Tunable Optimal Anomalous Reflection Using Discrete Impedance Metasurfaces

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Abstract—The cutting-edge RIS technology enables accurate management of electromagnetic waves within wireless environments. In this study, we aim to achieve the maximal efficiency of the targeted anomalous reflection without scattering at unwanted angles even if the needed reflection angle is very large. To address this, we present a robust optimization technique that utilizes a mode-matching approach for a periodically non-uniform metasurface. It uses the apparatus of discretized sheet impedance and ensures the easy implementation and passivity of the metasurface.

Index Terms—Reconfigurable Intelligent Surface (RIS), Wireless communication, Angular stability.

I. INTRODUCTION

The quest for higher data rates in wireless networks has spurred research in higher-frequency wireless communication for 5G and 6G cellular networks [1], [2]. Reconfigurable intelligent surfaces (RIS) are panels with active/passive elements that reshape the communication environment, enabling signal reception in non-line-of-sight (NLOS) directions. The current RIS-based wireless communication often employs phased-array design [3]. This involves locally periodic approximation to scatter incoming waves per unit cell, as depicted in Fig. 1 of [4]. Accepting this approximation, reflector efficiency diminishes notably as the angle between incident and reflected waves widens. Estakhri and Alù [5] identified the impedance mismatch between incoming and desired wavefronts as the intrinsic constraint of locally passive surfaces. Hence, to attain perfect anomalous reflection, incorporation of evanescent modes on the surface is necessary [6]. Addressing this impedance mismatch could considerably enhance reflector efficiency, especially at wider angles.

Our paper focuses on a novel design strategy to attain optimal anomalous reflection for large tilt angles of the reflected wave. We consider an periodically non-uniform metasurface (MS) as an impedance sheet on a metal-backed dielectric substrate. We start by discretizing this impedance sheet into finite elements – unit cells characterized by a specific value of the local sheet (grid) impedance. In our case, the problem is 2D and these unit cells are impedance strips. For the given incidence angle and the needed tilt of the reflected wave the period of our MS is determined. In our impedance sheet, this period can be identified as a supercell consisting of impedance strips and we need to optimize the distribution of the sheet impedance over the supercell that grants the minimal scattering loss. We find the needed sheet impedances of the strips via the inverse design method – maximizing the desired Floquet harmonic amplitude, that automatically implies minimal total value for parasitic Floquet harmonics, propagating and evanescent.

The similar technique was earlier developed by D.-H. Kwon’ [7]. The novelty of our approach is related with the inherent structural discreteness. The Kwon’s method implied the continuous sheet impedance and its numerical application via the impedance discretization leads to the worsening compared to the optimal results. In contrast, our technique employs the discretized sheet impedance from the outset, enabling direct realization via appropriate unit cell and load impedance design which are optimal for the given unit cell size. Moreover, we ensure the passivity by assigning reactive values only, that advantageously shares our work from the row of previous similar studies [8], [9], [10]. By manipulating varactor diode voltage, optimal anomalous reflection can be achieved for discrete tilt angles by assigning desired capacitance sets to unit cells.

II. PROBLEM FORMULATION

In this study, our goal is to maximally approach the full deflection of incident waves from the zero incidence angle to significant tilts, namely ∼ 60°–90°. Our method can be called the sheet (grid) impedance approach. First, we use the non-local strategy to obtain the desired sheet (grid) impedance values of unit cells. Next, we optimize the capacitance values of varactor diodes while considering periodic boundary condition and performing accurate numerical calculation of the far scattered field. In this stage, we introduce the lumped loads resulting in the final optimization of the MS.

As depicted in Fig.1(c), a supercell in the periodically non-uniform MS includes K discrete elements serving as unit cells. For reconfigurability, unit cells maintain the same shape and differ by the lumped load impedance values. Fig.1(b) demonstrate the shape and the geometrical parameters of the unit cell. For tunability, the first gap, g1 incorporates the use of a hyper-abrupt varactor diode (MAVR-000120-14110P). This varactor diode can operate up to 70-GHz, offering low serial resistance and a capacitance range of 0.1 to 1.1 pF [11]. We need a maximal control of the grid impedance, that
demands the opportunity to minimize the overall capacitance of the grid. For it we incorporate an additional fixed capacitor (GJM1555C1HR15RB12D) in the second gap, denoted as $g_2$. This capacitor is advantageous due to its fine capacitance tolerance of $+/-0.03pF$, and it has a nominal capacitance value of 0.15pF [12]. The sheet impedance $Z_s(x)$ or admittance $Y_s(x)$ is a periodically modulated function (period $D$), expressed using a Fourier series expansion:

$$Z_s(x) = \sum_{m=-\infty}^{+\infty} a_m e^{-jm\beta_M x}$$

$$Y_s(x) = \sum_{m=-\infty}^{+\infty} b_m e^{-jm\beta_M x}$$

in which $\beta_M = 2\pi / D$ is the spatial modulation frequency of the surface impedance, and $a_m$, $b_m$ are the Fourier coefficients of the impedance and admittance functions, respectively.

When a periodically non-uniform surface is illuminated by a plane wave at an incident angle $\theta_i$, it scatters discrete sets of Floquet harmonics including propagating and evanescent waves. The tangential wave vector for these scattered Floquet modes is given as $k_{x,n} = k_0 \sin \theta_i + n\beta_M$, where $k_0$ is free space wavenumber ($k_0 = \omega_0 \sqrt{\mu_0 \varepsilon_0}$), $\omega_0$ is the angular frequency of the incoming wave, and $n$ denotes the number of Floquet harmonics. The far-field zone propagating modes with reflection angle $\theta_r$ fulfill $|k_{x,n}| < k_0$. Therefore, we can express the $n$-th propagating mode’s reflection angle as:

$$\sin \theta_{r,n} = \sin \theta_i + \frac{n\lambda}{D}$$

where $\lambda$ is the working wavelength.

Given the surface impedance and incident angle, the amplitudes and phases of all scattered Floquet harmonics can be uniquely determined via the mode-matching technique ([13], Sec. 6.2) at the metasurface plane ($z=0$). To aid the analysis, we adopt a transmission line model as shown in Fig. 1(d), treating the grounded substrate as a short-circuit transmission line of length $h$ ($h$ is the substrate thickness). With the periodically nonuniform MS generating a multitude of propagating and evanescent waves, expressing corresponding voltage and current becomes feasible using an infinite series:

$$I_s(x) = \sum_{n=-\infty}^{+\infty} i_n^s e^{-jk_{x,n}x}$$

$$V_s(x) = \sum_{n=-\infty}^{+\infty} v_n^s e^{-jk_{x,n}x}$$

The current and voltage should adhere to Ohm’s law ($V_s(x) = Z_s(x).I_s(x)$). Further details can be found in [14], where the same method has been adopted to design the “static” MS enabling the creation of anomalous reflectors at $\theta_i = 0^\circ$ in the D-band.
After obtaining the discretized sheet impedance, the surface (input) impedance of the MS can be calculated as the parallel connection of the discretized sheet impedance \( Z_{gd} \) and the surface impedance of the grounded substrate \( Z_{tot} \). We denote the surface impedance of our MS as \( Z_{tot} = Z_{gd}||Z_{gd} \). The phase and amplitude of all the scattered modes can be determined via this surface impedance as follows:

\[
\Gamma_{TM} = \frac{Z_0 - Z_{tot}}{Z_0 + Z_{tot}} \quad \text{(6)}
\]

\[
\Gamma_{TE} = \frac{Y_0 - Y_{tot}}{Y_0 + Y_{tot}} \quad \text{(7)}
\]

where \( Z_0 \) is the diagonal matrix filled with the free-space wave impedance. Then, for the tangential component of the reflected electric and magnetic fields we can write respectively for TE and TM:

\[
E_r = \Gamma_{TE}E_i, \quad H_r = \Gamma_{TM}H_i.
\]

The outlined analytical approach allows us to retrieve all scattered harmonics, encompassing both propagating and evanescent waves. However, computing specific Fourier coefficients \( a_n \) or \( b_n \) for individual harmonics is a complex task. Our goal is to identify optimal combinations of discrete impedance strips \( (Z_{1...K}) \) that maximize the desired propagating harmonic. This endeavor transforms the design process into an inverse design.

For the incident TE polarized wave, we put \( E_i = [0, ...0, 1, 0, ...0]^T \) as the incident electric field vector. The reflected electric field vector can be expressed as \( E_r = [0, ...0, A_{goal}, ...0]^T \). According to [15], the target amplitude to ensure complete incident power redirection for our desired anomalous reflection is \( A_{goal} = \sqrt{\frac{\cos\theta_i}{\cos\theta_r}} \). The optimization scheme can be outlined as follows. We start from initial values for discrete impedance strips \( (Z_{1...K}) \). Next, using Eq. 3, we set the supercell period based on the desired reflection angle to be \( D = \lambda/\sin\theta_r \).

Next, we perform the optimization in MATLAB assuming an array of \( Z_{1...K} \) and computing the amplitude of the desired reflected harmonic, denoted as \( A_{cal} \) for given value of \( Z_{1...K} \). Indeed, the goal is to achieve \( |A_{cal}| = |A_{goal}| = 1 \), i.e. \( A_{goal} \) is an imaginary exponential. Defining the cost function as \( F(Z_{1...K}) = |A_{cal} - A_{goal}| \), and employing the MultiStart and Fmincon optimization algorithms, Matlab searches for the proper set of values \( Z_{1...K} \) which minimize the cost function.

### III. RESULTS, AND DISCUSSION

Operating at 8 GHz, we commence optimization from the normal direction \( (\theta_i = 0^\circ) \). For exclusive anomalous reflection toward \( \theta_r \), we apply Eq. 3 with \( \theta_r = 77^\circ \) and eight discretized impedance sheet elements \( (K=8) \), adopting the unit cell dimension \( P = 4.8 \) mm. We choose Rogers RT5880 substrate, possessing relative permittivity 2.2, \( h = 1.575 \) mm thickness, and 0.0002 loss tangent. Simplifying practical implementation of sheet impedance, we utilize an optimization technique ensuring that \( Z_{1...K} \) falls within the interval \([-300j, -50j]\).
Fig. 2(a) displays numerical results of scattered harmonic amplitudes for an infinite periodic structure ($K=8$, $\theta_r = 77^\circ$). Discretized grid impedance values in the initial stage are as follows: $Z_{1\sim8} = [-103j, -82j, -80j, -123j, -185j, -111j, -146j, -91j]$. These outcomes showcase complete incident power reflection in the desired direction ($n = 0$), with minimal amplitudes for specular reflection ($n = 0$) and parasitic ($n = +1$) harmonic order. In Fig. 2(c), we depict similar results for the case $K=9$ when $\theta_r = 60^\circ$. In this example, initial approximation values for discretized grid reactance are: $\text{Im}(Z_{1\sim9}) = [-85, -70, -185, -185, -185, -102, -99, -101]$. The next step is to approach the ideal discretized grid impedance profile. For these two examples, the results are shown in Fig. 2(a) and (c), through the designed unit cell. Using the curve in Fig. 1(a), we can straightforwardly obtain the required capacitances $C_n$ for obtaining the ideal values $Z_{1\sim8}$ and $Z_{1\sim9}$, respectively. Besides, the angular stability [16] of the grid impedance of our designed MS is clearly seen in Fig. 1(a). Fig. 2(b) and (d) display reflection amplitude of the infinite periodic MS for the first ($K=8$, $\theta_r = 77^\circ$) and second ($K=9$, $\theta_r = 60^\circ$) examples, respectively. The dotted line represents scattering coefficient for the desired Floquet harmonic ($n = -1$), assuming lossless diodes, indicating a reflection amplitude near 0.99. As a result, power efficiency, quantified as squared scattering parameter ($\eta = |S_{11}|^2$) for each mode, reaches 98%. These findings validate full-wave numerical simulations with theoretical predictions, confirming full reflection redirection toward desired anomalous reflection. However, considering diode and capacitor losses, efficiency for Floquet harmonic ($n = -1$) reduces to $\eta_{K=8} = 0.81\%$ and $\eta_{K=9} = 0.88\%$.

IV. CONCLUSION

In this work, we have developed the grid impedance method for the optimization of periodically non-uniform metasurfaces enabling efficient anomalous reflection for large tilt angles – maximally close to the grazing direction. Of course, the imposed finite element size limits the achievable reflection angles, but additional impedance elements introduced on the second stage of the procedure allow us to maximally extend the coverage.

Rapid numerical optimization provides necessary discretized sheet impedance profiles. Our optimization techniques allowed us to achieve over 98% efficiency for the lossless scenario. Prospective applications could involve Time-division multiple access (TDMA) RIS-based wireless communication, directing efficient anomalous reflection to multiple users in distinct time slots.

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