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MORPHOGENETIC METASURFACE ANTENNAS FOR SATELLITE COMMUNICATION

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Abstract—This paper presents a novel approach to designing self-organized metasurface antennas with high gain and bandwidth, suitable for satellite communications. Due to their unique behavior, metasurfaces have become a focal point in antenna design. In our work, we employed a morphogenetic synthesis approach, inspired by Alan Turing's research on the emergence of complex structures in biological systems, to automate the synthesis and self-structuring of meta-atoms. We adapt his conceived reaction-diffusion principle to control anisotropic tensors for the synthesis of metasurface antennas, enabling the self-organization of sub-wavelength elements without gradient descent optimization, and achieving desired electromagnetic characteristics on a macroscopic scale. The simplicity of this approach, combined with the introduction of partial disorder into the meta-atom arrangement, enhances the design process and homogenization efficiency.

I. INTRODUCTION

Metasurfaces have gained considerable attention in antenna design due to their electromagnetic and physical properties, including ease of integration, compactness, embedded feeding structures, surface-boundary electromagnetic interactions, and fabrication advantages. Metasurface antennas are designed by arranging sub-wavelength elements on a grounded slab [1]-[3]. The feeding structure typically comprises a surface wave launcher located at the center of the antenna, which couples the input mode to a transverse magnetic surface wave. Surface waves generated by this launcher interact with the modulated impedance of the metasurface, converting these waves into leaky waves that radiate in the desired directions [4]. Impedance modulation can be achieved by varying the orientation and size of the sub-wavelength elements. When the modulation period is constant, any mismatch between the surface wave wavelength and this period can impede the gain-

bandwidth product [5]. The relative bandwidth of a metasurface antenna has been shown in [6] to be inversely proportional to the antenna radius in terms of wavelength by choosing an adequate modulation index. This bandwidth can be increased by considering a trade-off of the aperture efficiency [5], [7].

In this work, we employed a morphogenetic synthesis approach first deployed in [8] to design metasurface antennas suitable for satellite communication. This generative method, derived from Alan Turing's research on the emergence of complex structures in living organisms [9], enables the automated synthesis and self-structuring of meta-atoms. Specifically, we implement the reaction-diffusion principle conceived by Turing to control anisotropic tensors for the synthesis of metasurface antennas [10]. This approach facilitates the self-organization of sub-wavelength elements without gradient descent, to synthesize the physical parameters expected on a local scale, so that electromagnetic radiation constraints can be obtained on a macroscopic scale, analogous to the emergence of the complex characteristics of living organisms. One notable advantage of this synthesis method is the simplicity of design and the efficiency of homogenization in generating meta-atoms and their self-organizing patterns by introducing partial disorder into the structures. Previous works have elaborated this methodology for metasurface antenna synthesis [8], the design of correlated disordered media [11], and metasurface antennas as a solution to enhancing security identification and ensuring end-to-end communication integrity on physical layer applications [12].

The subsequent sections of this paper are organized as follows: Section II begins by describing the methodology adopted in this work in detail, and this will be presented in three headings including the generation model, anisotropic pattern characterization, and morphogenetic synthesis approach. Section III presents the result obtained for a typical metasurface antenna designed for satellite communication by adopting the synthesis approach discussed in this work. Following

the results, a discussion ensues to validate the designed antenna's relevance in satellite communication. Finally, section IV highlights the key findings and concludes the study.

II. METHODOLOGY

The methodology used in this study is based on the reaction-diffusion principle. This section is divided into three themes to give insight into the flow of the method adopted for realizing this work.

A. Generation model

The generation model used in this study enables the generation and synthesis of self-organized anisotropic patterns. Stemming from the work of Alan Turing, the reaction-diffusion model was developed as a mathematical model to facilitate the analysis of the growth of the complex patterns of living organisms. Of such retained systems is the Gray-Scott model [10] described by two partial differential equations as in (1). The \mathbf{U} and \mathbf{V} parameters are referred to as concentrations of morphogens. A finite difference scheme is utilized in solving the model (1) in line with the interaction of the morphogens giving rise to the generation of diverse patterns.

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} &= d_u \nabla^2 \mathbf{U} - \mathbf{U}\mathbf{V}^2 + f(1 - \mathbf{U}), \\ \frac{\partial \mathbf{V}}{\partial t} &= d_v \nabla^2 \mathbf{V} + \mathbf{U}\mathbf{V}^2 - (f + k)\mathbf{V}. \end{aligned} \quad (1)$$

The Gray-Scott model in itself is limited to the generation of isotropic-shaped elements. Hence, there is a need to adapt the model for generating anisotropic elements suitable for the design of metasurface antennas that allow for complex polarization control [8]. The surface impedance required for the control of anisotropic patterns is tensorial, and to reflect that, we introduce a diffusion tensor $\underline{\mathbf{D}}$ in our model that is defined at every point on the surface analogous to that of surface or reactance tensor. The modified model for generating self-organized anisotropic patterns is given in (2). The parameters f and k referred to as feed and kill rate control the generation and extinction of patterns respectively. The diffusion coefficients d_u and d_v determine the size of the generated pattern associated with the Laplacian operator ∇^2 .

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} &= d_u \nabla \cdot (\underline{\mathbf{D}} \nabla \mathbf{U}) - \mathbf{U}\mathbf{V}^2 + f(1 - \mathbf{U}), \\ \frac{\partial \mathbf{V}}{\partial t} &= d_v \nabla \cdot (\underline{\mathbf{D}} \nabla \mathbf{V}) + \mathbf{U}\mathbf{V}^2 - (f + k)\mathbf{V}. \end{aligned} \quad (2)$$

B. Anisotropic Pattern Characterization

Designing a morphogenetic metasurface antenna requires defining parameters enabling the growth of patterns and the characterization of the generated pattern, which is typical of a conventional metasurface antenna.

This process is summarized as illustrated in Fig. 1. The couple of f and k and other morphogenetic parameters are defined to achieve the growth of elliptical patterns. The patterns grow by splitting themselves in a manner related to mitosis, to occupy the entire defined domain over time.

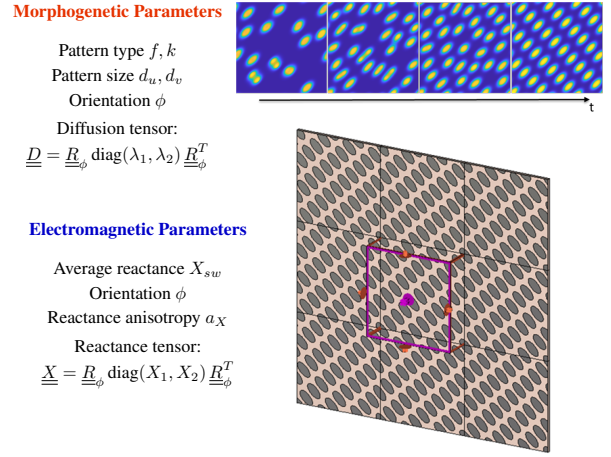


Fig. 1: Characterization of Anisotropic Patterns: Defining Morphogenetic Parameters for Pattern Generation, FEM Analysis, and Extraction of Electromagnetic Properties.

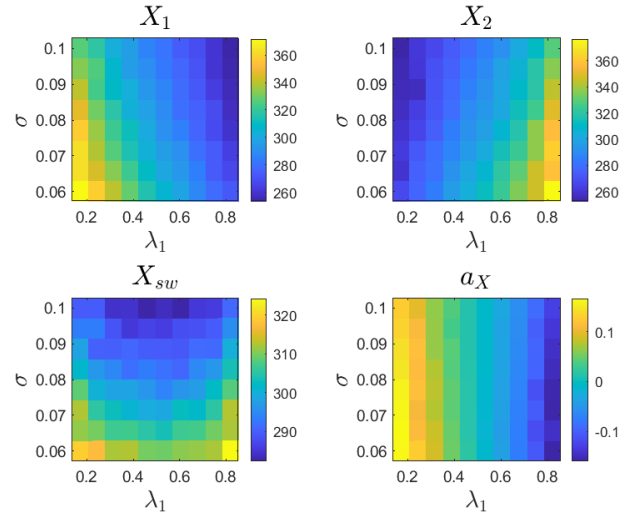


Fig. 2: Map showing reactance eigenvalues, average reactance, and reactance modulation.

The generated pattern is then characterized using an EM solver to obtain the electromagnetic parameters required for designing the full metasurface. The domain for generating the pattern is defined to suit the dimension of the substrate chosen for characterization. The commercial *CST studio suite* is utilized for the electromagnetic characterization of the unit cell pattern, the impedance tensor is extracted and a conversion

method proposed in [1] is adopted for deriving the tensor necessary for converting surface waves to radiated ones. Fig. 2 depicts the eigenvalues of the reactance tensor, the average reactance, and the reactance modulation obtained by characterizing a pattern printed on a 12 mm *Rogers 3035* substrate of permittivity $\epsilon_r = 3.6$ and thickness, $h = 1.52$ mm at an operating frequency of 20 GHz. This characterization considers two degrees of freedom; λ_1 and σ . The latter is a threshold parameter that is applied for adjusting the gap between the generated pattern and λ_1 is one of the eigenvalues of the diffusion tensor, required for the control of the anisotropy of the reactance tensor.

C. Morphogenetic Synthesis Approach

Following the characterization of the generated pattern, the reactance tensor is extracted revealing the eigenvalues X_1 and X_2 . We thus obtain the average reactance X_{sw} and reactance modulation a_X as displayed in Fig. 2 using (3). The next step in designing a morphogenetic metasurface antenna is to define the radiation objectives and impedance boundary conditions. These objectives are then converted into morphogenetic parameters facilitating the growth of sub-wavelength patterns, to synthesize physical parameters locally, so that the set objectives can be obtained on a macroscopic scale.

$$\begin{aligned} X_{sw} &= \frac{X_1 + X_2}{2} \\ a_X &= \frac{|X_1 - X_{sw}|}{X_{sw}} \end{aligned} \quad (3)$$

$$\mathbf{E}_t|_{z=0^+} = j\mathbf{X} \cdot \mathbf{J} = j\mathbf{X} \cdot J_0 H_1^{(2)}(-jk_{sw}\boldsymbol{\rho})\hat{\boldsymbol{\rho}} \quad (4)$$

$$\beta_{sw} = k_0 \sqrt{1 + \left(\frac{X_{sw}}{\eta_0}\right)^2} \quad (5)$$

The impedance boundary condition defined in (4) is a first-order model utilized in this work, where \mathbf{E}_t is the electric field continuous on the surface of the metasurface, \mathbf{J} is the surface current modeled using $H_1^{(2)}$, the Hankel function of the first order and second kind in (4), and k_{sw} given by $(\alpha + j\beta_{sw})$ is the surface wave having its imaginary part directly proportional to the average reactance as defined in (5). The reactance tensor required for the efficient conversion of the surface wave to the radiated wave is defined in [8] as follows:

$$\begin{aligned} \mathbf{X}_{\rho\rho} &= X_{sw}(1 + a_X^{\max} \mathbf{M}_{\rho\rho} \sin(\arg(\mathbf{E}_\rho/\mathbf{J}_\rho))) \\ \mathbf{X}_{\rho\phi} &= X_{sw} a_X^{\max} \mathbf{M}_{\rho\phi} \sin(\arg(\mathbf{E}_\phi/\mathbf{J}_\rho)) \\ \mathbf{X}_{\phi\rho} &= \mathbf{X}_{\rho\phi} \\ \mathbf{X}_{\phi\phi} &= X_{sw}(1 - a_X^{\max} \mathbf{M}_{\rho\rho} \sin(\arg(\mathbf{E}_\rho/\mathbf{J}_\rho))) \end{aligned} \quad (6)$$

Fig. 3 illustrates the synthesized pattern for the full metasurface, with the antenna feed visible at the center.

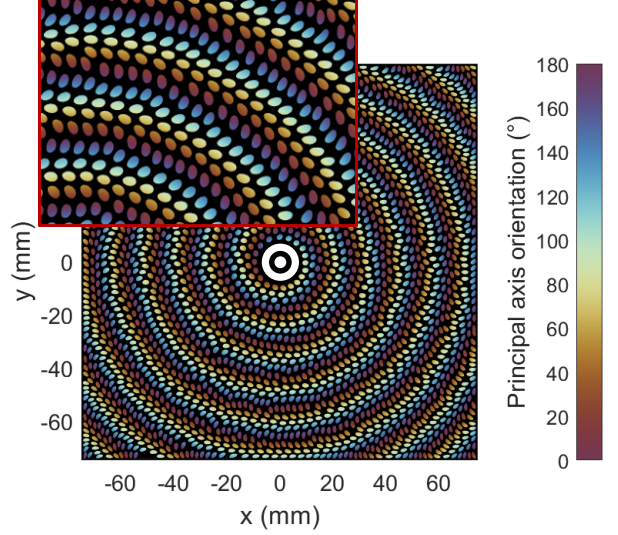


Fig. 3: Morphogenetically synthesized pattern for the design of the full metasurface antenna, revealing the antenna feed at the center. The color map indicates the direction of the principal axis of the pattern.

This metasurface is designed to radiate a left-hand circularly polarized beam at 20 GHz having an average reactance of, $X_{sw} = 298 \Omega$. This design is achieved on a 150×150 mm *Rogers 3035* substrate of permittivity, $\epsilon_r = 3.6$ and thickness, $h = 1.52$ mm. This substrate is arbitrarily chosen to demonstrate the morphogenetic synthesis approach described in this paper. The result of the fully characterized morphogenetic metasurface antenna is presented in the subsequent section.

III. RESULTS

The result obtained from the full wave characterization shows a maximum directivity of 24.30 dB and a realized gain of 23.91 dB with a loss of 0.39 dB and aperture efficiency of 21.4 %. The axial ratio computed as highlighted in Fig. 5 is less than 3 dB for the entire frequency range from 18 GHz to 22 GHz, and less than 1 dB from 20 GHz to 22 GHz. The half power beam width (-3 dB of the maximum realized gain) is 1.8 GHz at the operating frequency of 20 GHz, resulting in the relative bandwidth of 9 %. Fig. 4 displays the radiation pattern and reveals the antenna's maximum directivity and polarization preference. The cross-polarization as viewed in Fig. 4c is less than 5 dB for a maximum co-polarization of 24.3 dB.

IV. DISCUSSION AND CONCLUSION

From the result presented, we obtain a good relative bandwidth of 9 % and an axial ratio less than 3 dB for the entire frequency band from 18 GHz to 22 GHz. This is particularly impressive indicating that the circular

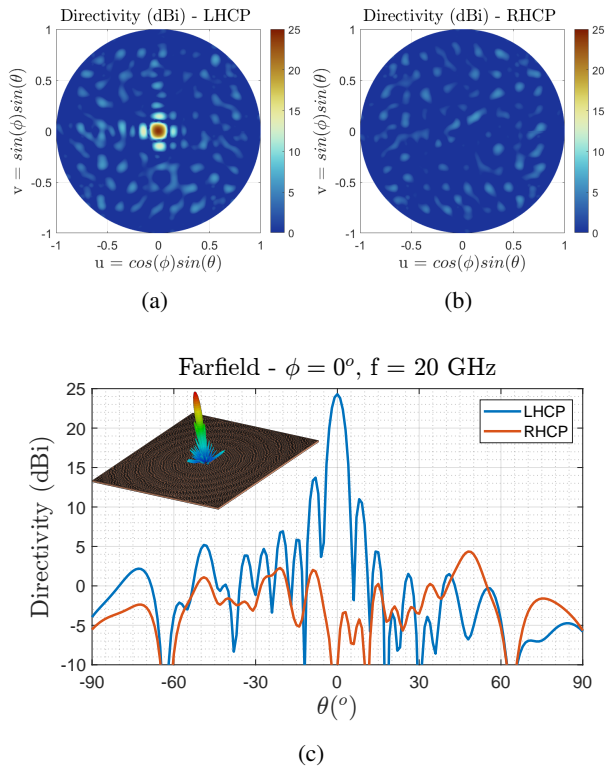


Fig. 4: Radiation pattern of a morphogenetic metasurface antenna radiating a left-hand circularly polarized beam designed at 20 GHz operating frequency.

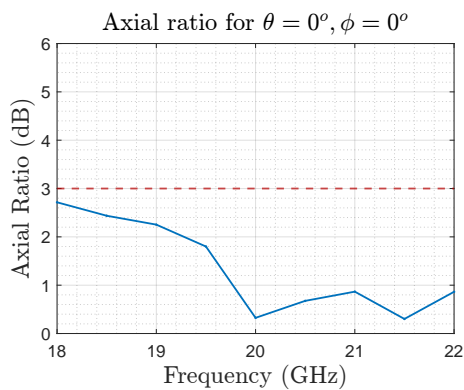


Fig. 5: Axial ratio obtained for a morphogenetic metasurface antenna designed at 20 GHz.

polarization obtained is near ideal. A low axial ratio is essential in satellite communication as it helps to maintain signal integrity, reduce signal interference, and minimize polarization mismatch between transmitting and receiving antennas. We achieve a satisfactory polarization purity, the cross-polarization obtained is less than 5 dB, equivalent to 20 % of the co-polarization.

These results underscore the effectiveness of the morphogenetic approach, which enables the automatic generation and synthesis of anisotropic patterns, leading to enhanced homogeneity of the patterns compared to

conventional metasurface antennas that rely on Cartesian grids. While the current results are promising, there are a lot of opportunities for improvement in future work. The periodic lobes observed in the radiation pattern in Fig. 4 can be justified and mitigated in future work. The morphogenetic approach streamlines the design process without gradient design optimization, indicating its potential to advance metasurface antenna design.

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