation Magazine, 64(4), 96-109 (2022).

[15] Gao, Z., Xu, C., Zhu, R., et al., "Multifunctional anisotropic coding metasurface with low emissivity and high optical transmittance," Infrared Physics & Technology, 117, 103845 (2021).

[16] Wu, H., Liu, S. and Wan, X., et al., "Controlling energy radiations of electromagnetic waves via frequency coding metamaterials," Adv. Sci. 4(9), 1700098 (2017).