A Modified Approach to Optimize Phase-Gradient Metasurface-Based Beam-Steering Systems

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***Abstract*—In this work, we compare two different simulation environments to aid in optimizing Phase-Gradient Metasurfaces for applications in beam-steering antenna systems. Such a strategical arrangement of supercell for optimization reduces the simulation cost and time and enhances the design efficiency. A Floquet-analysis-based optimization approach is followed to reduce the grating lobes in a Near-Field Meta-Steering system.**

***Index Terms*—Metasurfaces, Beam-steering, Phase-gradient metasurfaces, near-field phase transformation, SATCOM, LEO.**

I. INTRODUCTION

A growing interest in mobile satellite communication and satellite-based internet with global coverage has increased the demand for high-gain antennas with dynamic beam-steering capability. Several limitations associated with already existing beam-steering technologies, such as parabolic dishes and electronically steered phase-arrays, have had researchers investigate prospective alternatives, among which Near-field Meta-Steering (NFMS) systems stand as a potential candidate [1]. In addition to being a completely passive beam-steering solution, the NFMS systems are planar, low-profile, consume low power, have high gain, exhibit broad beam-steering capability, and are aesthetically pleasing [1], [2]. In an NFMS system, the relative rotation between the pair of phase-gradient metasurfaces (PGMs) placed in the near-field region of a high gain base antenna steers the antenna beam in 3D volume [2]. The popularity of this method gained impetus in 2017, and since then, several significant contributions have been made based on this concept [3].

One of the challenges in existing NFMS systems is increased sidelobes and grating lobes with beam-steering. The PGMs are periodic structures inherently prone to grating lobes. When used with a base antenna to steer the beam, they exhibit increased grating lobes due to spurious diffraction [4]. Continuous effort is being made to optimize the metasurfaces to suppress the unwanted grating lobes and enhance the efficiency of the NFMS sytems [4]. In this work, we use Floquet-mode-based analysis to optimize PGM used in NFMS systems. We investigate two simulation environments for this optimization and propose that one is better than the other in terms of computational resource usage and total time consumed.

II. FLOQUET BASED OPTIMIZATION APPROACH

Fig.1 shows a periodic supercell with a phase gradient of 30°. A supercell represents one period of a PGM and essentially mimics a diffraction grating and a detailed design approach is provided in [4]. It is simulated with Floquet port excitation and periodic boundary conditions along x and y directions in CST MWS. It supports 10 propagating modes (each mode corresponds to a lobe in the far field [4]). The optimization goal is to bring 9 undesired modes (UDMs) that correspond to grating lobes below -35 dB and simultaneously maintain the desired mode (DM) corresponding to the main lobe above -0.1 dB. The fitness function (FF) is defined as a weighted sum of objectives mentioned above to suppress the unwanted grating lobes selectively:

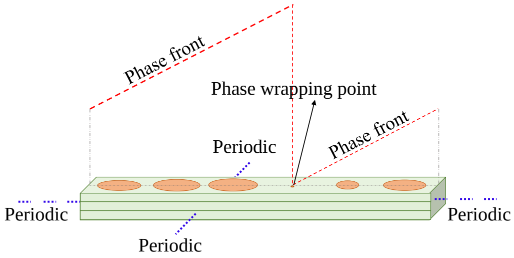

Fig. 1. Supercell with 30° phase-gradient.

$$FF = [w_m\{\max(0,(-0.1-DM))\}]^2 \qquad (1)$$
$$+\sum_{i=1}^{9}[w_i\{\max(0,(UDM-(-35)))\}]^2,$$

where w_m is the weight assigned to the DM, and w_i are the weights assigned to the UDM. The value of w_m is fixed to 20, and w_i can vary between 1 to 19 with higher weights assigned to undesired modes with higher magnitude and vice-versa.

A. *Case I: Optimizing single supercell*

The PSO algorithm in CST optimizer is used to optimize supercell shown in Fig.1 with normal plane wave incidence for lower PGM as explained in [4] and oblique plane wave incidence (with $\theta_{in} = 30°$) for upper PGM as detailed in [5]. The optimized supercells are used to create a complete 2D upper and lower PGM to be used above a base antenna in NFMS system design.

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B. Case II: Optimizing supercells as a pair

An alternate approach is to optimize the PGM pair directly. For this purpose, one supercell is placed $\lambda_0/4$ above the other, as shown in Fig. 2. The lower supercells is oriented at $\psi_1 = 0°$ and the upper supercell is oriented at $\psi_2 = 180°$, with respect to x-direction. This configuration of PGM-pair in an NFMS system creates the main beam in the broadside direction. A similar optimization approach as described in Case-I is implemented and the dimensions of patch in both supercells are varied simultaneously. Thus, the number of variables do not increase. Since the overall length of this model is same as the model in Case-I the number of Floquet modes supported by this configuration is also 10. The same fitness function defined in (1) is used to enhance the DM and suppress the UDMs to eventually suppress the grating lobes.

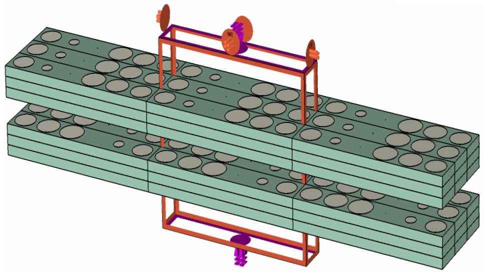

Fig. 2. Two supercells placed one above the other, $\psi_1 = 0°$ and $\psi_2 = 180°$.

III. RESULTS

The optimized dimensions for Case-I and Case-II are compared in Table I. The supercells optimized in the two cases are used to design 1D PGMs by periodically repeating them 6 times along x-axis to match the aperture of actual antenna as shown in Fig. A pair of these PGMs is simulated in CST time-domain solver with "open add space" boundary in the x -direction and periodic boundary $(E(t) = 0)$ in the y-direction to predict their performance when placed above a base antenna in pairs to steer the beam. The predicted far-field pattern for a pair of unoptimized PGMs is plotted in Fig 3. The far-field pattern predicted for PGM-pair in Case I and Case II are compared in Fig 4. It is observed that both optimization approaches have reduced the grating lobe at ±30° which is above 10 dB in the far-field pattern for unoptimized PGM pair.

TABLE I
OPTIMIZED DESIGN PARAMETERS OF SUPERCELL IN mm.

Case-I Lower PGM *Length, Radius*	**Case-I Upper PGM** *Length, Radius*	**Case-II** *Length, Radius*
L1 = 3.5, R1 = 1.99	L1 = 3.27, R1 = 2.12	L1 = 3.52, R1 = 2.01
L2 = 3.85, R2 = 2.14	L2 = 3.93, R2 = 2.1	L2 = 3.64, R2 = 2.18
L3 = 4.1, R3 = 2.22	L3 = 4.11, R3 = 2.18	L3 = 4.1, R3 = 2.29
L4 = 0.09, R4 = 0.05	L4 = 0.1, R4 = 0.04	L4 = 0.08, R4 = 0.05
L5 = 2.99, R5 = 0.97	L5 = 3.07, R5 = 0.87	L5 = 3.02, R5 = 1
L6 = 3.3, R6 = 1.9	L6 = 2.93, R6 = 1.93	L6 = 3.26, R6 = 1.89

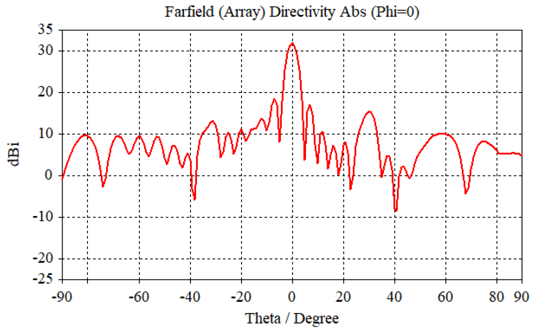

Fig. 3. Broadside radiation pattern for unoptimized PGM pair

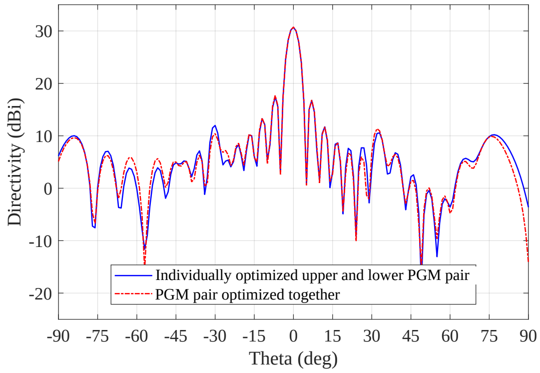

Fig. 4. Comparison between the broadside radiation pattern for optimized PGM-pair in Case-I with Case-II).

IV. DISCUSSION

The radiation pattern for both Case-I and Case-II is very similar, and the grating lobes are significantly suppressed. The simulation time for a single supercell is approximately 7 minutes and 21 seconds. On the same computer, the supercell-pair simulation takes 9 minutes and 47 seconds. Separately optimizing each supercell (lower and upper) will be time and resource-consuming in terms of computational memory and cost. Thus, optimizing supercell as a pair is an economical, time-efficient option and a more accurate approach to designing a PGM-pair above a high-gain base antenna with uniform plane wave radiation.

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