2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI) | 978-1-7281-4670-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/APS/URSI47566.2021.9704134

Dimer Dielectric Huygens' Metasurface: Realizing Perfect Anomalous Reflection at 60 GHz

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***Abstract*—This paper reports a coarsely discretized dielectric Huygens' reflective metasurface featuring two meta-atoms known as *meta-dimer* per metasurface period. We termed the resulting metasurface as *dimer dielectric Huygens' metasurface* (Di-DHMS). The coarse discretization dramatically simplifies the design and reduces mutual coupling effects, leading to a cost-effective, robust, and highly efficient metasurface design. Through full-wave simulations at 60 GHz, we demonstrate that the proposed Di-DHMS can achieve perfect anomalous reflection for the oblique plane wave incidence.**

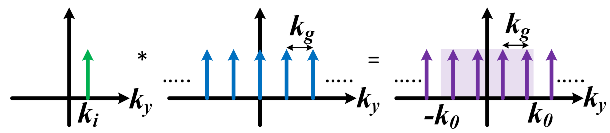

Fig. 1. k-space operation of a periodic metasurface. Arrows denote possible spectral components' spatial frequencies but do not provide information about the amplitude and phase. The violet box indicates the propagation regime.

I. Introduction

With the inception of *metasurfaces*–the planarized version of the bulk metamaterials, there has been a paradigm shift in the research of *surface electromagnetics*, allowing one to manipulate electromagnetic (EM) waves in a nearly arbitrary manner across different frequency regimes. They have led to a plethora of fascinating phenomena, including anomalous refraction/reflection, flat lenses, special beam generation, to name a few [1].

Among the large group of metasurfaces, *Huygens' metasurface* [2], [3] (HMS)–fundamentally based on the *surface equivalence principle*, has gained stupendous attention over the past lustrum for their exceptional capabilities of transforming EM waves at will. In general, the implementation of HMS comprising metallic polarizable particles either requires vias or stacked topology to realize the collocated orthogonal electric and magnetic dipoles [4], [5]. Such requirements sometimes hindered the fabrication, particularly at high frequencies, such as millimeter-wave (mm-wave), terahertz, and beyond. Moreover, the ohmic losses associated with the metallic particles are more prominent at high frequencies, which significantly degrade the overall performance of the metasurface.

To alleviate the aforementioned drawbacks of metallic HMS, the idea of *dielectric Huygens' metasurface* (DHMS)–consisting of low-loss and high-index dielectric resonators, has been put forward for controlling the EM waves via the interplay of electric and magnetic resonances [6]. The dielectric Huygens' source can be realized by the superposition of crossed electric and magnetic dipoles in a single layer structure, and the array of such dielectric particles constitutes a dielectric Huygens' metasurface.

Recently, the concept of *coarse discretization*, which feature single [7] or few elements [8]–[13] per metasurface period, has been suggested to realize simple yet highly efficient and robust metasurfaces without the need for deeply subwavelength sized meta-atoms. The basic design principle of coarsely discretized metasurface relies on the diffraction grating physics, where the meta-atoms are engineered to suppress the undesired propagating *Floquet-Bloch* (FB) modes and to allow the desired ones to radiate into the far-field. Such metasurface feature a relatively larger element size, which helps to (i) overcome the fabrication difficulties at high frequencies and (ii) reduce mutual coupling effects. In this paper, we report a ground-backed DHMS for anomalous reflection, consisting of only two elements per metasurface period, which we termed as *dimer dielectric Huygens' metasurface* (Di-DHMS). Through full-wave simulations using HFSS, we show that the proposed Di-DHMS perfectly reflect an incoming EM wave at $\theta_i = 10°$ in the anomalous direction towards $\theta_r = -52°$.

II. Theory of Metasurface Discretization

A periodic metasurface in free-space with period Λ_g and spatial frequency $k_g = \frac{2\pi}{\Lambda_g}$, when illuminated by a plane wave, scatters a discrete set of *Floquet-Bloch* (FB) modes in different directions. The transverse spatial frequencies of FB modes are expressed as

$$k_{yp} = k_{yi} + pk_g = k_{yi} + \frac{p\lambda_0}{\Lambda_g}, \tag{1}$$

where k_{yi} is the y-directed spatial frequency of the incident wave, $p\ (= 0,\ \pm1,\ \pm2,\ \cdots)$ represents the FB mode number. Fig. 1 illustrates the k-space operation of such metasurface, and it can be expressed mathematically as

$$\Omega_o(k_y) = \sum_p A_p \delta(k_y - k_{yp}) \tag{2}$$

where $\Omega_o(k_y)$ is the output k-space spectrum, A_p represents the amplitude, and k_{yp} is given by (1). The output k-space

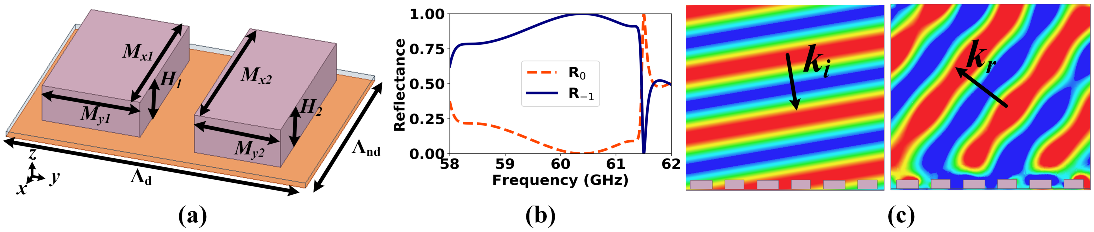

Fig. 2. (a) Schematic of the Di-DHMS. $M_{x1} = 2.55$, $M_{y1} = 1.7$, $H_1 = 0.7$, $M_{x2} = 2.9$, $M_{y2} = 1.5$, $H_2 = 0.75$, $\Lambda_d = 5.2 = 1.04\lambda_0$, $\Lambda_{nd} = 3.6 = 0.72\lambda_0$ (all dimensions are in mm). (b) Reflectance (linear scale). (c) Left panel: incident wave ($\theta_i = 10^\circ$) and right panel: reflected wave ($\theta_r = -52^\circ$).

spectrum consists of an infinite number of FB modes illustrated by purple arrows in Fig. 1. However, only a finite number of these modes, which falls in the propagation range $k_y \in [-k_0, k_0]$ (represented by a purple box in Fig. 1) can scatter into the far-field, whereas the modes outside the propagation range are evanescent in nature.

Wong and Eleftheriades in [8] have suggested that *N*-fold discretization within the metasurface period is adequate to determine *N* FB modes that can radiate into the far-field. Underlying this concept, a perfect anomalous reflector [8] and retroreflector [13] has been demonstrated.

III. Dimer Dielectric Huygens' Metasurface

We seek to design a reflective metasurface operating under oblique incidence, considering the manipulation of only two FB modes *i.e.* the specular mode ($p = 0$) and the first higher-order mode ($p = -1$). Therefore, in this case, a binary discretization ($N = 2$) will suffice for controlling the aforementioned modes. For this purpose, we choose a ground-backed dielectric Huygens' meta-atom designed for the incident angle of 10°. The relative permittivity of the rectangular dielectric block is 12, and the losses are not accounted for in the simulation.

We first generate a meta-atom library having different reflection phases by varying the length, width, and height of the meta-atom. From the library, we choose two elements having the reflection phase difference of 180° to construct meta-dimer *i.e.* one period of the metasurface (refer Fig 2(a)). The meta-dimer is simulated employing the periodic boundary conditions and Floquet ports, where the structure is illuminated by a $x-$polarized plane wave propagating in the $-z$ direction.

Fig. 2(b) shows the reflectance plot for the two FB modes. Examining the plot, it is clear that at 60 GHz, the reflection is maximized to the desired R_{-1} mode, whereas the specular mode (R_0) is completely suppressed. For the reflectance $R \geq 0.75$, the relative bandwidth of 5.5% is achieved. The electric field distribution shown in Fig. 2(c) depicts the anomalous reflection under oblique incidence. For $\Lambda_d = 1.04\lambda_0$ (λ_0 being calculated at 60 GHz), $\theta_i = 10^\circ$, and $p = -1$, the reflected angle computed using [12] is $\theta_r = -52^\circ$.

IV. Conclusion

We have presented a coarsely discretized perfect anomalous reflector at 60 GHz. The proposed metasurface comprising two elements per period can anomalously redirect an incoming EM wave from $\theta_i = 10^\circ$ to $\theta_r - 52^\circ$, with high efficiency. Such coarsely discretized metasurface provides a promising platform to design efficient mm-wave and terahertz meta-devices for next-generation (5G and beyond) wireless communication systems. Moreover, it can be easily scaled to optical frequencies and beyond, enabling the design of efficient all-dielectric nanophotonic devices.

V. Acknowledgement

This work is supported by an Early Career Scheme from the Research Grants Council of the Hong Kong under Grant 21211619.

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