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Design of unit cells and demonstration of methods for synthesizing Huygens metasurfaces

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Abstract

The systematic design of unit cells for a Huygens metasurface, a particular class of metasurface, is presented here. The design of these unit cells uses transmission-line theory. This is validated through application to 1D refraction and Gaussian-to-Gaussian beam focusing. The 1D refraction is further validated experimentally. These applications demonstrate the practical utility of these Huygens metasurfaces. The Huygens metasurfaces presented here are printed on two bonded boards instead of many stacked, interspaced layers. This simplifies fabrication and enables the scaling down of the metasurfaces to shorter wavelengths. These two bonded boards implement a single, collocated layer of electric and magnetic dipoles. The electric and magnetic dipoles are synthesized using sub-wavelength arrays of printed elements. These printed elements can be manufactured using standard PCB fabrication techniques, and are capable of synthesizing the full range of impedances required. Furthermore, in contrast to frequency-selective surfaces (FSSs) and traditional transmitarrays, which are on the order of a wavelength thick, these designs are only $\lambda/10$ thick while incurring minimum reflections losses.

Keywords: Metasurface; Equivalence principle; Transmitarrays; Flat lens

1. Introduction

Due to the challenges presented by loss, dispersion, and fabrication, metasurfaces, the 2D analog to volumetric metamaterials, have attracted much interest. In many cases, the metasurface can encode the same functionality as its metamaterial counterpart. The interaction of a metasurface with electromagnetic fields can be described in general through an impedance boundary condition collocated with its magnetic dual [1]. The same description can be independently arrived at from the perspective of polarizabilities instead of impedances [2]. Examples of the applications of these descriptions to metasurfaces, in terms of impedances or susceptibilities, have included extraction of susceptibilities for both mono and bi-anisotropic scatterers [3,4], electromagnetic shielding [5], circuit modeling of Huygens sources [6], active cloaking [7], interfacial refraction [8,9], Gaussian-to-Bessel beam transformers [9], electromagnetic resonators [10], waveguides [11], exciting surface waves and complex modes [12], leaky-wave antennas [13], tunable metasurfaces [14], and plasmonic metasurfaces [15]. For a detailed review of the literature pertaining to metasurfaces, see [16].

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The theoretical foundation and experimental verification of a Huygens metasurface has recently been discussed in [6,8,9]. This particular class of metasurface is an application of both the Huygens principle and the equivalence principle. Composed of a single layer of sub-wavelength unit cells containing both a loop and a dipole, it implements an array of Huygens sources. That is, the electric and magnetic responses are collocated in a single layer. The characteristics of a Huygens source provides the flexibility needed to engineer both the electric and magnetic surface currents enforcing the equivalence principle. This in turn provides the flexibility necessary for a wide range of applications. In [9], 1D interfacial refraction and Gaussian-to-Bessel beam transformation are demonstrated. In the case of refraction, suppression of side-lobes and reflections are seen. Furthermore, an accurate Bessel beam is reproduced with near-unity transmission.

Until recently, attempts with both metasurfaces and transmitarrays for interfacial refraction have only been partially successful in efficiently coupling to the refracted beam. In the case of metasurfaces, this is because the responses are purely electric or magnetic. Furthermore, in [17] the metasurface operates only on the cross-polarized radiation. For transmitarrays, the implementation of a linear phase profile has been shown to always excite higher-order Floquet modes which manifest as side-lobes [18]. The inclusion of both an electric and magnetic response in a single layer in the Huygens metasurface suppresses these side-lobes and the reflections simultaneously. In [19] optical metasurfaces for 1D refraction and focusing are discussed and are without these issues. In this case, the response is exclusively electric. However, the design requires three interspaced layers of electric dipoles, as opposed to a single, collocated layer of electric and magnetic dipoles.

However, to this date not much attention has been given to the discussion of the design of the constituent unit cells in the Huygens metasurface. In [6], a lattice circuit model is proposed for the Huygens source unit cell. Here we aim to incorporate this model to provide a systematic approach to the unit cell design process. This process is then applied to the 1D refraction and focusing of an incident Gaussian beam. In both cases, suppression of side-lobes and reflections is demonstrated. Experimental results for refraction are presented. Partial preliminary results have been disclosed in [20].

In contrast to the Huygens metasurface of [9], this implementation is printed on two bonded boards instead of many stacked, interspaced layers. This considerably simplifies fabrication and allows the scaling of the metasurfaces to millimeter-wave frequencies and beyond. This simple design contains both the electric and magnetic responses, embodied in the printed elements. These printed elements can be manufactured using standard PCB fabrication techniques, and are able to synthesize the full range of impedances required. Furthermore, in contrast to FSSs and traditional transmitarrays, which are on the order of a wavelength thick, these designs are only $\lambda/10$ thick while incurring minimum reflections losses.

2. Theory

Fig. 1 illustrates the scenario considered for this discussion. The definitions are shown in the figure. From array theory, the electric and magnetic surface currents can be interpreted as arrays of electric and magnetic dipoles [21]. The infinitesimal magnetic dipole is equivalent to an infinitesimal electric loop. Thus, the surface currents located along the same boundary, enforcing the equivalence principle, can be engineered through sub-wavelength arrays of collocated electric dipoles and loops. This sub-wavelength condition is precisely the homogenization required in metamaterials. This allows the homogenization with reactive sheets. Pairs of collocated electric and magnetic dipoles correspond to Huygens sources. Furthermore, these currents can be related to impedances corresponding independently to the electric and magnetic responses [8,9].

Due to both the equivalence principle and the uniqueness theorem, these electric and magnetic impedances constitute a transfer function between a predetermined excitation and the desired response. Practically, we are limited not only by the applications that can be conceived, but also by the impedances that can be synthesized. Ideally, the impedances are passive, lossless, and moderate in value. Often though these are active, lossy, and extreme. Thus, further research would involve both the synthesis of improved unit cells, as well as methods for approximating the ideal transfer functions with more realizable ones.

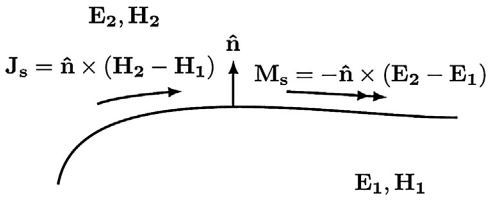

Fig. 1. Huygens metasurface. A Huygens metasurface can be designed such that equivalent surface currents ($\mathbf{J}_s$, $\mathbf{M}_s$) transform an incident field ($\mathbf{E}_1$, $\mathbf{H}_1$) into a transmitted field ($\mathbf{E}_2$, $\mathbf{H}_2$). The normal to the boundary is $\hat{\mathbf{n}}$.