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26 October 2026

Current-only Inverse Design of Anomalous Reflection Metasurfaces

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***Abstract*—We discuss the automated design (inverse design) of metasurfaces to achieve anomalous reflection and minimize radiation into the specular direction – a condition often referred to as "perfect anomalous reflection". We effect the design with a current-only method, in which the object of the optimization is the current (density), as opposed to the surface impedance; the latter is obtained from the current in a post-processing step. The method obtains a significant reduction of radiation in unwanted directions, confirmed by simulation with an external (CST) tool of the entire structure. This communication also adds to the ongoing discussion on locality vs. non-locality to achieve the desired pattern.**

I. Introduction

Metasurfaces are two-dimensional engineered structures composed of a large number of sub-wavelength scatterers, for the control and manipulation of electromagnetic waves [1].

Among the many applications of metasurface, significant effort has been devoted recently to employing them in the context of Smart Radio Environments (SRE) and more specifically in Reflecting Intelligent Surfaces (RIS) (a.k.a. Smart Skins).

Of special importance in this field is the issue of designing planar metasurfaces able to reflect a (locally plane) wave in a desired direction different from the natural specular reflection; this is called Anomalous Reflection, and sometimes also "non-Snell" reflection. This can be done in a simple manner, but that design does not suppress the specular reflection. This is undesirable in most practical applications, and approaches have been studied to overcome this limitation.

This paper deals with the automated design (inverse design) of metasurfaces to achieve anomalous reflection and minimize radiation in the specular direction, a condition often referred to as "perfect anomalous reflection" [2]–[5].

II. Metasurfaces for Anomalous Reflection

In view of its sub-wavelength texture, the metasurface interaction with the field is usually approximated by the homogenizing approximation of surface Impedance Boundary Condition (IBC) linking the locally averaged tangent electric and magnetic fields:

$$\boldsymbol{E}_{\mathrm{t}}(\boldsymbol{r}) = \overline{\overline{\boldsymbol{Z}}}(\boldsymbol{r}) \cdot \boldsymbol{J}(\boldsymbol{r}), \qquad \boldsymbol{J} = \hat{n} \times \boldsymbol{H} \tag{1}$$

This is especially convenient in the design phase.

Under the IBC approximation and for an infinitely extended layered dielectric background, the original boundary-value problem can be recast in terms of the standard Electric-Field Integral Equation with IBC (EFIE-IBC), The electromagnetic scattering problem is formulated as an integral equation (EFIE-IBC),

$$\boldsymbol{E}_{\mathrm{inc}} + \mathcal{L}\boldsymbol{J} = \overline{\overline{\boldsymbol{Z}}} \cdot \boldsymbol{J} \tag{2}$$

where $\boldsymbol{E}_{\mathrm{inc}}$ is the incident (source) field, and $\mathcal{L}$ is the Electric Field Integral Operator for the layered background dielectric medium (see e.g. [6]). The current $\boldsymbol{J}$ is expanded as a linear combination of RWG basis function and the discretization of the problem follows the usual Method of Moments procedure with Galerkin testing, thereby resulting in a linear system.

A. Baseline Phase Gradient Design

In the specific case of anomalous reflection, the profile of the surface impedance can be found in closed form starting from the enforcement of the phase gradient of the local reflection coefficient. For a reflection with same polarization as the incident wave it is necessary to retain only one term of the (otherwise tensor) surface impedance, and for the TE case, e.g. one has

$$Z^{TE}(x) = \mathrm{j}\frac{\eta}{\cos(\theta_i)}\cot(\Phi(x)/2) \tag{3}$$

where $\Phi(x) = k(\sin(\theta_i - \sin\theta_r)x$ is the phase gradient required to obtain reflection in the desired θ_r direction, with $k = \sqrt{\omega\epsilon\mu}$ and η being the wavenumber and the wave impedance of the background medium.

Throughout this work we will consider the case of a medium with $\mu_{\mathrm{r}} = 1$, $\varepsilon_{\mathrm{r}} = 6.5$ and thickness $h = 2.286$ mm at a frequency of 8 GHz. The considered metasurface is a rectangle with length $L = 20\lambda \approx 600$ mm in the incidence plane $\phi = 0°$, and width $W = 2\lambda \approx 60$ mm across. The surface is discretized with 53 670 RWG basis functions in the EFIE-IBC solver.

We consider the case of incidence along $\theta_i = 0$ and a desired (anomalous) reflection in the direction $\theta_r = 70°$, in the $\phi = 0°$ plane.

The phase-gradient (PhG) impedance is shown in Fig. 1, with a regularization to exclude inductive (unfeasible) values. We solve the EFIE-IBC in (2) for this surface impedance and the resulting scattered field is shown in Fig. 4. As seen there, the desired anomalous reflection peak is indeed generated, along with its (unavoidable) specular direction at $\theta = -70°$ and the natural specular reflection at $\theta = 0°$ However, it is seen that the unwanted natural reflection is de-emphasized, at ~ -11dB from the desired radiation direction.

The next step is verifying the performance of the actual physical structure underlying the IBC distribution. We realize

the structure using square patches, depicted in Fig.2; we use the usual periodic approximation to compute the impedance chart shown in Fig.3; as seen there, the impedance range matches the one of the simulated IBC in Fig.1. The physical structure in Fig. 5 is then simulated with CST, yielding the result depicted in Fig.4. As apparent there, the suppression of the natural reflection has disappeared.

This highlights the shortcoming of the basic PhG approach, based on Physical Optics (PO) approximation. This fact has prompted research along different lines; probably the most consistent was the work of Tretyakov and co-authors [4], [5]. They have related the shortcoming to the *local* nature of the IBC; approached the design adding what they termed "non-locality" to the design, and demonstrated a reduction of the intensity of the unwanted reflection terms. That analysis and design method was based on a periodic approximation with a "super-cell" of a period large enough to allow the necessary number of Floquet wave into the visible.

We will address the IBC synthesis for anomalous reflection using the framework presented in [6]. An optimization problem is formulated where the design variable is the equivalent surface current only (not the impedance); the cost function to be minimized embeds physical constraints (passivity, absence of losses) and all design requirements (pattern masks, impedance range) *without* requiring the *surface impedance* explicitly (not even for impedance range). The functional is minimized with a non-linear conjugate gradient algorithm, with a closed-form line-search procedure that fully exploits the polynomial structure of the objective function. The algorithm is applicable to large structures by exploiting common fast numerical algorithms for the computation of the scattered fields from the currents.

This approach allows the minimal computational cost per iteration, as it never requires to solve the EFIE-IBC (2). This feature has an additional importance in the present endeavor: at all steps of the optimization, only the computation of the scattered field

$$\boldsymbol{E}_s = \mathcal{L}\boldsymbol{J}$$

is performed. This means that nowhere during current synthesis the *locality* of the IBC is assumed or employed. It can therefore be conjectured that the algorithm can escape the shortcoming of the IBC-based design.

Once the optimal current $\boldsymbol{J}$ is found, an IBC distribution *can* be computed from $\boldsymbol{J}$ and the associated field $\boldsymbol{E}_s$: but at this step that only amounts to taking the averages of both fields over the considered cell area – with both fields having been determined without any locality assumption or use of the IBC (3) or EFIE-IBC (2).

The only limitation is in the way the impedance of unit cells is computed to build a look-up table, as in Fig.3: we still use the periodic approximation. In it, there is no locality in the strict sense (all interactions are accounted for in the periodic environment), but the assumption of periodicity obviously limits accuracy, e.g. with respect to approaches where a super-cell of a wavelength is considered.

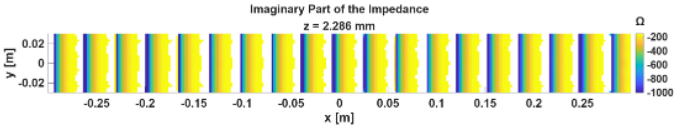

Fig. 1: Phase Gradient: Regularized Impedance.

The results of the current-only inverse design are shown in Fig.8. The synthesized impedance distribution in Fig.6 has significant deviation from a periodic pattern in the terminal part, which can be expected, and a non totally periodic pattern also elsewhere; the impedance range is the same as employed for the PhG. The resulting physical layout is shown in Fig.7 and the scattered field are shown in Fig.8. As can be observed, there is some deterioration in the actual structure performance with respect to the (more approximate) EFIE-IBC prediction, but a difference of about 5dB is preserved between the desired radiation and the natural specular one. Of interest is also the fact that the EFIE-IBC results of baseline PhG are significantly better than the corresponding ones for the inverse design; however, the latter remain largely unchanged through the actual realization, thus showing a higher degree of fidelity in representing the physics of the phenomena.

This means that the relevant phenomena are captured in this approach, unlike in the Phase Gradient IBC approach. Within the perspective of locality vs. non-locality of [4] one can infer that the current-only inverse design capture at least some of the effects of non-locality.

III. Conclusions

In this work, a current-based algorithm for the synthesis of metasurface has been employed in the design on Anomalous Reflection reflecting panels. Unlike the baseline Phase-Gradient approach, the synthesized structure mantains an appreciable difference in intensity between the desired anomalous reflection direction and the natural, unwanted specular direction. It is conjectured that this shows ability to capture non-local effects typical of straight surface impedance (IBC) approximation.

ACKNOWLEDGEMENT

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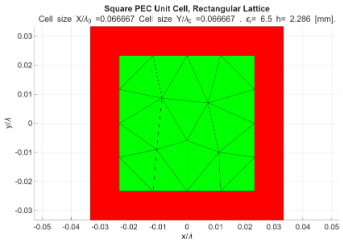

Fig. 2: Impedance Database: PEC Square Unit Cell mesh layout (green) and periodic lattice (red).

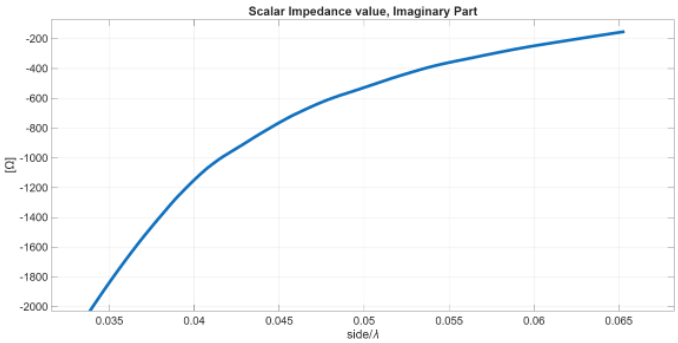

Fig. 3: Impedance Database: PEC Square Unit Cell, feasible impedance values.

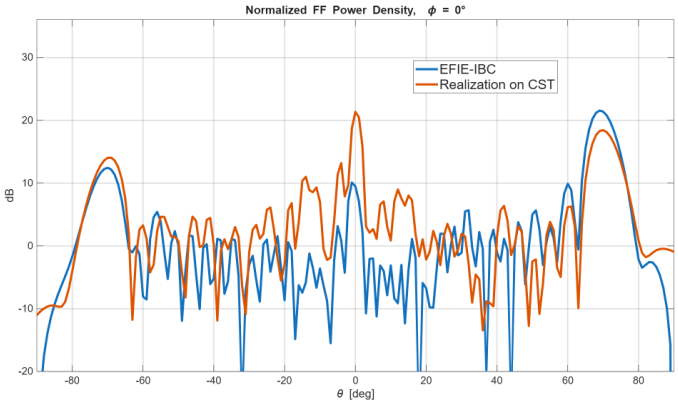

Fig. 4: Phase Gradient Design: Normalized Far Field cut at $\phi = 0°$ due to EFIE-IBC currents and the realization on CST.

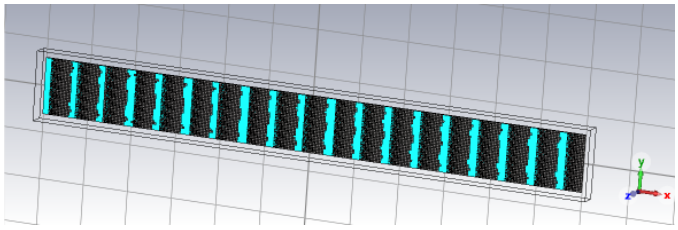

Fig. 5: Phase Gradient: Realized Layout in CST.

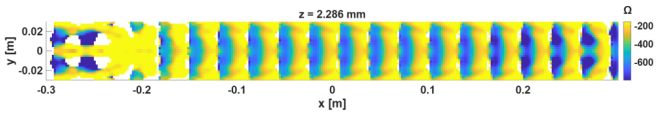

Fig. 6: Optimization: Regularized Impedance.

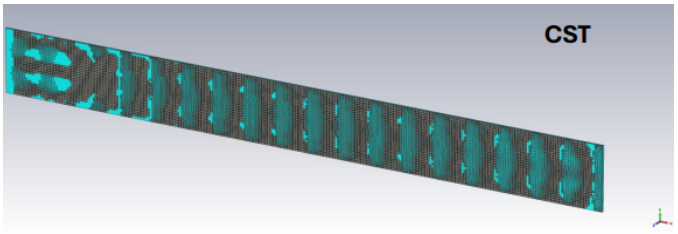

Fig. 7: Optimization: Realized Layout in CST.

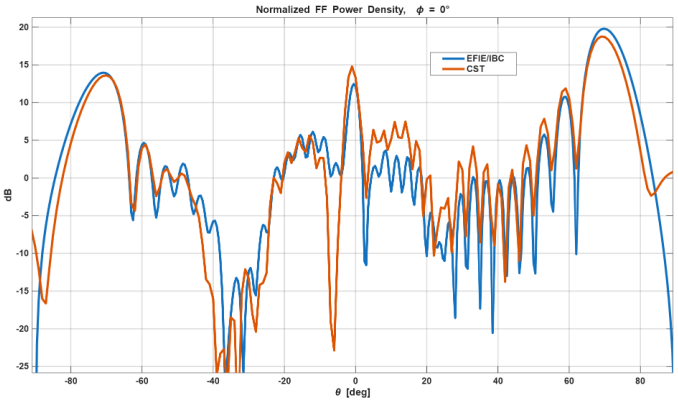

Fig. 8: Optimization Design: Normalized Far Field cut at $\phi = 0°$ due to EFIE-IBC currents and the realization on CST.

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