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Electromagnetic scattering reduction using sparse metasurfaces

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Abstract—The present work exploits a simulation-based design procedure to reduce the scattering of a metallic cylinder in desired directions using conformal sparse metasurfaces.

Keywords—cloaking, sparse metasurface, scattered energy reduction/control

I. INTRODUCTION

Reducing the energy scattered by an object in all directions and hence allowing it to be electromagnetically invisible, has attracted enormous interests in the last decades [1]–[5]. Cloaking technology finds many fascinating applications, such as stealth and antenna coupling reduction [6]. In the meantime, metamaterials and metasurfaces have experienced an unprecedented development and have proven to be a powerful tool for wavefront manipulation and wave shaping [7]. In this paper, we exploit the simulation-based design procedure described in [8] to design a conformal sparse metasurface capable of reducing the scattering of a metallic cylinder illuminated by a plane wave. We present the theoretical design as well as simulation results that validate the proposed approach.

II. THEORY

Let us consider the structure depicted in Fig 1. A metallic cylinder with diameter of the order of the wavelength λ is cloaked with a sparse metasurface composed of N loaded wires equally distributed on a substrate of thickness h and relative permittivity ε_{s} . The wires are modelled as thin metallic cylinders of effective radius r_{eff} ($\ll \lambda$), oriented along the translation-invariant direction (*z*-axis). A plane wave with the electric field E_0 directed parallel to the *z*-axis and propagating towards the *y*-axis, illuminates the structure and excites a polarization current along the N loaded wires placed on the substrate. The polarization currents' scattered field observed in the far field region is expressed as:

$$E_z^{sca}(r,\Phi) = \sum_{q=1}^N G_{zz}(r,\Phi;r_q) I_q$$
(1)



Fig. 1. 2D schematic of a cloaked metallic cylinder with a conformal metasurface, comprised of 12 loaded wires. The effective radiuses r_{eff} of the wires are enlarged on the schematic for the sake of clarity.

where $G_{zz}(r,\Phi;\mathbf{r}_q)$ is the q^{th} wire's Green's function, and I_q is the polarization current along its surface. The total electric field $E_z(r,\Phi)$ is the sum of the fields due to the external sources (wires absent) and the fields scattered by the wires:

$$E_z(r,\Phi) = E_z^{ext}(r,\Phi) + \sum_{q=1}^N G_{zz}(r,\Phi;r_q) I_q \qquad (2)$$

In such sparse metasurfaces, Ohm's law links the field applied to the wires, the currents and the load impedance densities:

$$Z_{q}I_{q} = E_{z}^{ext}(r_{q}) - \sum_{p=1}^{N} Z_{qp}^{(m)}I_{p}$$
(3)

where Z_q is the q^{th} wire's load impedance density and $Z_{qp}^{(m)}$ is the mutual-impedance density.

By choosing the number of wires N and the load impedance densities Zq appropriately, the scattered field can be tailored as desired.

III. SCATTERING REDUCTION PROCEDURE

The goal is to control $E_z(r,\Phi)$ in the far field region for several directions Φ by using a simulation-based design procedure. The far field $E_z^{ext}(r,\Phi)$ and near field on the substrate's surface $E_z^{ext}(r_q)$ scattered by the cylinder alone and the loaded wires' Green's functions $G_{zz}(r,\Phi;\mathbf{r}_q)$, are extracted using a commercially available numerical simulation software (Ansys HFSS in our case). In order to find $G_{zz}(r,\Phi;\mathbf{r}_q)$, a single wire is placed on the substrate and a known current is applied. From the far field simulation data, we retrieve :

$$G_{zz}(r,\Phi;r_q) = \frac{E_z^{sca}(r,\Phi)}{l_q}$$
(4)

The matrix of mutual impedance densities is constructed from the near field data:

$$Z_{qq}^{(m)} = -G_{zz}(r_q, r_p)$$

$$Z_{qq}^{(m)} = -\frac{1}{2\pi r_{eff}} \oint G(r, r_q) dr$$
(5)

where r_i is the position of the *i*th wire on the substrate.

Then, the desired electric field in the far-field region $E_z(r,\Phi)$ is set and the complex currents I_q are calculated using Eq. (2). If no constraint is set to Eq. (3), its resolution returns Z_q with complex values. Load impedance densities with $Re[Z_q] \neq 0$ are required in this case, which implies the use of lossy and/or active elements.

IV. RCS REDUCTION: SIMULATION EXAMPLES

As equation Eq. (2) allows a control of $E_z(r,\Phi)$, we set $E_z(r,\Phi) = 0$ in a number of desired directions and tackle the cloaking problem with the proposed approach. The working frequency f_0 is set to 5 GHz and the diameter R_0 of the inner metallic cylinder to 30 mm ($\sim\lambda/2$). The thickness *h* of the substrate coating the cylinder, is set to 10 mm and the relative permittivity to $\varepsilon_s = 1$.

In a first case scenario (Fig. 2), the scattered field is reduced in the direction $\Phi_{abs} = 270^{\circ}$, by placing one single wire on the substrate at the angular position $\Phi_{pos} = \Phi_{abs}$. As the energy is absorbed in the desired direction using a single wire, we extend the approach to absorb the energy in two distinct directions (255° and 285°) using two loaded wires.

In a second case scenario (Fig. 3), 12 wires are used to reduce the scattered field in 12 directions. Deploying active and/or lossy elements, i.e Z_q with a real part different than 0 (green curve), reduces the scattered field considerably in all directions, even the critical forward scattering, leading to a configuration close to cloaking. However, if we allow only lossy elements, i.e Z_q with a positive real part (blue curve), a significant forward scattering is inevitably observed. As imposed by the optical theorem [2], the scattering from a cylinder can only be totally eliminated by using a lossless or active coating.



Fig. 2. Simulated scattering cross-section of a metallic cylinder coated with a metasurface (red curve) and without the coating (green curve) versus azimuthal angle Φ . Left: 1 wire is placed at $\Phi_{pos} = 270^{\circ}$. Right: 2 wires are placed at $\Phi_{mer} = 255^{\circ}$ and $\Phi_{mer} = 285^{\circ}$.



Fig. 3. 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 Zq.

V. CONCLUSION

A simulation-based design procedure has been exploited to design a conformal sparse metasurface capable of cloaking a metallic cylinder. A significant reduction of the scattering has been achieved with 12 wires having complex impedances.

Nonetheless, considering the difficulty to manufacture active elements for a future practical realization of the metasurface, we will further investigate the use of lossy and reactive elements only. This condition is mandatory in order to design the load impedances from printed capacitors and inductors using the local periodic approximation [9].

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