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Inverse Design of Pixelated Electromagnetic (EM) Skins for Army Applications

by Quang M. Nguyen, Daniel Lu, Theodore K. Anthony, and Gregory Mitchell

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Inverse Design of Pixelated Electromagnetic (EM) Skins for Army Applications

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1. Introduction

Metasurfaces are an effective platform for manipulating electromagnetic (EM) wave propagation through subwavelength unit cells. Conventional metasurface designs commonly rely on canonical symmetric geometries, which provide low-profile structures that are relatively simple to analyze, fabricate, and optimize.¹ However, these geometries explore only a small portion of the available EM design space, as shown in Figure 1, limiting the achievable responses.

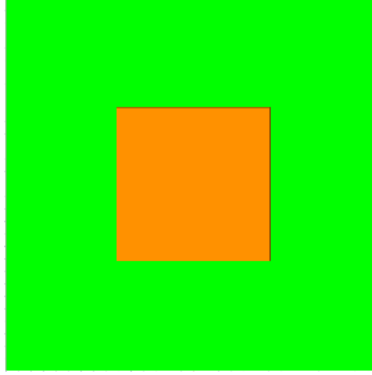


Figure 1. Conventional square patch antenna.

Figure 2 shows how we can represent the conducting layer as binary pixelizations, where we assign each pixel as either metal or air. Rather than optimizing geometric dimensions, we allow the entire pixelated mask to evolve iteratively, significantly increasing the number of possible unit cell configurations. This larger design space enables unconventional geometries capable of producing EM responses that are difficult to realize using traditional parameterized geometries while maintaining the advantages of planar metasurface structures.

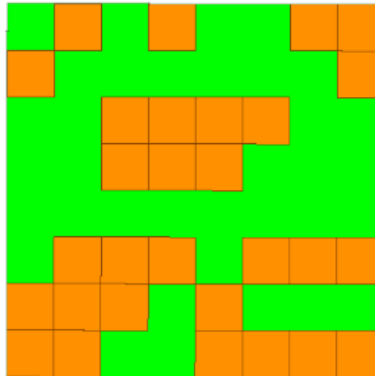


Figure 2. Pixelated antenna.

The objective of this work is investigating optimization-driven inverse design techniques for pixelated metasurfaces and demonstrating their application to

backscattering and beam steering. First, we developed an automated simulation framework to generate and evaluate pixelated unit cells. We then used this framework with a binary genetic algorithm (GA) to design unit cells to alter backscattering of incoming RF signals. We also extended the framework to beam-forming reflectarrays by generating a large database of pixelated unit cells that are organized into quantized phase states.

Section 2 describes the automated framework used to generate and simulate the pixelated unit cells. Section 3 presents the binary GA used for inverse design. Section 4 applies this approach to the design of a checkerboard metasurface for backscattering and presents simulated and measured results. Section 5 extends the automated framework to beam steering by generating a large database of pixelated unit cells and selecting the required reflection phase states for a reflectarray. Section 6 presents the completed beam-steering metasurface and its simulated performance, followed by the conclusion in Section 7.

2. Automated Design Framework for Pixelated Metasurfaces

Since every pixelated mask requires a full-wave EM simulation, manually constructing and evaluating thousands of geometries is time consuming. To overcome this limitation, we developed an automated design framework using Python and the PyAEDT library to control the Ansys High-Frequency Structure Simulator (HFSS; version 2023 R1). As a closed-loop successor to Banks et al.,² the framework automatically generates binary pixel masks, converts each mask into a physical unit cell geometry, performs the EM simulation, and exports the resulting reflection coefficients for further processing.

In this report, a binary matrix describes each unit cell, where a value of “1” represents a metallic pixel and “0” represents air or the absence of metal. A binary representation allows interpretation of the pixel arrangement as a chromosome for the GA while enabling automated geometry generation inside HFSS. Figure 3 illustrates the overall GA-based optimization and simulation workflow. Upon simulation completion, we extract the complex reflection coefficient and store together with the corresponding pixel mask.

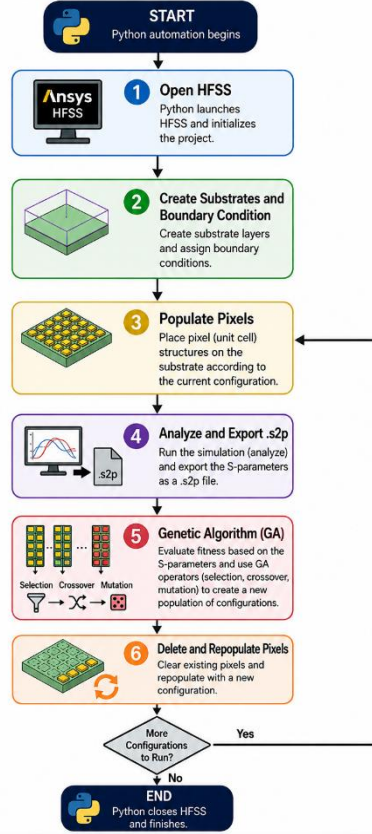


Figure 3. Automated pixel population with genetic algorithm analysis framework.*

The automated workflow significantly reduces the manual effort for model construction and allows the efficient generation and analysis of thousands of unique pixelated unit cells, highlighting the foundation for the optimization and beam-forming investigations we describe in this work.

3. GA for Inverse Design

The large number of possible pixel arrangements makes evaluation computationally inefficient. For an 8×8 pixelated unit cell, the design space consists of 2^{64} possible heuristic design searches, making conventional optimization techniques impractical. We selected a binary GA for its ability to efficiently explore the large design space while reducing the likelihood of minimum local convergence.

Within the GA, each binary pixel mask represents an individual chromosome, while every pixel corresponds to a gene. The model represents metallic pixels as “1” and empty pixels as “0.” The initial population consists of randomly generated unit cell

* Figure 3 was generated by ChatGPT, a generative AI chatbot (OpenAI; San Francisco, California).

masks. HFSS automatically simulates every candidate design and compares the resulting reflection coefficient with a desired target response. The fitness function evaluates the absolute error between the simulated and target complex reflection coefficients across the operating bandwidth. We select designs producing smaller errors for the next generation of populations.

The selected populations undergo crossover and mutation operations to generate new candidate solutions. Crossover combines characteristics from multiple favored parents, while mutation randomly modifies individual pixels to introduce additional diversity into the population. Through repeated generations, the overall population gradually converges toward the desired EM response.

4. Application 1: Backscattering Reduction

To demonstrate the effectiveness of the inverse design framework, we first applied the GA to synthesize two pixelated unit cells exhibiting approximately 180° reflection phase difference while maintaining low reflection loss. We obtain the inverse design targets from a previously published 5.75-GHz reconfigurable intelligent surface (RIS) unit cell that achieves two phase states of 0° and 180° through PIN diode switching.³ We show the reference unit cell as an inset in Figures 4 and 5, together with the simulated reflection magnitude and phase responses for the PIN diode “on” and “off” states. The region with a 180° phase difference overlap is highlighted within the bounded red lines in Figure 6.

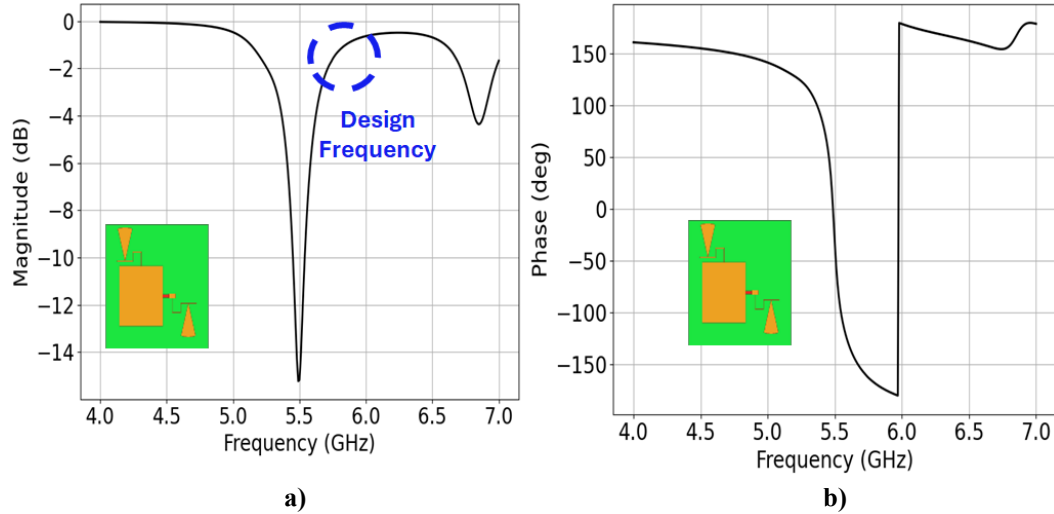


Figure 4. Plot of target a) magnitude and b) phase in the “on” state. Insets: target “on” state unit cell design.

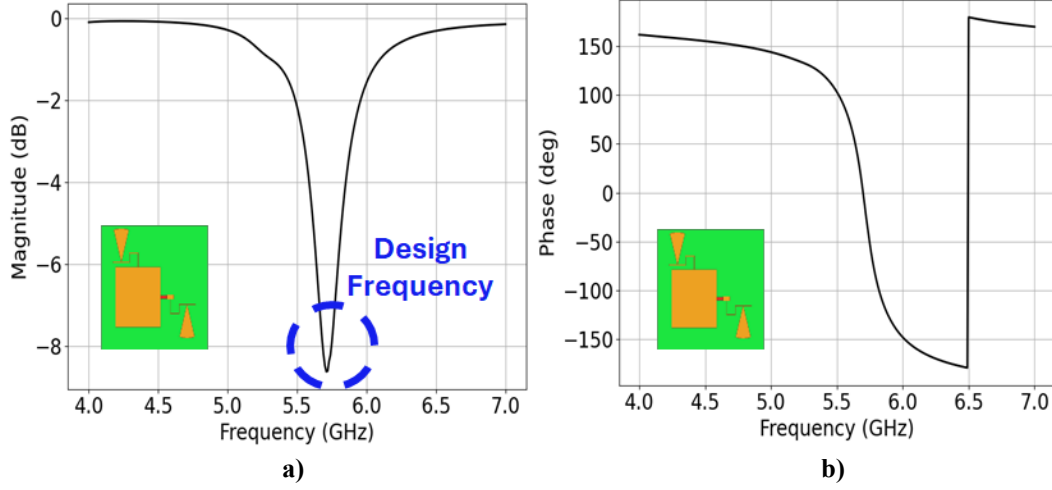


Figure 5. Plot of target a) magnitude and b) phase in the “off” state. Insets: target “off” state unit cell design.

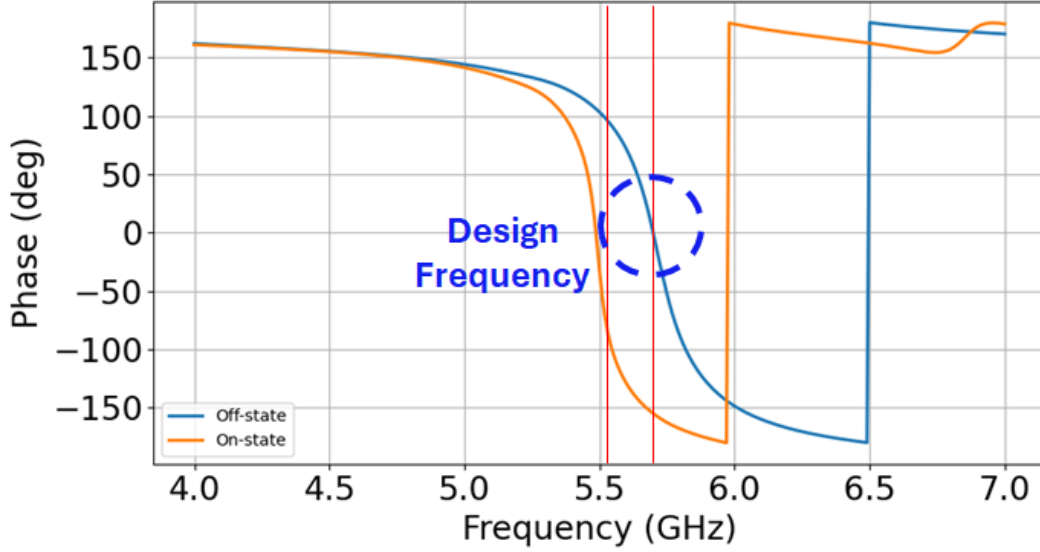


Figure 6. Phase overlap of the “on” and “off” states.

For each population, we translate the binary masks to the physical layout by placing corresponding pixel patches onto a $\frac{\lambda}{2}$ (25.85-mm) unit cell consisting of an FR4 substrate backed by a copper ground plane. We simulate each unit cell from 4.0 to 7.0 GHz using a total of 301 frequency points. The GA algorithm receives an automatic export of the resulting S-parameters to allow the GA fitness function to find the cost C associated with each population using

$$C = \min\left(\frac{1}{N_{n_f}} \sum_{i=1}^{n_f} |\Gamma_T^{n_f} - \Gamma_{GA}^{n_f}|\right), \quad (1)$$

where n_f is the frequency being evaluated, N_{n_f} is the total number of frequency points evaluated, Γ_T is the target complex reflection coefficient, and Γ_{GA} is the complex reflection coefficient obtained from the GA design.⁴ Since the cost function calculates C from the differences of the complex values, the function considers both the magnitude and phase responses at each frequency point. The GA algorithms evaluate the calculated cost for each population and guide toward lower-cost designs over successive generations until reaching convergence.

Using the RIS states as targets, the GA successfully inverse-designs a pixelated geometry for each state. We selected a cost of $C = 0.1$ as the convergence criterion. After 1750 iterations, both designs shown in Figure 7 satisfy this criterion, reaching a final cost of 0.049 for the “on” state (Figure 7a) and 0.079 for the “off” state (Figure 7b). Figures 8 and 9 show the final reflection responses for both designs compared with the target response for the “on” and “off” states, respectively. Figures 8a and 9a present magnitude comparisons for the lowest-cost designs, while Figures 8b and 9b present the corresponding phase responses.

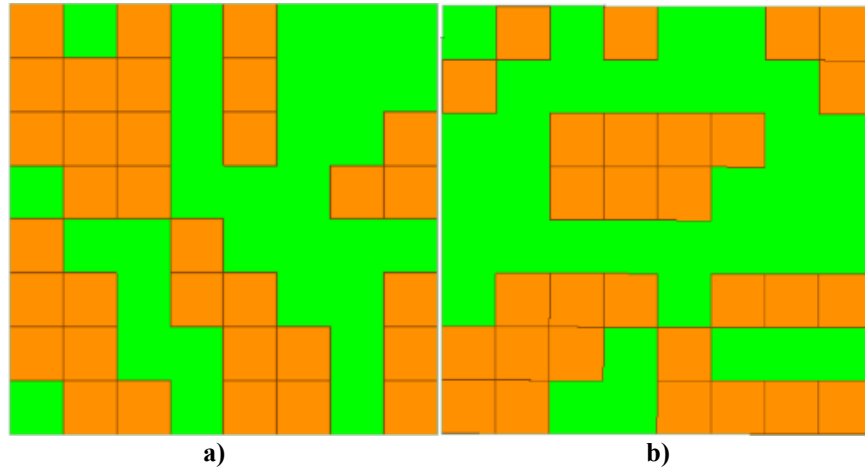


Figure 7. Pixelated inverse design for a) “on” and b) “off” states.

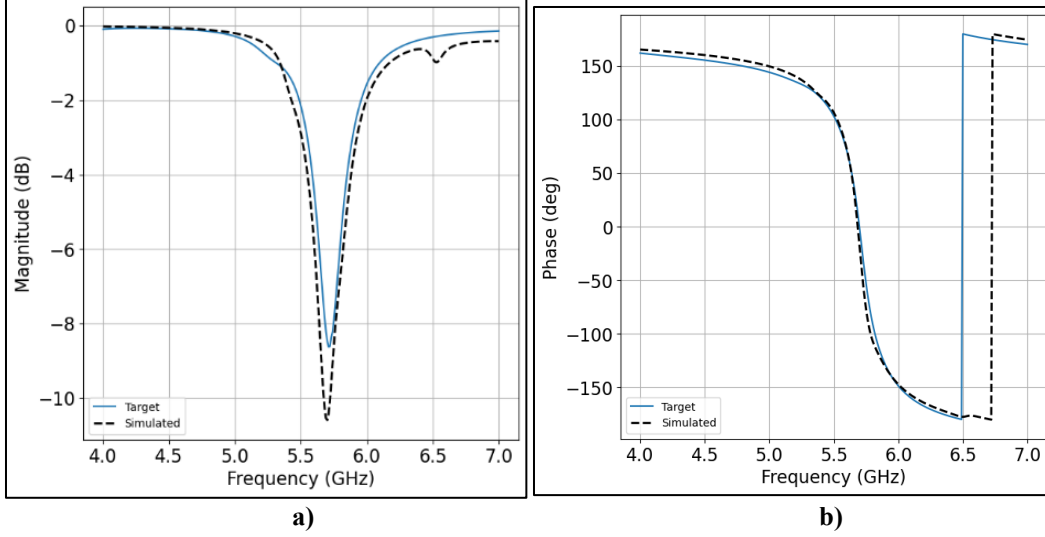


Figure 8. a) Magnitude and b) phase plot of the “on” state pixelated design compared against the target S-parameter.

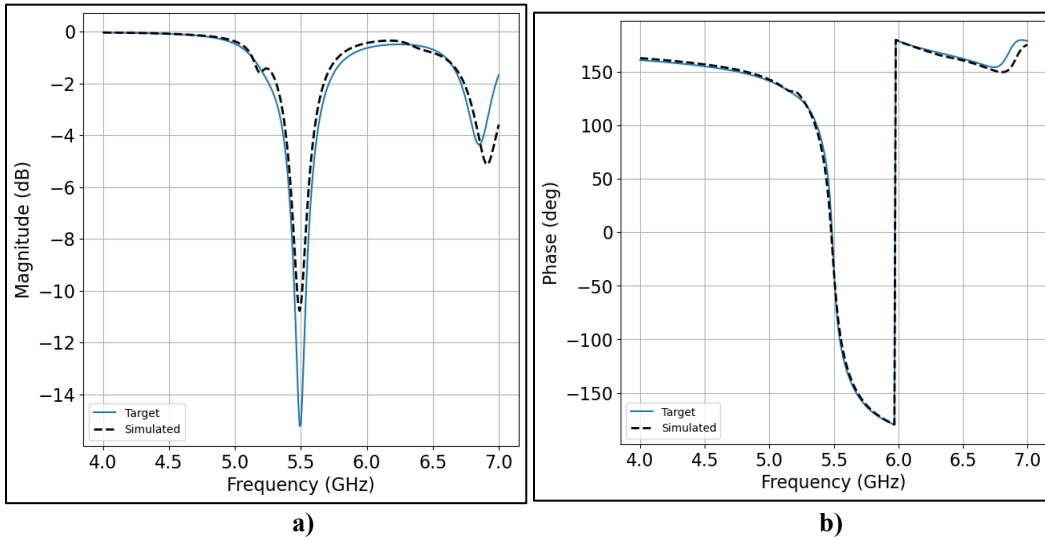


Figure 9. a) Magnitude and b) phase plot of the “off” state pixelated design compared against the target S-parameter.

By alternating two-unit cells of 180° phase difference with a periodicity of λ in electrical length, destructive interference occurs in the specular direction, lowering the backscattered energy magnitude.^{5,6} The scattered energy redistributes into sidelobes 45° along the diagonal plane, resulting in monostatic backscattering reduction.

For a tolerable phase difference of $180 \pm 37^\circ$ between the two states,^{5,6} the expected operational bandwidth is approximately 180 MHz, as shown in Figure 10. Figure 11 illustrates the constructed checkerboard metasurface with overall dimensions of 206.8×206.8 mm, equating to $4\lambda \times 4\lambda$.

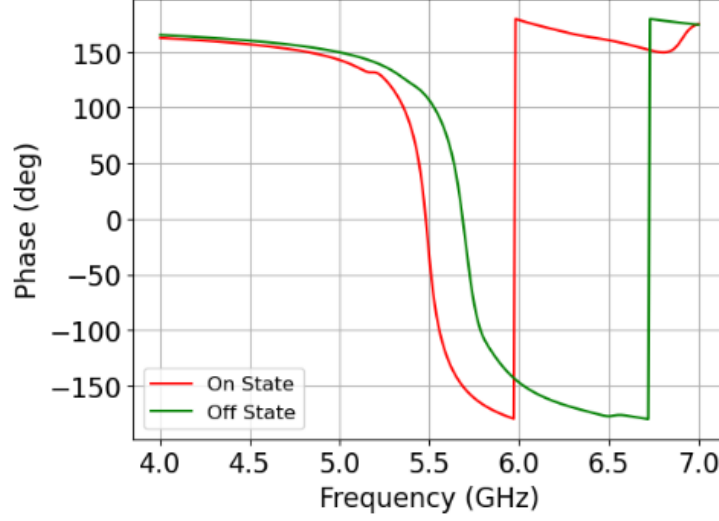


Figure 10. Phase difference between the “on” and “off” states.

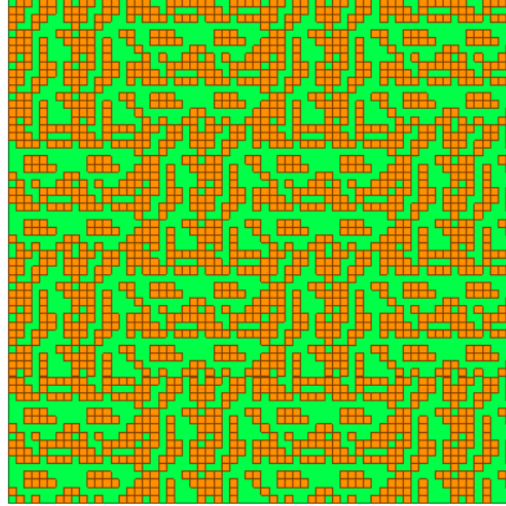


Figure 11. Checkerboard metasurface in λ periodicity.

We simulated far field scattering over angular ranges of $-180^\circ \leq \phi \leq 180^\circ$ and $-90^\circ \leq \theta \leq 90^\circ$ to evaluate the monostatic backscattering reduction under broadside incidence. A total of 75 frequency points between 5.0 and 6.5 GHz were evaluated. The frequency-dependent backscattering reduction, shown in Figure 12, indicates a maximum main-lobe suppression of 10.93 dB at 5.7 GHz compared with the response at 6.4 GHz. Figure 13 shows the top views of the scattered patterns at these two frequencies. The results confirm the 10.93-dB reduction in the main lobe and shows redirection of scattered energy into sidelobes at 45° off-axis along the diagonal planes.

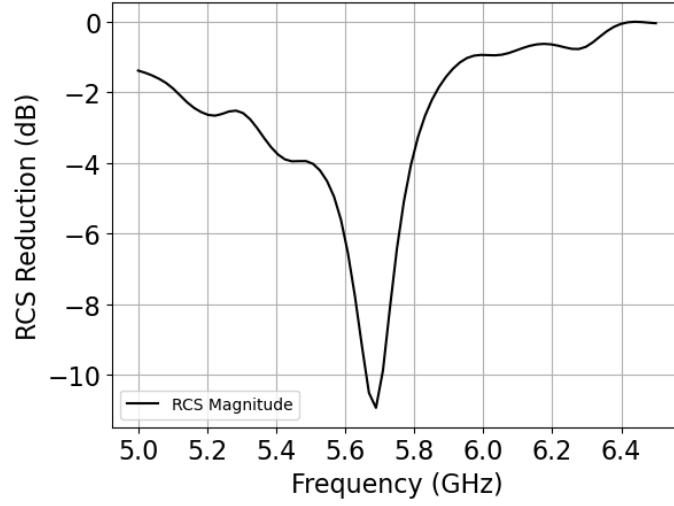


Figure 12. Normalized simulated backscattering reduction.

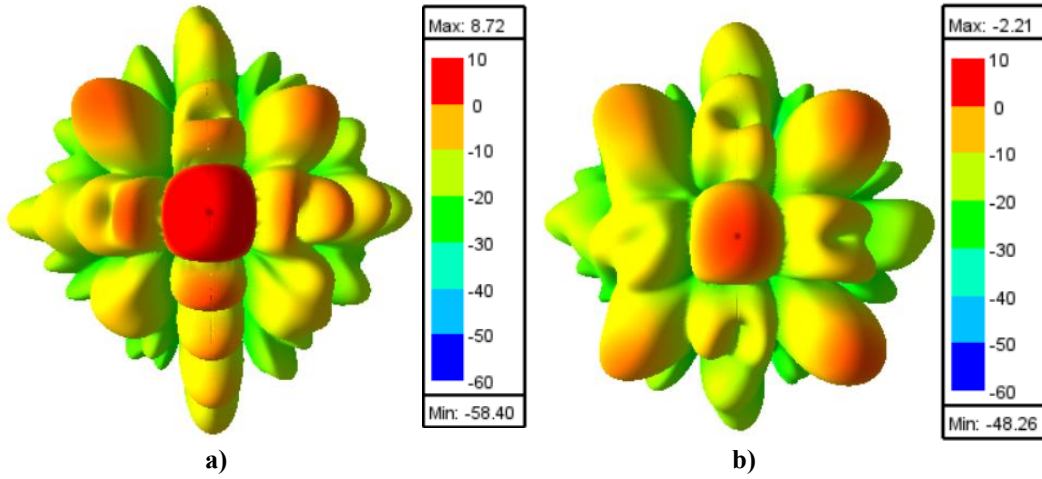


Figure 13. Top view of far field scattered pattern at a) 6.4 and b) 5.7 GHz.

We conducted a quasi-monostatic measurement in the Arizona State University Electromagnetic Anechoic Chamber to validate the simulated results. We performed the measurement from 3.7 to 6.9 GHz using 801 frequency points. Figure 14 compares the simulated and measured backscattering reduction, showing good agreement between the two results with a slight frequency shift resulting from fabrication tolerances in the metasurface prototype. Despite the frequency shift, the metasurface achieves more than 10 dB of backscattering reduction, validating the performance predicted by the simulation.

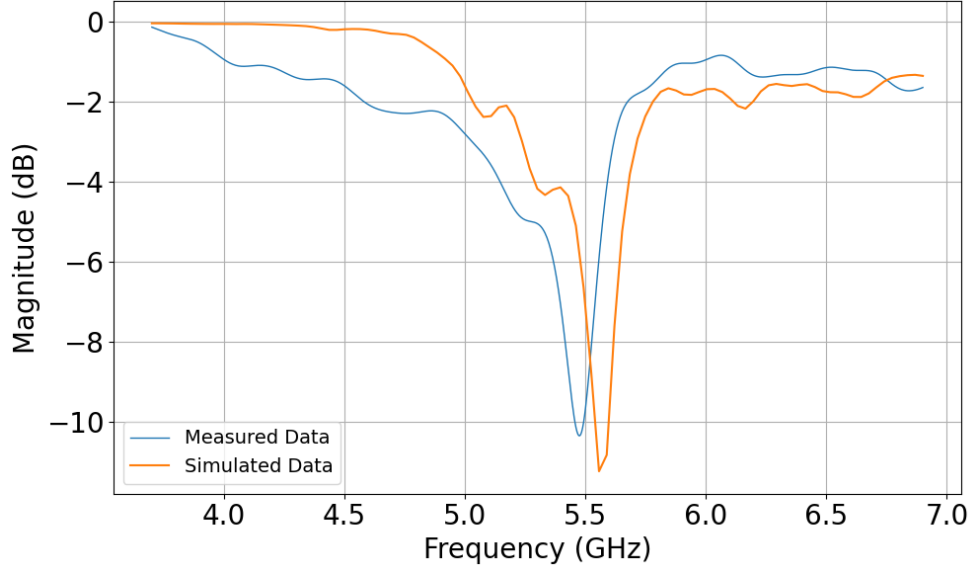


Figure 14. Comparison of simulated and measured results of the checkerboard metasurface.

5. Application 2: Beam Steering

Although the GA inverse algorithm successfully designed the unit cells, the optimization process remains computationally expensive because every new design begins with a randomly generated pixel mask. Depending on the target response, convergence may require thousands of full-wave simulations. While this approach is practical for only two-phase states, beam-forming metasurfaces typically require multiple discrete reflection phases distributed across the aperture, resulting in increased computational cost.

To investigate beam steering, we conducted a second study using different unit cell size, substrate material, and pixel dimensions at a center frequency of 10 GHz. Instead of optimizing only two-phase states, we generated approximately 23,000 unique 8×8 pixelated unit cells using constrained random sampling. This approach enforced fixed metal pixel populations of 8, 16, 24, 32, 40, 48, and 56 active pixels to ensure that the database contained a balanced distribution of pixels while achieving phase diversity at 10 GHz.

We simulated every randomly generated unit cell using the automated HFSS framework, producing a database of reflection magnitude and phase responses over the operating bandwidth of 8 to 12 GHz. Rather than searching for a single optimal design for each phase target, the objective of this process was to establish a large database of candidate unit cells with different phases for reflectarray implementation.

For the beam-steering study at the 10-GHz design frequency, each unit cell measured 6.5×6.5 mm, corresponding to approximately $\frac{\lambda}{4.62}$. Each pixel for this unit cell is 0.8125 mm. The substrate was a 3.048-mm-thick Rogers 6035HTC substrate with a dielectric constant of $\epsilon_r = 3.6$ and loss tangent of $\tan\delta = 0.0013$. One example of randomly generated pixelated geometries is shown in Figure 15a.

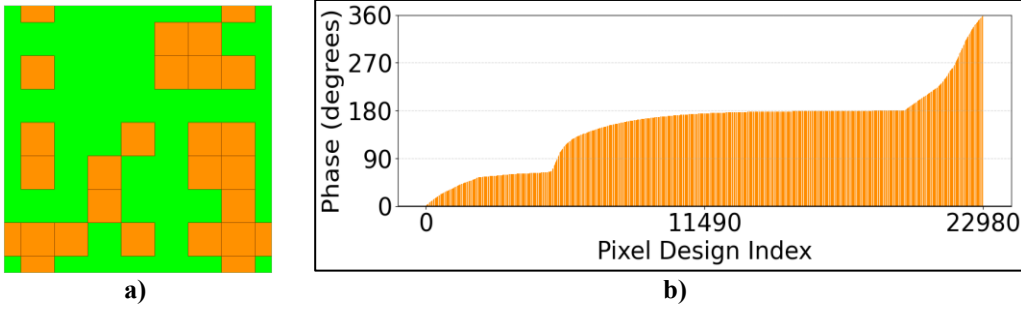


Figure 15. Pixelated unit cell database used for the beam-steering design: a) example of generated unit cell and b) reflection phase of the 23,000 generated candidate designs at 10 GHz.

Grant et al.⁷ investigated a similar pixelated unit cell configuration using the same overall unit cell dimensions but with different pixel dimensions. The reflection phases reported in Grant et al.⁷ follow a similar trend to the phase distribution shown in Figure 15b. In this work, we simulated a larger number of randomly generated unit cells to provide a denser sampling of the available reflection phases.

We evaluated the reflection responses of the generated designs at 10 GHz to determine the available phase coverage. Retaining candidate unit cells with a reflection magnitude greater than 0.9 reduces the loss introduced when constructing the reflectarray. Figure 15b shows the reflection phases of the retained designs. The distributed dataset of pixelated geometries showed phase coverage throughout 0° to 360° , demonstrating that a large set of pixel masks can provide the phase required for beam forming.

We designed the reflectarray under broadside illumination, where the incident plane wave propagates normal to the surface at $\theta = 0^\circ$. The goal was to redirect the reflected field away from the broadside specular direction and toward a desired steering angle of $\theta = 40^\circ$. Figure 16 illustrates both the incident and desired reflected directions of the incident wave.

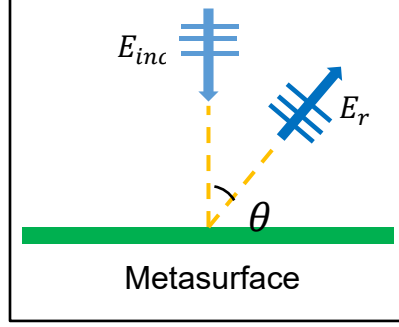


Figure 16. Reflectarray geometry under broadside illumination $\theta = 0^\circ$ with the reflected beam directed toward $\theta = 40^\circ$.

Under broadside plane wave illumination, the incident field has a uniform phase front across the reflectarray aperture. Redirecting this field toward 40° requires the introduction of a spatial phase progression along the surface. Each element contributes to the total reflected field with a phase determined by its position and its assigned reflection phase.⁸ By properly varying the reflection phase across the aperture, the contributions from the individual elements combine constructively in the desired direction. For an array of $M \times N$ elements, we represent the total reflected field as the summation of the individual element contributions:

$$E(\theta, \phi) = \cos^{q_e} \theta \sum_{m=1}^M \sum_{n=1}^N e^{-jk(|\vec{r}_{mn} - \vec{r}_f| - \vec{r}_{mn} \cdot \hat{u})} e^{j\phi_{mn}},$$

where q_e is the power patterns of the RIS element; θ is the observation angle measured from the broadside direction of the RIS; ϕ_{mn} is the reflection phase applied by the m, n -th RIS element; k is the wavenumber; r_{mn} is the position of the m, n -th element from the reflectarray center; r_f is the distance from the feed to the reflectarray elements; and $\hat{u}$ represents the observation direction. The associated phase term in red corresponds to the phase accumulation from the feed to each element and toward the observation direction. The phase term in blue corresponds to the phase shift applied by each reflectarray element.

For broadside illumination, we determine the required phase distribution by the phase progression needed to compensate for the path difference from each element toward the desired 40° direction. The resulting phase distribution provides the condition for constructive interference in the steered direction while reducing the reflected field in the original broadside direction. We calculated the required continuous phase at each of the 23×23 element locations for a steering angle of 40° . Figure 17a shows the resulting ideal phase profile, where every element location assumes an arbitrary reflection phase. We quantized the continuous phase

distribution into 10 discrete states separated by 36° , being $\{0, 36, 72, 108, 144, 180, 216, 252, 288, 324, 360\}^\circ$.

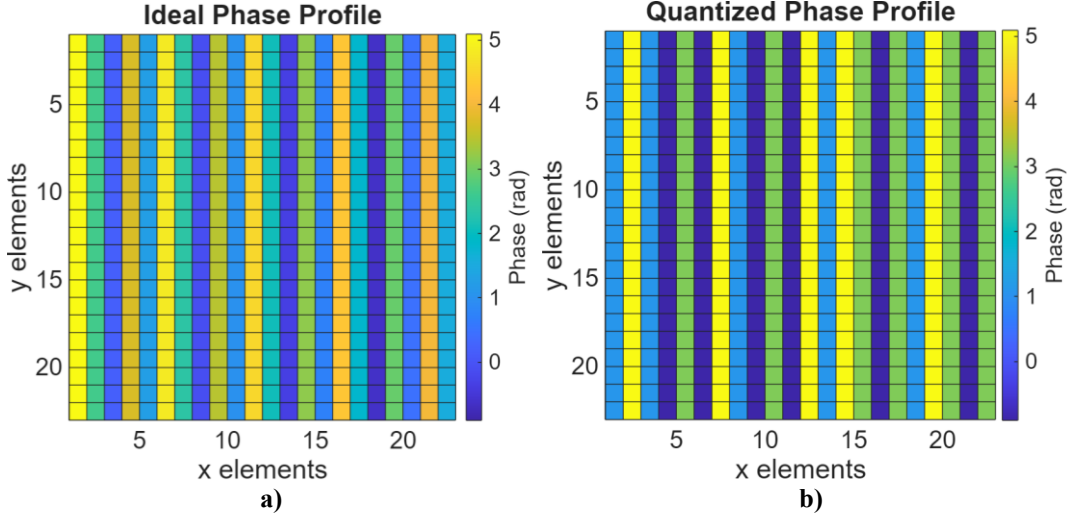


Figure 17. Reflectarray phase distribution for 40° beam steering under broadside illumination: a) ideal continuous phase profile and b) phase profile quantized into 10 discrete states.

For each desired phase state, we selected a pixelated geometry from the database based on its simulated reflection response at 10 GHz. The selected geometries maintained a reflection magnitude greater than 0.9 while providing a reflection phase near the corresponding desired state. Figure 18 shows the 10 selected pixelated geometries that demonstrate how different arrangements of the same binary pixels produce the range of phases needed for beam steering. After identifying these 10 states, we replaced the continuous phase required at each location of the reflectarray by the nearest available phase state. Figure 17a shows the continuous phase profile calculated for 40° steering, while Figure 17b shows the corresponding phase distribution after phase quantization.

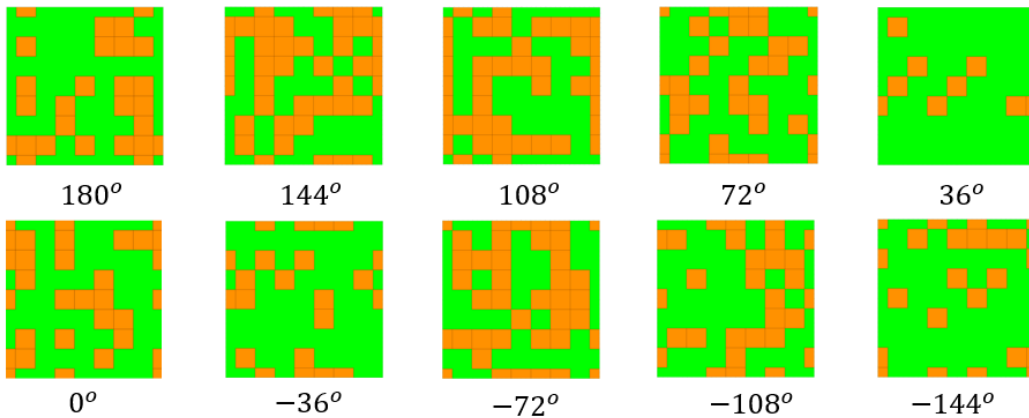


Figure 18. Selected pixelated unit cells representing the 10 discrete reflection phase states at 10 GHz.

As shown in Figure 17, the quantized phase maintains the overall spatial phase progression of the ideal distribution. The difference between the continuous phase and the nearest available phase state introduces a phase quantization error at each element. With a 36° spacing between adjacent states, the maximum error introduced by ideal nearest-state quantization is $\pm 18^\circ$.

6. Beam-Steering Metasurface

After quantization, the corresponding pixelated unit cell from Figure 18 replaces each phase value in Figure 17b. The final reflectarray consists of 23×23 elements, resulting in a total of 529 individually assigned unit cells. With each unit cell period of 6.5 mm, the measured metasurface aperture dimensions are 149.5×149.5 mm, corresponding to approximately $5\lambda \times 5\lambda$ at the 10-GHz design frequency. Figure 19 shows the completed pixelated reflectarray. The collection of these locally selected phase states produces the spatial phase progression needed to redirect the broadside incident field toward 40° .

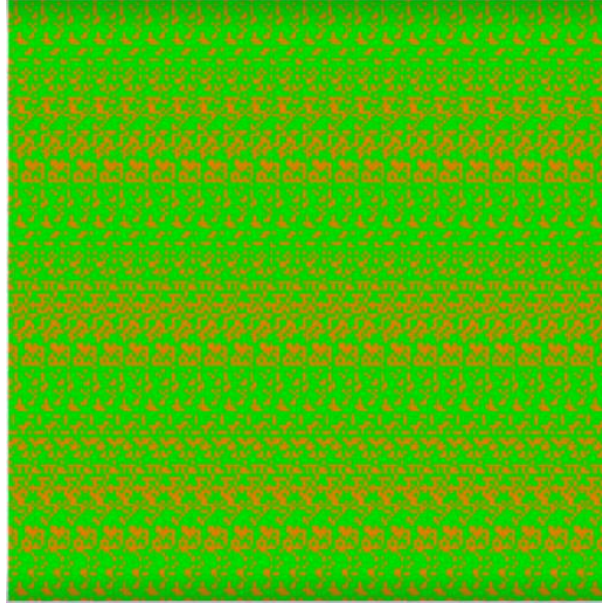


Figure 19. 23×23 pixelated reflectarray constructed with 10 quantized phase states for 40° beam steering.

Using HFSS, we simulated the reflectarray under the same broadside illumination used to calculate the phase distribution. We evaluated the far-field scattered response to determine whether the quantized pixelated metasurface successfully redirected the incident energy toward 40° . The results in Figure 20 show beam steering towards the desired direction of 40° with 10 dB of side lobe level. To further evaluate the beam-steering performance, the simulated response was compared with the theoretical array factor analysis. Both responses produce a main

beam near 40° , indicating that the quantized phase distribution successfully redirects the broadside incident field toward the intended steering direction at the expense of initially higher sidelobe levels.

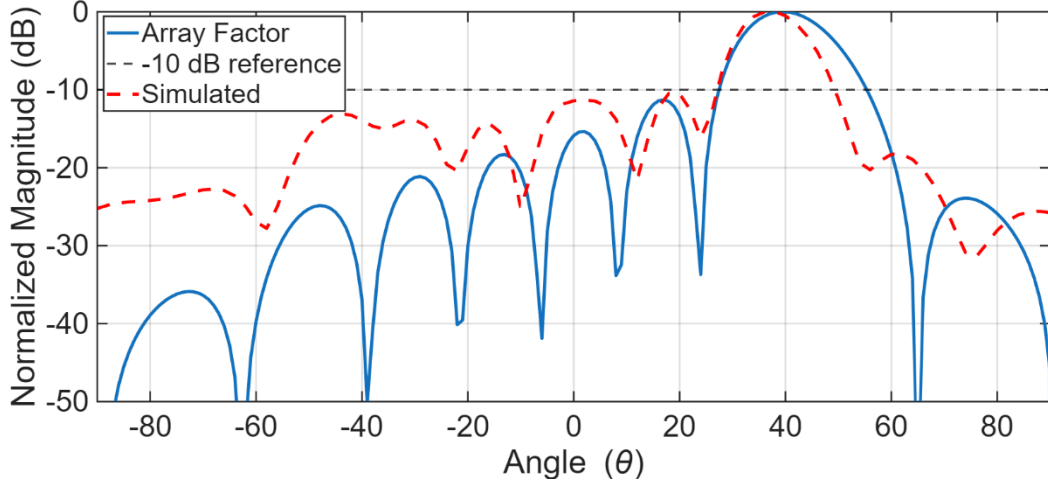


Figure 20. Comparison of normalized beam-steering performance of the pixelated reflectarray at 10 GHz between theoretical array factor analysis and full-wave simulation.

7. Conclusion

This work demonstrates an automated framework for generating and simulating pixelated metasurface unit cells. The framework was first combined with a binary GA to inverse design two-unit cells for checkerboard backscattering reduction. The resulting metasurface achieved more than 10 dB of backscattering reduction in both simulation and measurement. We then used the framework to generate a database of approximately 23,000 pixelated unit cells for beam steering. By selecting 10 phase states from this database, we constructed a 23×23 reflectarray, which successfully redirected the incident field toward the desired direction of 40° in an HFSS full-wave simulation.

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List of Symbols, Abbreviations, and Acronyms

AI	Artificial Intelligence
C	Cost
Γ_{GA}	Complex Reflection Coefficient Obtained from the GA Design
Γ_T	Target Complex Reflection Coefficient
ϵ_r	Dielectric Constant
EM	Electromagnetic
GA	Genetic Algorithm
HFSS	High-Frequency Structure Simulator
N_{nf}	Total Number of Frequency Points Evaluated
nf	Frequency Being Evaluated
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
$\tan\delta$	Loss Tangent

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