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Sparse Metasurface: Design and Implementation

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Abstract—Metasurfaces present high capabilities for wavefront tailoring. Classical metasurfaces composed of densely packed meta-atoms with local electromagnetic response show limitations in terms of efficiency. Here, we present and discuss the design of sparse metasurfaces composed of only few elements with strong electromagnetic non-locality. Sparse metasurfaces of arbitrary geometry are designed and validated at microwave frequencies for antenna applications.

I. INTRODUCTION

Electromagnetic wave control has reached a new plateau thanks to metamaterials and metasurfaces [1]. Classical metasurfaces are composed of densely packed meta-atoms with local electromagnetic response. By controlling the reflection and/or transmission characteristics of these metasurfaces, they have been successfully implemented for antennas [2-3], lenses [4-6], anomalous reflection and refraction [7-10], polarization control [11], vortex beam generation [12-14] and holograms [15-18]. For wavefront manipulation, most metasurfaces rely on the generalized law of reflection and refraction discussed in [7]. However, several studies have shown that this approach suffer from low efficiency, particularly in configurations where extreme wave manipulation is considered [19-21].

Recently, metagratings have been proposed as an interesting alternative to metasurfaces for enhancing wavefront manipulation efficiency [22-29]. They are designed to engineer diffraction by cancelling a finite number of undesired propagating diffraction orders and allowing desired ones to radiate. In general, a metagrating is an array of scatterers separated by a distance of the order of the operating wavelength. Compared to metasurfaces, the sparse arrangement of scatterers does not allow one describing metagratings in terms of local reflection and transmission coefficients (or surface impedances). A metagrating consists of a limited number of meta-atoms in a supercell (period) compared to a metasurface which is composed of supercells incorporating numerous meta-atoms with subwavelength periodicity. Therefore, both metasurfaces and metagratings are periodic structures operating under plane-wave illumination.

In this work, we present the design of a sparse metasurface, which is not a periodic structure conversely to a metagrating and where the meta-atoms are distantly spaced when compared to classical metasurface. The physics of the sparse metasurface is governed by the superposition principle and the Ohm’s law. As a practical implementation for wavefront manipulation, we design a sparse metasurfaces with an excitation placed in its close vicinity.

II. DESIGN OF THE SPARSE METASURFACE

The sparse metasurface is composed by a finite set of N loaded wires distributed along the surface of an arbitrarily shaped dielectric substrate and oriented along the translation-invariant direction. Microscopically, a loaded wire represents itself as a chain of subwavelength meta-atoms and macroscopically, the loaded wire is modeled as uniform and having a deeply subwavelength effective radius r_{eff} .

An arbitrary external source with the electric field directed along x -axis radiates a background wave and excites polarization currents in the loaded wires to tailor the field radiated by the metasurface:

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

where r and ϕ are polar coordinates: radius and polar angle, respectively. The total field $E_x(r, \phi)$ is represented by 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 that are calculated by means of a Green’s function. Sparse configuration of the metasurface allows one to accurately take into account the interactions between the wires via Ohm’s law as detailed in [30]. A load-impedance density (impedance per unit length of a wire) Z_q is a characteristic of a loaded wire and is engineered by tuning the geometrical parameters of meta-atoms constituting a wire. By appropriately choosing Z_q and the number of wires N , we are then able to shape the field at will. The inverse scattering problem can be solved by maximizing power scattered by the metasurface in desirable directions in far-field region.

III. RESULTS

As an illustrative example, one can reconstruct in the far-field region the shape of a “heart” as radiation pattern, after the required corresponding load-impedance densities are found. The required load-impedance densities correspond to passive elements with $\text{Re}[Z_q] > 0$. Fig. 1(a) shows the corresponding profile of the electric field in the proximity of the metasurface and the resulted far-field pattern depicted in Fig. 1(b) is compared to the ideal shape of “heart”. In this particular configuration, $N = 21$ wires was used on the cylindrical sparse metasurface. More details can be found in [30].

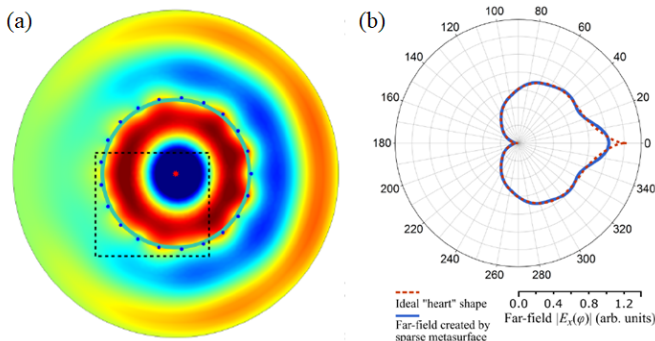


FIG. 1. (a) Profile of the electric field created by a cylindrical sparse metasurface. (b) Far-field pattern created by the sparse metasurface compared to an ideal “heart” shape.

IV. CONCLUSION

The design of sparse metasurfaces been proposed without appealing to a complex theory. The versatility of the approach allows considering different metasurface geometries and arbitrary excitation sources. Particularly, sparse metasurfaces for realizing a programmable metasurface with low number of reconfigurable meta-atoms to avoid high ohmic losses and complex bias networks can be further considered.

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