Studies on Programmable Metasurfaces Using Deep Learning Techniques

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Abstract.

This study focuses on programmable metasurfaces that have shown great potential in shaping optical wavefronts in comparison to bulky geometric optics devices. These metasurfaces rely on meta-atoms, which are their fundamental building blocks and work by reflecting and scattering from their surfaces to achieve desired electromagnetic responses. The characterization of meta-atom structures with various physical and geometric parameters is a laborious process that demands a substantial amount of computational resources. This review investigates the use of a deep learning-based approach for meta-atom modeling, which can considerably reduce the time required for characterization while preserving accuracy. The suggested approach is founded on a convolutional neural network (CNN) architecture that can model meta-atoms with almost unrestricted 2D patterns, distinct lattice sizes, varying material refractive indices, and thicknesses. Furthermore, this method enables the prediction of a comprehensive spectrum response of a meta-atom within milliseconds, making it ideal for applications that necessitate rapid on-demand design and optimization of a meta-atom or metasurface.

Keywords: Programmable metasurface, meta-atom, deep learning, convolutional neural network, optimization.

1. INTRODUCTION

Metasurfaces are two-dimensional structures composed of subwavelength structures arranged in various shapes and distribution functions, which have been used in various applications such as spectrum filtering, holographic imaging, and polarization conversion [1], [2]–[4]. The subwavelength structures, known as meta-atoms, act like atoms or molecules of natural materials and cause phase mutations when hit by electromagnetic waves. This allows metasurfaces to control the phase, amplitude, and polarization of reflected or transmitted waves in space. By changing the geometry of individual meta-atoms, desired responses can be achieved for complete control of light propagation. However, designing optimal meta-atom structures is a critical challenge due to the non-intuitive design process. Current design approaches include trial-and-error methods and optimization algorithms or deep neural networks (DNNs) based on inverse design methods.

Programmable metasurfaces, also called coding meta-surfaces, are a recent development that has the ability to manipulate electromagnetic waves in real-time [2], [5]-[7]. This is achieved by integrating active components, such as PIN diodes and varactors, into the metasurface elements. By changing the state of these components, the reflected wave's phase can be adjusted for each element, leading to complex spatial waveforms and more control over wave propagation. The quantization of element reflection phase into binary codes is another benefit of coding metasurfaces. For instance, the 1-bit code "0/1" indicates an element with two different reflection coefficients, while the 2-bit code "00/01/10/11" represents four additional states for the element reflection coefficients. Digital anisotropic coding metamaterials have been recently introduced as a means of controlling polarization with flexible and independent anisotropic coding sequences, enabling multiple functionalities with different polarizations. While most coding metasurfaces employ metallic subwavelength resonators at radio frequencies, there have been recent proposals for using high-permittivity dielectric materials that leverage Mie resonances, allowing for the possibility of all-dielectric coding metasurfaces for controlling electromagnetic waves. Compared to their metallic counterparts, dielectric resonator-based metasurfaces exhibit high efficiencies as they avoid the intrinsic non-radiative losses associated with metals.

This study utilizes deep learning methods to program a metasurface, which involves mastering internal rules from a vast amount of data. To achieve this, deep convolutional neural network is used to understand the coding techniques from conventional methods, such as the back-projection and nonlinear optimization approaches. By designing and training the neural network, we can create a data-driven routine for programming the metasurface.

2. METHODOLOGIES

A. **Back-Projection Method:** The back-projection (BP) method is a critical process for calculating the scattering pattern of a programmable metasurface comprise of M × N unit cells, based on the array-theory method. The back-projection method is capable of precisely forecasting the element phase when presented with a solitary beam direction. Nevertheless, its precision tends to diminish when confronted with intricate radiation pattern demands, like dual-beam directions with restrictions on the side-lobe levels. Calculating a coding matrix that satisfies all these limitations simultaneously can prove to be a difficult task, which is where optimization techniques come into play. By using optimization techniques, we can calculate the coding matrix, or discrete element phase, required in these situations [2].

B. **Nonlinear Optimization Approach:** In order to determine the coding matrix necessary for a particular scattering pattern of a metasurface, we must solve a non-linear and non-convex optimization problem. The primary goal of the optimization process is to minimize the discrepancy between the computed radiation pattern and the desired outcome, and this is typically accomplished through the use of stochastic nonlinear optimization algorithms such as genetic algorithm (GA) and particle swarm optimization (PSO). These algorithms repeatedly search for the optimal solution and are able to locate a global minimum that gives the metasurface optimal performance due to their randomness. This study employs GA to calculate the element codes required for programmable metasurfaces based on the desired scattering waveform. GA is a technique based on the principles of natural genetics [8] and has been extensively employed in electromagnetic and optical engineering to reduce the difference between the computed and desired beam pattern. Throughout the optimization process, the desired outcome can be transformed into the lower and upper pattern mask.

C. **Deep Learning Approach:** This study proposes the utilization of a fully convolutional neural network (ConvNet) based on deep learning to predict the coding matrix for the beam pattern requirement. The architecture of the proposed ConvNet is inspired by the VGG net [9] and comprises of eleven convolutional layers and five pooling layers.

The pooling layers introduce spatial pooling after the first, second, fourth, fifth, and sixth convolutional layers. The ConvNet architecture incorporates small-sized receptive fields that use 1×1, 3×3, 4×4, and 5×5 convolutional kernels. Using small convolutional kernels in layers 1 to 7 instead of relatively large kernels introduces more nonlinearity, making the ConvNet more discriminative. The ConvNet takes the required parameters of the scattering beam pattern as input and generates the coding matrix of the programmable metasurface that can produce scattering beam patterns that fulfill the input requirement as output. The generated scattering beam pattern should meet the requirement, and the ConvNet is trained to reduce the discrepancy between the computed and desired beam patterns.

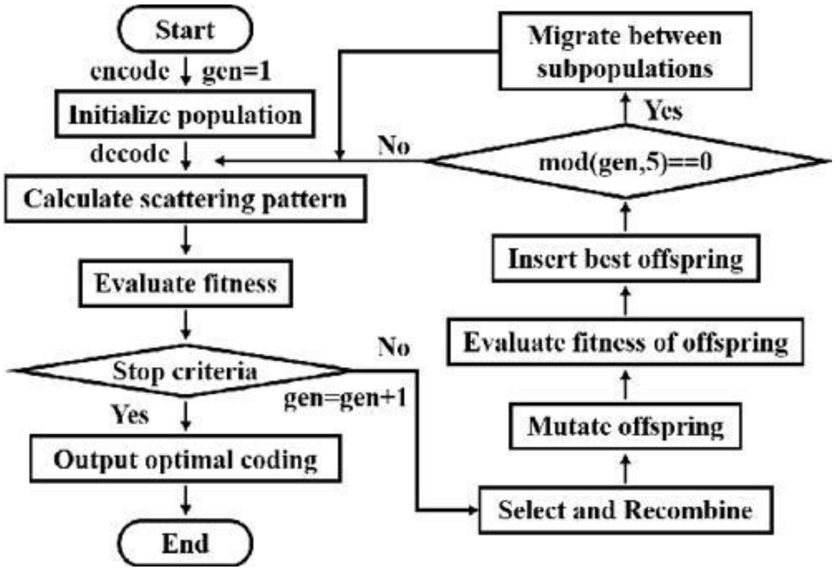

Fig.1 Multiple-population genetic algorithm flowchart.

3. CONCLUSION

This research investigates the potential of utilizing deep learning techniques to program metasurfaces for multi-beam steering. Employing a deep convolutional neural network, we can find the element codes to generate scattering patterns that meet given requirements. The findings indicate that this approach can compute coding matrices that produce beam patterns that are nearly identical, with computation taking only milliseconds. With precise control circuits, programmable metasurfaces can modulate EM waves in both the spatial and time domains, with applications in microwave, optical, and acoustic engineering. Future studies aspire to expand this deep neural network to calculate more intricate wave scattering patterns. This research marks a preliminary foray into the application of deep learning techniques in electromagnetic engineering, which is usually dominated by the study and development of physical laws. With continued advancements in deep learning techniques, it is conceivable that machines will be able to "learn" from vast amounts of physical data and "comprehend" physical laws in specific boundary conditions. This literature review offers a persuasive illustration of how deep learning can be applied to calculate coding matrices for programmable metasurfaces in real-time. Furthermore, by augmenting the depth and scope of deep neural networks, we can substantially enhance their learning and generalization capabilities, which may further benefit their effectiveness in physical tasks such as this study.

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