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Design of Huygens Metasurfaces for Composite Vortex Generation and Field Manipulations

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Abstract

Huygens metasurfaces offer a versatile platform for tailoring electromagnetic wavefronts. In this contribution, we focus on their application to generate composite vortex beams, enabling precise control over the phase and amplitude of incident waves and simple reconfiguration strategies. Through some numerical simulations, the effectiveness of the proposed Huygens metasurfaces in composite vortex generation and in manipulating the overall transmitted beam is demonstrated, with possible applications in beam shaping for communication systems or imaging technologies.

1. Introduction

Inspired by the Huygens principle, which asserts that each point on a wavefront can act as a secondary source, Huygens metasurfaces provide a powerful platform for the complex tailoring of electromagnetic waves through subwavelength elements [1]. In particular, each element of the Huygens Metasurface is ideally characterized by a unitary transmission, zero reflection, and full control of the transmission phase, which can be locally engineered to mold the transmitted field. Applications span from antenna beamforming and beam-steering systems at microwave frequencies [2]-[4], to various wavefront manipulation devices up to THz and visible wavelengths [5]-[6].

Concurrently, composite vortex theory presents intriguing possibilities for manipulating electromagnetic fields [7]. This theoretical framework involves the combination of multiple vortices to create complex wavefronts and control the behavior of the overall electromagnetic wave. Indeed, the phase singularity points and corresponding amplitude nulls associated with superimposed vortex modes can be strategically placed to engineer the overall field and to exhibit specific behaviors at those locations.

This contribution aims to merge these two research domains and take advantage by their main characteristics, i.e. the capability to deeply mold the electromagnetic field by using Huygens metasurfaces, and the simple tuning mechanism that could be implemented by exploiting the insights of composite vortex theory.

2. Theoretical Background for Composite Vortex Generation with Huygens Metasurfaces

Huygens metasurfaces are conceived to manipulate an incident field by imparting a given phase profile corresponding to a desired aperture field [1]. Indeed, once conceived a subwavelength particle able to transmit an incident plane wave with almost a unitary amplitude transmission and a controllable transmission phase, the overall metasurface can be designed by distributing the particles for implementing the required phase shift with respect to a given incident field. While effective in transforming almost at will the transmitted wavefront, this approach requires a continuous tuning of each metasurface element to reconfigure the structure according to the specific incident field or desired output characteristics. On the contrary, composite vortex theory offers a simple strategy to reconfigure the properties of the overall field. Indeed, by superimposing two different vortex beams, the overall amplitude and phase patterns can be controlled by acting on the amplitude and relative phase between the two beams [7]. This reconfiguration strategy has been already used at microwave frequencies to shape the radiation or scattering patterns of radiating structures [8] and reflective intelligent surfaces [9], respectively. Here, we extend this approach for tailoring the transmitted field by a Huygens metasurface, as schematically represented in Fig. 1.

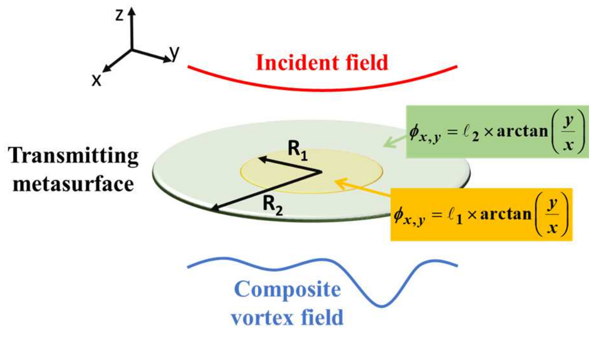
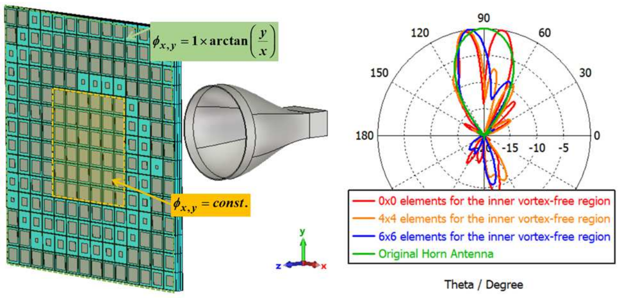


Figure 1. Schematic representation of a Huygens metasurface designed for transforming an incident beam (e.g. a cilyndrical wave) into a composite vortex field.

For this purpose, a Huygens metasurface can be divided in two concentric regions, each one exhibiting a phase profile corresponding to a vortex mode of different topological charge (ℓ_1 and ℓ_2) [10].

3. Field Manipulation Example

To preliminarily demonstrate the proposed approach, we have designed a Huygens metasurface, shown in Fig. 2 (a), able to convert the field radiated by a horn antenna into the superposition of a vortex-free component ($\ell_1 = 0$) and a vortex mode with unitary topological charge ($\ell_2 = 1$). In this case, from the insights into the composite vortex theory [9], we expect that the shape and the pointing direction of the overall radiation pattern can be manipulated by appropriately acting on the amplitude of the two constituting beams. In particular, by increasing the inner region of the metasurface imparting a constant phase shift (i.e. the amplitude of the vortex-free component), different radiation patterns can be achieved, as preliminary reported in Fig. 2 (b).



(a) (b)

Figure 2. (a) Schematic representation of a Huygens metasurface designed for generating a composite vortex field and shaping the beam of a horn antenna; (b) corresponding normalized radiation pattern (on the *yz*-plane) for different numbers of inner unit cells exhibiting a constant phase shift.

4. Conclusions

In this contribution, we have investigated the possibilities offered by Huygens metasurfaces for generating composite vortices and the possible applications for field manipulation. In particular, we have presented an example of antenna application, where a Huygens metasurface is exploited to transform the field radiated by a horn antenna in the superposition of a vortex and a vortex-free component, enabling the manipulation of the overall radiation pattern. Further analysis on the actual possibilities offered by this approach as well as more details on the design procedure and on a practical reconfiguration strategy will be provided at the conference.

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References

[1] A. Epstein, G. V. Eleftheriades, "Huygens' metasurfaces via the equivalence principle: design and applications," *Journal of the Optical Society of America B*, **33**, 2, 2016, pp. A31-A50, doi: 10.1364/JOSAB.33.000A31

[2] A. Epstein, J. Wong, G. Eleftheriades, "Cavity-excited Huygens' metasurface antennas for near-unity aperture illumination efficiency from arbitrarily large apertures," *Nat Commun*, **7**, 10360, 2016, doi: 10.1038/ncomms10360

[3] A. Monti et al., "Quadratic-Gradient Metasurface-Dome for Wide-Angle Beam-Steering Phased Array With Reduced Gain Loss at Broadside," *IEEE Transactions on Antennas and Propagation*, **71**, 2, 2023, pp. 2022-2027, doi: 10.1109/TAP.2022.3222716.

[4] M. Longhi et al., "Array Synthesis of Circular Huygens Metasurfaces for Antenna Beam-Shaping," *IEEE Antennas and Wireless Propagation Letters*, **22**, 11, 2023, pp. 2649-2653, doi: 10.1109/LAWP.2023.3315774

[5] P. Genevet and F. Capasso, "Breakthroughs in Photonics 2013: Flat Optics: Wavefronts Control With Huygens' Interfaces," *IEEE Photonics Journal*, **6**, 2, pp. 1-4, 2014, doi: 10.1109/JPHOT.2014.2308194

[6] A. Özdemir, et al, "Polarization independent high transmission large numerical aperture laser beam focusing and deflection by dielectric Huygens' metasurfaces," *Opt Commun,* **401**, 46, 2017, doi: 53.10.1016/j.optcom.2017.05.031

[7] I. D. Maleev and A. G. Swartzlander, "Composite optical vortices," *J. Opt. Soc. Am. B*, **20**, pp. 1169-1176, 2003, doi: 10.1364/JOSAB.20.001169

[8] M. Barbuto, M. Miri, A. Alù, F. Bilotti and A. Toscano, "A Topological Design Tool for the Synthesis of Antenna Radiation Patterns," in *IEEE Transactions on Antennas and Propagation*, **68**, 3, March 2020, pp. 1851-1859, doi: 10.1109/TAP.2019.2944533.

[9] M. Barbuto, A. Alù, F. Bilotti and A. Toscano, "Composite Vortex Manipulation as a Design Tool for Reflective Intelligent Surfaces," in *IEEE Antennas and Wireless Propagation Letters*, **22**, 10, Oct. 2023, pp. 2392-2396, doi: 10.1109/LAWP.2023.3288944.

[10] N. Hassan, et al, "Generation of Mixed-OAM-Carrying Waves Using Huygens' Metasurface for Mm-Wave Applications" *Sensors*, **23**, 5, 2023, doi: 10.3390/s23052590.