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Design of Conformal Sparse Metasurfaces using Green's Function

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Abstract—In this work, numerical calculation of Green's functions is employed to design arbitrarily-shaped sparse metasurfaces composed of few elements for wavefronts tailoring. Several metasurfaces are designed in the microwave domain for beamforming and scattering reduction functionalities.

I. INTRODUCTION

Since the last two decades, metasurfaces are showing their superior ability to tailor wavefronts over a broad frequency spectrum [1]–[3]. As such, a plethora of metasurface-based planar devices has been proposed and validated. Nowadays, more and more application environments require conformal metasurfaces that are able to perfectly match curved geometries. However, such conformal metasurfaces cannot be designed using existing approaches developed for planar counterparts. The design of a conformal metasurface is generally based on a geometrical optics approach, where a proper spatial distribution of local coefficient should be established along the metasurface. But this heuristic approach has strong limitations in terms of efficiency and versatility. On the other hand, since metasurfaces can be described by continuous surface impedances, theoretical modeling with accurate analysis of the metasurface geometry and curvilinear coordinates can be envisaged, but remains still highly challenging.

In this work, an original analytical model based on the numerical calculation of Green's functions is presented and employed to design sparse metasurfaces for any type of illuminating incident waves. The proposed approach does not use any complex local coordinate system matched to a particular geometry such that arbitrarily-shaped metasurfaces can be considered without any accommodation. The design procedure is described and validated at microwave frequencies for beamforming and scattering reduction scenarios.

II. DESIGN METHODOLOGY

The studied sparse metasurface is composed of a finite set of N loaded wires distributed along the surface of an arbitrarily shaped dielectric substrate and oriented along the translation-invariant direction. To a microscopic point of view, a loaded wire represents itself as a chain of subwavelength meta-atoms, and macroscopically, the loaded wire is modelled as uniform with a deeply subwavelength effective radius r_{eff} . An electric field directed along x -axis of an arbitrary external illuminating wave excites polarization currents I_q in the loaded

wires to tailor the radiation from the metasurface. The total field $E_x(r, \phi)$ is given as the superposition of the wave radiated by external sources $E_x^{(ext)}(r, \phi)$ and waves $G_{xx}(r, \phi; \mathbf{r}_q)I_q$ scattered by the wires ($G_{xx}(r, \phi; \mathbf{r}_q)$ is the Green's function corresponding to the q^{th} wire at \mathbf{r}_q) [4], [5]:

$$E_x(r, \phi) = E_x^{(ext)}(r, \phi) + \sum_{q=1}^N G_{xx}(r, \phi; \mathbf{r}_q)I_q \quad (1)$$

where r and ϕ are polar coordinates.

As the considered system does not have a translational symmetry in the 2D plane, the Green's function $G_{xx}(r, \phi; \mathbf{r}_q)$ is a function of the observation point \mathbf{r} and the position of the wire \mathbf{r}_q (not their difference). Importantly, $E_x^{(ext)}(\mathbf{r})$ and Green's functions should be calculated in the presence of the substrate and all other non-engineered elements of the metasurface (dielectric and/or metallic parts of the system). Sparse configuration of the metasurface allows one to accurately take into account interactions between the wires via Ohm's law:

$$Z_q I_q = E_x^{(ext)}(\mathbf{r}_q) - Z_q^{(in)} I_q - \sum_{p=1, p \neq q}^N Z_{qp}^{(m)} I_p. \quad (2)$$

A load-impedance density Z_q is a characteristic of a loaded wire and is engineered by meta-atoms constituting a wire. The right-hand side of (2) represents the total electric field at the position of the q^{th} wire, where $Z_{qp}^{(m)} = -G_{xx}(\mathbf{r}_q, \mathbf{r}_p)$ is the mutual-impedance density. The self-action of the q^{th} wire is accounted via the input-impedance density defined as $Z_q^{(in)} = -G_{xx}((r_q + r_{eff})\hat{\mathbf{r}}_q, \mathbf{r}_q)$. Equation (2) allows one to know in advance the impact of one polarization current on another and to accordingly adjust the load-impedance densities. By appropriately choosing Z_q and the number of wires N , wavefronts can be controlled as desired.

III. IMPLEMENTATION AND RESULTS

In a first scenario, three sparse metasurface samples are designed on thin ($\lambda_0/240 = 0.25$ mm) flexible substrates ($\epsilon_r = 2.2$ and $\tan \delta = 0.001$) to show different beamforming functionalities at 5 GHz. The inverse scattering problem is solved by maximizing power in the desired direction and minimizing the sidelobes level radiated by the sparse metasurface in desired directions, and the maximization procedure is implemented as a particle swarm optimization [6]. Each sample is

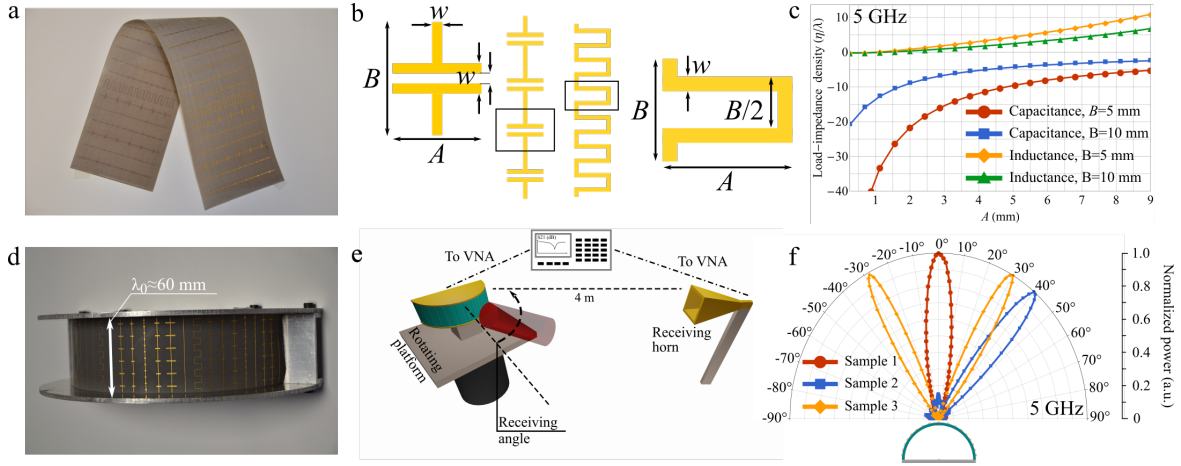


Fig. 1. (a) A fabricated sparse metasurface on a thin flexible substrate. (b) Schematics of a printed capacitance (left) and inductance (right). (c) Retrieved load-impedance densities of capacitively- and inductively-loaded wires at 5 GHz. (d) A photo of an assembled experimental mock-up. (e) Schematics of the experimental setup. (f) Measured far-field radiation patterns of fabricated samples.

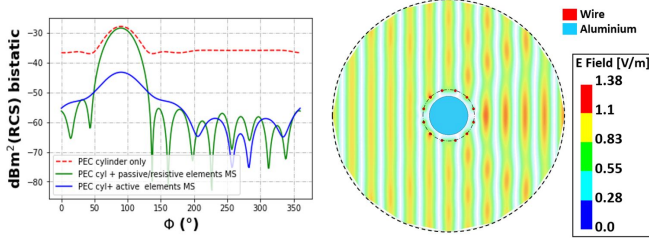


Fig. 2. Left: Simulated scattering cross section of the metallic cylinder coated with a sparse metasurface composed of 12 loaded wires equally spaced on a dielectric substrate. Right: Profile of the magnitude of the total electric field created by the structure using lossy/active Z_q .

composed of twenty nine wires equidistantly distributed along a $5.25\lambda_0 \approx 315$ mm long substrate, making the separation between two neighbouring wires approximately equal to $\lambda_0/5$ (Fig. 1(a)). The design of the loaded wires is performed within the local periodic approximation (LPA) developed in [7]. The wires are built up from printed capacitors (left design of Fig. 1(b)) and inductors (right design of Fig. 1(b)), which provide a wide range of accessible load-impedance densities as shown in Fig. 1(c). The ultra-thin samples are then conformed to create semi-cylindrical surfaces of 100 mm radius. The external source exciting the samples is made of two microstrip dipole antennas printed on a metal-backed substrate. The distance between the source and a sparse metasurface being 100 mm ($\approx 1.7\lambda_0$), the background field pattern is neither a plane wave nor a cylindrical wave. A photograph of the assembled prototype is presented in Fig. 1(d). The different configurations are experimentally validated by radiation patterns measurements (Fig. 1(e)). As shown by the experimental results in Fig. 1(f), the three desired radiation scenarios are achieved. It is important to note that the sparse metasurfaces are transmitting while possessing only electric response.

In a second scenario numerically studied at 5 GHz and

depicted in Fig. 2, 12 wires are distributed uniformly around a metallic cylinder of radius 30 mm for scattering reduction. Implementing active and lossy elements (blue curve) reduces the scattered field considerably in all directions, even the critical forward scattering, leading to a configuration close to cloaking. After a minimization procedure, solely lossy elements ($\Re[Z_q] \geq 0$) for a possible future practical implementation (green curve) can be considered. In this case, though the scattered field is reduced in several directions, forward scattering can still be observed in agreement with the optical theorem that relates forward scattering amplitude to total cross section of the cylinder (absorption and scattering).

IV. CONCLUSIONS

An approach based on the numerical calculation of Green's functions is proposed for the design of conformal sparse metasurfaces. Any type of illuminating incident waves can be considered for any arbitrarily-shaped geometry. Using an optimization algorithm, for a set of linear impedance densities, wavefronts can be controlled at will.

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