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Sparsely Discretized Refracting Dielectric Huygens' Metasurface at 28 GHz

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***Abstract*—We report a sparsely discretized refracting dielectric Huygens' metasurface comprising only two meta-atoms per period. The proposed metasurface is termed as *bipartite dielectric Huygens' metasurface* (Bi-DHMS), which dramatically simplifies the design and pave the way towards efficient electromagnetic (EM) wave manipulation. Such sparse discretization reduces inter-element mutual coupling, leading to efficient, cost-effective, and robust metasurface design. Through full-wave Floquet simulations at 28 GHz, we have demonstrated that a judiciously designed Bi-DHMS can refract an incoming electromagnetic wave from 15 deg to -45 deg, where more than 80% of the total transmitted power is coupled to the desired Floquet space harmonic.**

***Index Terms*—Anomalous refraction, dielectric metasurface, huygens' metasurface, millimeter-wave.**

I. INTRODUCTION

Huygens' metasurfaces (HMSs) has gained enormous attention in recent years for their advanced wavefront engineering, leading to a plethora of fascinating phenomena, such as anomalous refraction/reflection, cloaking, arbitrary electromagnetic wave generation, to name a few [1]. HMS–fundamentally based on the surface equivalence principle, primarily comprises co-located orthogonal electric and magnetic dipoles, which form an array of Huygens' sources, leading to unidirectional scattering with high transmission and full 360° phase control. The implementation of HMS consisting of metallic polarizable particles either require vias [2] or multi-layer configuration [3]. Such requirements cause fabrication complexities, particularly at high frequencies, such as mm-wave, terahertz, and beyond. Besides, the inevitable ohmic losses associated with the metallic meta-atoms are more prominent at high frequencies, degrading the overall performance of the metasurface.

To overcome the above limitations, dielectric Huygens' metasurface (DHMS) comprising low-loss and high permittivity dielectric resonators (DRs) has been suggested as an alternate route to control EM waves [4]. Each resonator or dielectric meta-atom of DHMS is characterized by spectrally overlapped orthogonal electric and magnetic dipoles in a single layer structure, which leads to unidirectional scattering with the unitary transmission (in the ideal case) along with 2π phase coverage over a wide bandwidth.

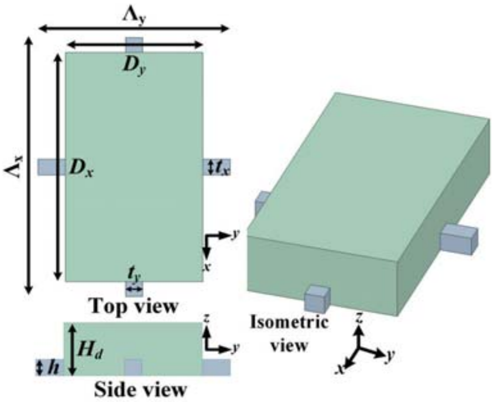

Fig. 1. Proposed dielectric Huygens' meta-atom. $\Lambda_x = 8$ mm, $\Lambda_y = 5.55$ mm, $t_x = t_y = 0.5$ mm. The dielectric constant of the DR is 12.

Recently, the concept of aggressive or sparse discretization has been put forward to design simple, efficient, cost-effective, robust metasurfaces. The sparsely discretized metasurface feature one or few elements per period [5]–[10] to realize extreme EM wave manipulation with high efficiency. In this paper, we present a transmissive DHMS based on the newly conceived idea of aggressive discretization. The proposed sparsely discretized DHMS consists of only two elements per period capable of controlling two propagating Floquet space harmonics (FSH). Through full-wave Floquet simulations at 28 GHz, we demonstrate that the proposed Bi-DHMS performs anomalous refraction, redirecting an obliquely incident EM wave towards $-45°$.

II. BIPARTITE DIELECTRIC HUYGENS' METASURFACE

Fig. 1 shows the proposed dielectric Huygens' meta-atom comprising a rectangular DR with four electrically thin dielectric connections that serve as a supporting structure as well as needed to build a prototype. The slight field perturbation due to these dielectric connections can be compensated through proper optimization. Before discussing the proposed metasur-

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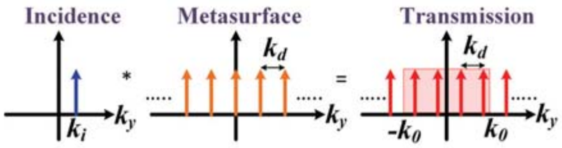


Fig. 2. k-space operation of a periodic metasurface which varies along y-direction. Arrow represents the Floquet space harmonics (not the amplitude) and the red box represents the propagation regime.

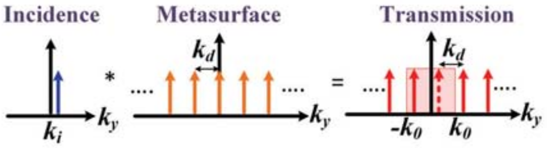


Fig. 3. The k-space operation of a periodic metasurface with discretization level of two elements per period under oblique incidence. The red box in the rightmost panel of the figure shows the propagation regime and arrows represent the Floquet space harmonics (not the amplitude).

face's design details, we briefly describe the theoretical aspect of the discretized metasurface.

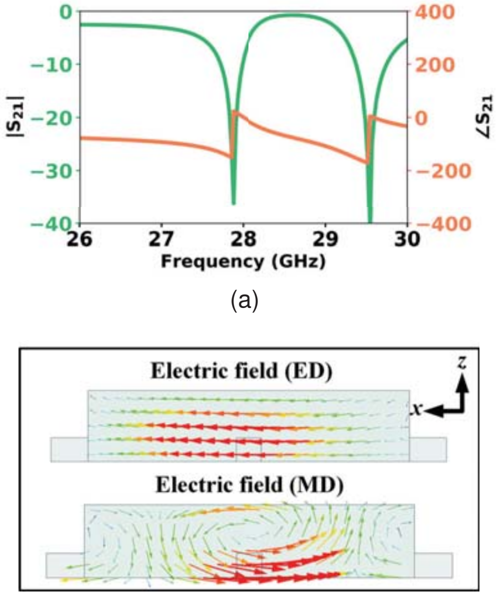
A. *Discretization effects*

Consider a periodic metasurface with period Λ_g and spatial frequency $k_d = \frac{2\pi}{\Lambda_g}$. When a plane wave illuminates the metasurface in free space, a discrete set of propagating and evanescent plane waves, known as Floquet space harmonics (FSH) are excited (shown by red arrows in the rightmost panel of Fig. 2.), which can, in principle, reflect and refract off the metasurface in different directions. The red box in the rightmost panel of Fig. 2 shows the propagation regime ($k_y \in [-k_0, k_0]$), and the space harmonics that fall in this range can scatter into the far-field, whereas rest become evanescent. Wong *et al.* in [6] have demonstrated that N-fold discretization within the metasurface is sufficient to control N-Floquet space harmonics. Fig. 3 depicts the k space operation for discretization level of $N = 2$. A discretization level of two elements per period ($N = 2$) is sufficient to realize anomalous refraction by manipulating the power carried by two Floquet harmonics. Based on this concept, we propose a DHMS comprising two elements per period, engineered to maximize the power coupling to the desired space harmonic while suppressing the undesired one including reflections. In the following, we present the design steps for Bi-DHMS.

B. *Design steps*

We seek to design a transmissive DHMS that redirect an incident wave from $\theta_i = 15^\circ$ to the first Floquet space harmonic ($n = -1$) propagating towards $\theta_t = -45^\circ$. For this case, the period of metasurface along y direction reads as: $\Lambda = \frac{\lambda_0}{|\sin\theta_i - \sin\theta_t|} = 1.04\lambda_0$, where λ_0 is the free space wavelength at calculated at 28 GHz.

- *Step 1:* We first characterize the dielectric meta-atom (refer to Fig. 1) placed in an infinite periodic array along the x and y directions. The periodic boundary conditions with Floquet ports are utilized for the simulation, and the structure is illuminated by a TE-polarized (x-directed electric field) plane wave propagating in yz-plane. Examining the transmission coefficient and electric field plots for a typical meta-atom in Fig. 4, it is clear that the electric and magnetic dipole modes for this rectangular DR geometry are excited at 27.8 GHz and 29.5 GHz, respectively.
- *Step 2:* In this step, the dimensions associated with the rectangular DR are now tuned to realize dielectric Huygens' meta-atom. The optimized dimensions of the rectangular meta-atom are: $D_x = 6.95$ mm, $D_y = 3.85$ mm and $H_d = 1.65$ mm. Fig. 5 depicts the transmission



(a)

(b)

Fig. 4. (a) Transmission spectra (magnitude in dB and phase in degrees) for the dielectric meta-atom under normal incidence. (b) Electric field distribution in yz plane at 29.5 GHz (upper panel) and 27.8 GHz (lower panel).

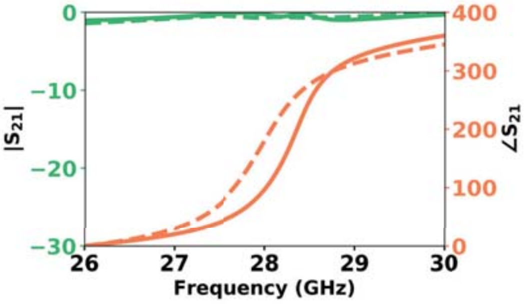
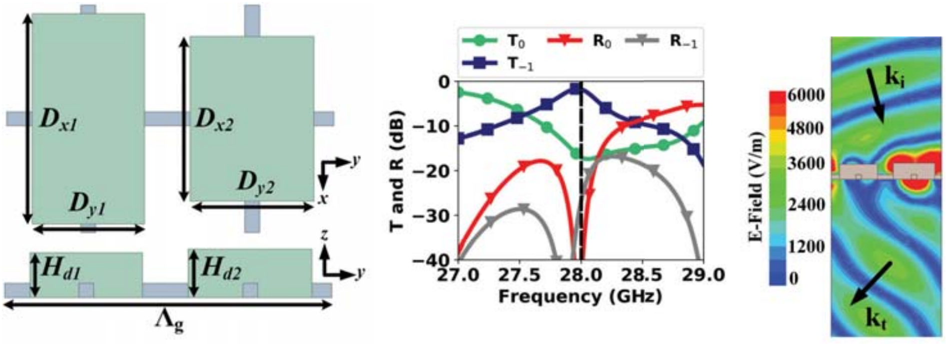


Fig. 5. Transmission spectra (magnitude in dB and phase in degrees) of the dielectric Huygens' meta-atom placed in an infinite periodic array in x and y directions. Dashed line: for normal incidence and solid line: for oblique incidence.



(a) (b) (c)

Fig. 6. Design and simulation of bipartite dielectric Huygens' metasurface. Note that the dielectric losses are not considered in the simulation. (a) One period of Bi-DHMS, $D_{x1} = 7.4$, $D_{y1} = 3.8$ $H_{d1} = 1.58$, $D_{x2} = 5.8$, $D_{y2} = 4.2$ and $H_{d2} = 1.7$. All the dimensions are in mm. (b) Transmittance and reflectance corresponding to the 0 and -1 space harmonics. (c) Electric field distribution at 28 GHz, showing anomalous refraction.

spectra (dashed line) of the dielectric meta-atom placed in a 2-D infinite periodic array. From the figure, it is clear that near unity (> -1 dB) transmission is obtained with almost 2π phase coverage across 26-30 GHz.

- *Step 3:* The meta-atom designed for normal incidence cannot be applied directly for oblique incidence. Our simulations suggest that when the incidence angle deviates from the normal, the transmission starts decreasing, which corroborates with the earlier findings for cylindrical geometry [11] . Considering this, the meta-atom is again re-optimized for the oblique incidence angle ($15°$ in our case). The new optimized dimensions are: $D_x = 7.1$ mm, $D_y = 3.95$ mm and $H_d = 1.62$ mm. The transmission spectra in Fig. 5 shows that the metasurface is almost transparent for $15°$ oblique incidence, achieving full 2π phase coverage across 26-30 GHz.
- *Step 4:* To realize the metasurface, we first characterized the meta-atom designed in *Step 3* for different geometrical parameters (D_x, D_y, and H_d) to generate a meta-atom library having different phases. From the library, we choose two elements having the transmission phase difference of $180°$ to construct one period of the metasurface, as shown in Fig. 6(a). At this stage, the meta-atoms are fine-tuned in the new simulation environment to account for any phase change due to the inter-element coupling between the adjacent elements. Fig. 6(b) plots the transmittance and reflectance corresponding to the two Floquet space harmonics *i.e.* $n = 0$ and $n = -1$. Examining the transmitted modes, the power is maximized to the desired $n = -1$ space harmonic at 28 GHz, while the specular mode ($n = 0$) is suppressed below -15 dB. Besides, the reflections from the metasurface are well suppressed below -30 dB at 28 GHz. Fig. 6(c) portrays the electric field distribution for one period of metasurface at 28 GHz in yz-plane. Observing the electric field distribution, it is clear that anomalous refraction is indeed achieved through the proposed Bi-DHMS.

III. CONCLUSION

We have presented a near-reflectionless sparsely discretized dielectric Huygens' metasurface for anomalous refraction. The proposed metasurface consisting two-elements per period can reroute the oblique incident wave in the anomalous direction corresponding to $-45°$. Such a sparsely discretized DHMS platform shows remarkable promise to design millimeter-wave meta-devices for next-generation wireless communications, such as 5G and beyond.

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