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Unit-Cell Design Framework for Current-Based Synthesis of Metasurface Antennas

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***Abstract*—The design of complex metasurfaces (MTS) is usually done in two steps: a) design of the surface impedance profile; b) realization of unit-cells, often using a periodic approximation. In this communication we propose an innovative approach for the comprehensive design of the MTS down to the unit-cell design. It is based on the recently introduced current-only metasurface synthesis. In the present approach, the unit-cell is designed based only on the optimized equivalent current, without having recourse to surface impedance. While maximally effective in association with current-only approaches, it can also be used with approaches aiming at the design of the impedance profile, still avoiding the periodic approximation.**

***Index Terms*—Antenna Synthesis, Metasurface Antennas, Method of Moments (MoM), Impedance Boundary Condition (IBC).**

I. Introduction

The intrinsic multiscale nature of metasurface antennas has prompted research on different methods for tackling their design in efficient ways. The most successful and widespread method involves a two-step procedure, in which the equivalent surface impedance is first designed by considering the system requirements (radiation pattern, input matching) and then locally implemented with shaped conductor patches on a grounded substrate [1].

The current-based synthesis method introduced in [2] allows to tackle the design of electrically large antennas by using fast numerical methods coupled with a tailored gradient-based optimization algorithm. This method, and similar ones where the current—not the impedance—is the quantity that is directly optimized [3], [4], need an additional step. In fact, from the knowledge of the optimized current, a procedure is needed to find the metallization shape that implements the required boundary condition. This can be done by finding the impedance value first, then picking the best candidate from a database of precomputed shapes analyzed using a periodic approximation [5]. Recently, new methods have been introduced where the periodicity assumption is dropped, and the cell is optimized in an environment that takes into account the actual optimized profile of the impedance [6].

In this work, we propose an innotive approach for the current-based synthesis of metasurface antennas, from system requirements down to the individual unit-cell layout. The method allows to find a suitable distribution of the metal over the dielectric layer without any periodicity assumption, and bypassing the notion of impedance altogether. The *local matching* of the boundary condition is expressed directly in terms of averages of the tangential current and electric field. The matching condition is then used in a local optimization problem to find the optimal shape.

II. Design of Metasurface Antennas

A. Metasurface modeling

While this approach does not explicitly employ the surface impedance as such, we review the modeling based on it for its relevance as underlying field homogeneization approximation.

Also, it serves to introduce the basics of the underlying electric-field integral equation (EFIE) and its Method of Moments (MoM) discretization; the latter are part of the current-only approach described further on.

The overall behavior of the metasurface is described using an infinitely thin layer of permeable surface impedance positioned on a grounded dielectric substrate. This response is governed by an Impedance Boundary Condition (IBC) that usually employs an impedance that exhibits tensor properties, but for the purpose of this contribution we will consider a scalar impedance $\overline{\overline{\boldsymbol{Z}}} = Z\overline{\overline{\boldsymbol{I}}}$:

$$\boldsymbol{E}_{\tan} = Z\,\hat{\boldsymbol{n}}\times\left(\boldsymbol{H}^{+} - \boldsymbol{H}^{-}\right) = Z\,\boldsymbol{J}, \tag{1}$$

where $\boldsymbol{J}$ is the equivalent surface electric current.
This problem can be reformulated as an *Electric Field Integral Equation* (EFIE-IBC),

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

where $\boldsymbol{E}_{\mathrm{inc}}$ is the incident source field and $\mathcal{L}$ is the *Electric Field Integral Operator* (EFIO).
We adopt a standard Method of Moments discretization [7], based on a triangular mesh and for which the approximation of the currents is given as a linear combination of the well known Rao-Wilton-Glisson (RWG) basis functions:

$$\boldsymbol{J}(\boldsymbol{r}) = \sum_{n=1}^{N} I_n \boldsymbol{\Lambda}_n(\boldsymbol{r}) \tag{3}$$

The integral equation (2) is tested with the *Galerkin's method*, resulting in the discrete form:

$$\mathsf{V}_{\mathrm{inc}} + \mathsf{L}\mathsf{I} = \mathsf{Z}\mathsf{I} \tag{4}$$

B. Current-only optimization approach

The optimization approach is based on the current-only algorithm presented in [2]. Defining respectively the optimization domain, the feeding system and the constraints, the problem can be formulated as the unconstrained minimization

of a non-convex objective function. This function is the sum of *realizability* and *radiation* constraints rearranged in such a way that they are explicitly dependent on the current only. We then solved the following minimization problem using a Non-Linear Conjugate Gradient algorithm:

$$\mathsf{I}^{\star} = \underset{\mathsf{I}\in\mathbb{C}^N}{\arg\min} \left(f_{\mathrm{rlz}}(\mathsf{I}) + f_{\mathrm{rad}}(\mathsf{I}) \right) \tag{5}$$

where $\mathsf{I}^{\star}$ is the array of the optimized current coefficients and I the one containing the coefficients of the current expansion.

C. Cell-based domain decomposition

The geometry of the surface is created using the domain decomposition approach described in [8], which confines the local current flow within small, electrically isolated cells. This approach relaxes the constraints, regularize the current and allows a faster convergence of the optimization. Additionally, it is more suitable for the implementation of the unit-cell design framework outlined in the next paragraph.

D. Unit-cell direct synthesis

At the end of the optimization process, instead of using the optimized current coefficients $\mathsf{I}^{\star}$ to compute the local value of impedance as in [2], [9], we built a cost function formulated in terms of the current and electric field only:

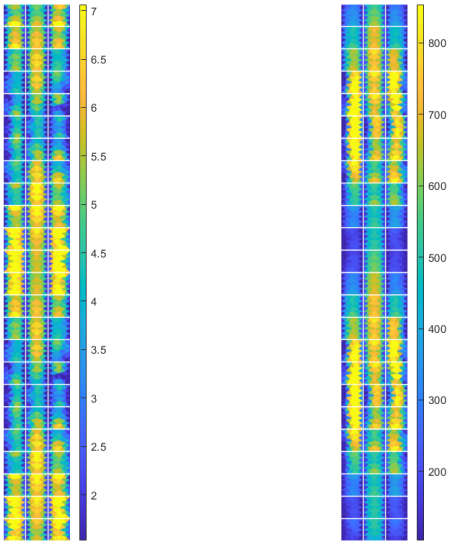
$$\rho = \frac{\|\boldsymbol{E}_{\mathrm{tar}} - \boldsymbol{E}_{\mathrm{opt}}\|}{\|\boldsymbol{E}_{\mathrm{tar}}\|} + \frac{\|\boldsymbol{J}_{\mathrm{tar}} - \boldsymbol{J}_{\mathrm{opt}}\|}{\|\boldsymbol{J}_{\mathrm{tar}}\|} \tag{6}$$

where $\boldsymbol{E}_{\mathrm{tar}}$ and $\boldsymbol{J}_{\mathrm{tar}}$ are respectively the target total electric field and the target current obtained averaging the local optimized values over the cells; and $\boldsymbol{E}_{\mathrm{opt}}$ and $\boldsymbol{J}_{\mathrm{opt}}$ are the total electric field and the current computed in a second optimization phase, imposing as RHS the total field radiated *only* taking into account the contribution of the currents *outside* the cell that we want to optimize.

We note that the proposed approach involves only quantities defined *inside* the *local* unit cell, while coupling with the rest of the metasurface is provided by the incident field, defined as the field radiated by all currents outside the considered cell. In this way, the size of the local optimization problem is reduced and the computational efficiency is maximized. This is particularly suitable as the number of unit cells for a realistic design, and therefore the number of local optimization instances to carry out, can easily reach tens of thousands. This is in contrast to previously proposed methods that require matching of the radiated fields over the entire surface *outside* the reference cell [6]. For the purpose of this manuscript, we employed a parameter sweep for the local optimization.

III. Numerical Results

As test case, we carried out the design of a strip anomalous reflector on a grounded slab, starting from a decomposition of the scatterer domain into separated pixel elements according to [8]. The excitation consists on an impinging TE-polarized plane wave from $\theta = 30^{\circ}$ in the plane $\varphi = 90^{\circ}$. The aim is to suppress the specular reflection at $\theta = -30^{\circ}$ of the grounded slab and redirect the radiated power at broadside.

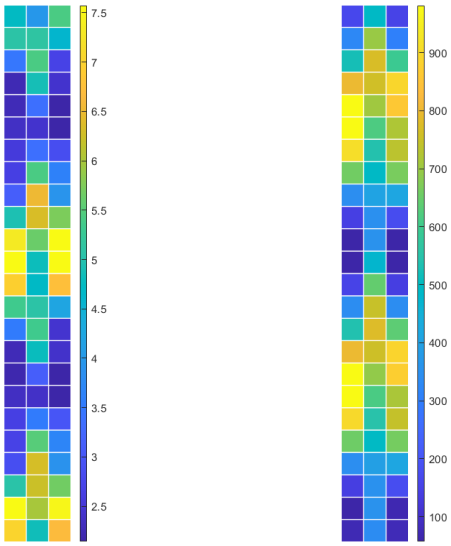


(a) (b)

Fig. 1: (a) Optimized current magnitude distribution (b) Optimized total electric field magnitude.

We chose a working frequency of 23 GHz, for a structure of $0.5\lambda \times 4\lambda$, internally subdivided into separated unit-cells with characteristic dimension of $\lambda/6 - \mathrm{tol}$, where tol is the PCB fabrication tolerance of 50 μm. The far fields mask constraints are imposed in order to have broadside radiation for the main beam and side lobes mask below 20 dB with respect to the main beam. Impedance constraints are set considering a bounded range of variation of the imaginary part between -120Ω and $-400\,\Omega$. The grounded dielectric slab has $\varepsilon_{\mathrm{r}} = 3.34$ and thickness $h = 0.508$ mm. The mesh of the square unit-cells have a size of $\approx \lambda/24$. The maximum number of iterations for the optimization have been set to 5000 with an uniform starting current for a total optimization time around 40 minutes.

At the end of the macroscopic optimization phase, we obtained the current and total field distributions in Fig. 1a and 1b. Those local values have been averaged over the square cells, as reported in Fig. 2a and 2b. For each cell we then proceeded with a parameter sweep optimization of a square unit-cell varying the edge length in the range $5\% - 95\%$ of the periodicity lattice $\lambda/6$, in order to minimize the cost function (6). For the sake of simplicity, in this contribution, we present only the design of a single unit-cell in the central part of the MTS characterized by an average current target value of $\approx 1.2\,\mathrm{A}$ and an average total field target value of $\approx 590\,\mathrm{V/m}$. According to the results of the optimization in Fig. 3, the unit-cell edge length that minimizes the cost function correspond to $0.55 \times \lambda/6$ and it has current and field distribution shown in Fig. 4a and 4b.



(a) (b)

Fig. 2: (a) Averaged current magnitude distribution (b) Averaged total electric field magnitude.

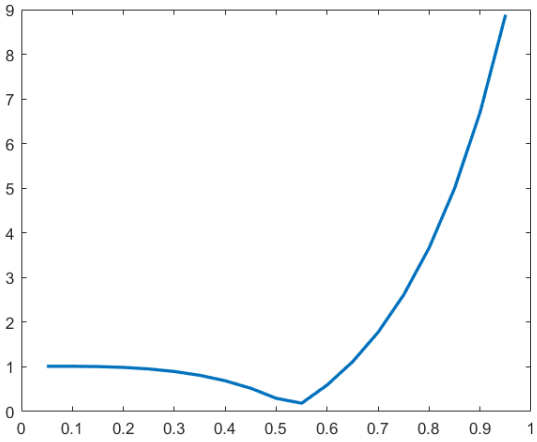
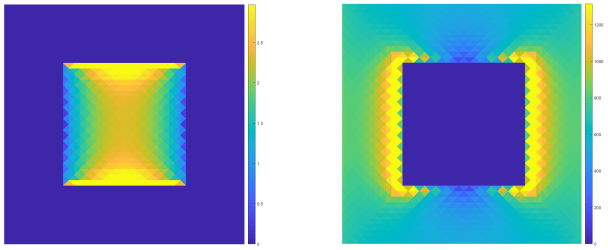


Fig. 3: Parameter sweep optimization result: on the x axis the ratio d/L, with d characteristic unit-cell dimension and $L = \lambda/6$ the periodicity lattice dimension; on the y axis the cost function (6) value.



(a) (b)

Fig. 4: Synthesized square unit-cell: (a) current magnitude, (b) total electric field magnitude.

IV. Conclusion

We discussed an innovative design framework for an a-periodic unit-cell synthesis that allows to bypass the impedance reconstruction working only with the current and the electric field, already computed in the macroscopic optimization. The presented test case employs a single parameter sweep optimization for a scalar impedance unit-cell (square). However, this approach can be easily extended to more complex form of optimization.

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