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# Controlling Wavefront using a Coarsely Discretized Dielectric Huygens' Metasurface

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***Abstract*—This paper reports a coarsely discretized dielectric Huygens' metasurface that comprises of only three elements per grating period. The resulting metasurface, which we termed as tripartite dielectric Huygens' metasurface (TD-HMS), greatly simplifies the design leading to a cost-effective and robust metasurface for efficient electromagnetic wave manipulation. Through full-wave electromagnetic simulations at 60 GHz, we show that the proposed TDHMS can achieve efficient anomalous transmission, where the desired diffracted mode contains more than 80% of the total transmitted power.**

## I. Introduction

Huygens' metasurface (HMS) [1], [2]–fundamentally based on the surface equivalence principle, has gained enormous attention for their ultimate capabilities of transforming electromagnetic fields [3]–[5]. The HMS comprises of collocated electric and magnetic polarizable particles, which provide both electric and magnetic responses to an incoming EM wave, leading to full control with great flexibility and high efficiency. However, the requirement of multilayer structure or wire-loop configuration to design HMS leads to fabrication difficulties, particularly in the millimeter-wave (mm-w) frequency regime and beyond. Additionally, the inevitable ohmic losses associated with the metallic inclusions can significantly degrade the performance of the metasurface.

In order to mitigate aforementioned drawbacks of the HMS, the concept of dielectric Huygens' metasurafce (D-HMS)–consisting of high-index low loss dielectric resonators, has been suggested as a new and promising route for controlling EM waves [6]. In D-HMS, the high-transmission and full 360° phase coverage can be realized by simultaneously overlapping the crossed electric and magnetic dipole modes of the dielectric meta-atom. In the recent years, all-dielectric meta-optics has seen stupendous growth and several designs have been reported [7]–[10].

More recently, the aggressively discretized metasurface–which features only a few elements per metasurface period–has been proposed to relaize highly efficient metasurfaces [11]–[14]. The metasurface designed with aforementioned concept are generally larger in size, and do not necessarily necessarily require full 360° phase coverage due to the reduced number of elements per period, leading to a simplfied, cost-effective and robust design as compared to their finely discretized counterparts. Additionally, the maximally discretized metasurface offer a means to overcome the fabrication difficulties even at the mm-w frequency regime.

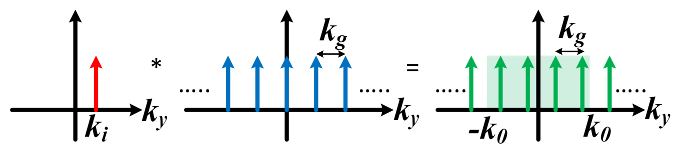


Fig. 1. $k$-space operation of a periodic metasurface which varies along y-direction. Arrow represents the diffraction modes (not the amplitude) and the green box represents the propagation regime.

In this paper, we present a spatially varying transmissive dielectric Huygens' metasurface based on coarse discretization. As a proof of concept, we design a tripariticle dielectric Huygens' metasurface, consisting of three meta-atoms per grating period at 60 GHz for efficient anomalous transmission.

## II. Metasurface Discretization: A Diffraction-Based Prespective

Consider a periodic metasurface in free-space with period $\Lambda_g$ and spatial frequency $k_g = \frac{2\pi}{\Lambda_g}$, which upon the incidence of a plane wave, scatters a discrete set of diffraction orders in different directions depending upon the local metasurface period. Fig. 1 shows the $k$-space operation of this metasurface, which can also be expressed mathematically as

$$\Omega_o(k_y) = \sum_m a_m \delta(k_y - k_{o,m}) = \sum_m a_m \delta(k_y - (k_i + mk_g)) \tag{1}$$

where, $\Omega_o(k_y)$ is the output $k$-space spectrum, which determines the tangential wave number of the output plane wave, $k_i$ is the tangential wave number of the input plane wave, $a_m$ represents the amplitude, and $m$ is an integer–representing the $m^{th}$ diffraction order. Although there exist infinite number of diffraction modes in $k$-space, only a finite number of diffraction modes falls within the propagation range $k_y \in [-k_0, k_0]$, where $k_0$ is the free-space wave number. The diffraction order that fall within the propagation range can scatter into the far-field, whereas the modes out of the propagation range will become evanescent. In [11], it has been shown that $M$-fold discretization within the metasurface period sufficiently determines the $M$ diffraction orders which propagate into the far-field. Based on this concept, a highly efficient metasurface can be designed employing aggressive discretization. A periodic metasurface with discretization level

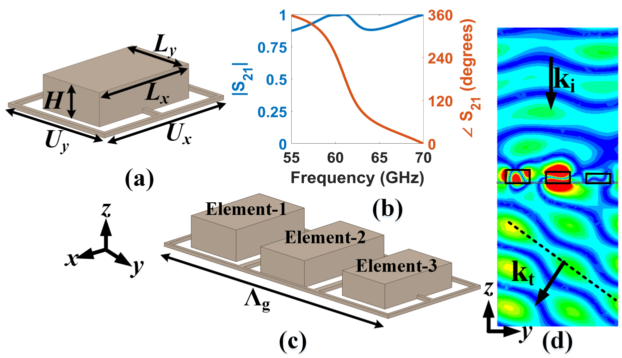


Fig. 2. (a) Schematic of rectangular dielectric Huygens' meta-atom. Geometrical parameters: $U_x \times U_y = 0.72\lambda_0 \times 0.58\lambda_0$ ($\lambda_0$ being calculated at 60 GHz), $L_x = 2.7$ mm, $L_y = 1.7$ mm and $H = 0.8$ mm. The relative permittivity used to design the DR is 12 (PREPERM 3D ABS1200 filament). (b) Transmission magnitude and phase of the dielectric Huygens' meta-atom. (c) Schematic depicting one period of the proposed triparticle dielectric Huygens' metasurface. (c) Electric field magnitude across yz-plane showing anomalous transmission upon normally incident plane wave. The metasurface is placed at the origin (z=0) and black rectangles highlight the location of dielectric particle.

of $M = 3$ can be sufficient to realize efficient anomalous transmission. In this case, the spatial frequency $k_g$ of metasurface should follow: $\frac{k_0}{2} < k_g < k_0$.

## III. Coarsely Discretized Dielectric Huygens' Metasurface

Fig. 2(a) shows a rectangular dielectric Huygens' meta-atom, which is realized by simultaneously overlapping the crossed electric and magnetic dipolar modes by properly tuning the associated geometrical parameters ($L_x$, $L_y$, $H$). A subwavelength thick ring attached to the rectangular DR serves the purpose of mechanical support. The aforementioned dielectric meta-atom is simulated using Ansys HFSS employing the periodic boundary conditions and Floquet ports. As depicted in Fig. 2(b), the meta-atom shows high transmission and full $2\pi$ phase coverage over 55-70 GHz frequency spectrum.

Next, a transmissive metasurface is designed based on coarse discretization, using three spatially varying dielectric Huygens' meta-atom per grating period as shown in Fig. 2(c). Here, we have used the phase gradient approach by choosing three unit-cells with near-perfect transmission and equidistant phase. The geometrical parameters related to each element is listed in Table I. Upon normal incidence of TE-polarized plane wave, anomalous transmission is achieved with more than 80% of the total transmitted power carried by the desired diffraction mode ($m = -1$). The transmitted angle under normal incidence can be determined using the following expression:

$$\sin\theta_{t(m)} = \frac{mk_g}{k_0} = m\frac{\lambda_0}{\Lambda_g}. \quad (2)$$

For $\Lambda_g = 1.74\lambda_0$ ($\lambda_0$ being calculated at 60 GHz) and $m = -1$, the transmitted angle is $\theta_{t(-1)} = -35°$. Fig. 2(d) depicts the magnitude of electric field across yz-plane, demonstrating the beam deflection at an angle predicted using (2).

TABLE I
Dimensions (in mm) corresponding to each element of TD-HMS.

| | Element-1 | Element-2 | Element-3 |
|---|---|---|---|
| Lx | 2.65 | 3.10 | 2.60 |
| Ly | 1.75 | 1.70 | 1.65 |
| H | 0.95 | 0.80 | 0.75 |

## IV. Conclusion

In conclusion, a coarsely discretized dielectric Huygens' metasurface platform shows remarkable promise towards efficient manipulation of electromagnetic waves. As a proof of principle, a triparticle dielectric Huygens' transmissive metasurface has been proposed, demonstrating efficient anomalous transmission at 60 GHz under normal incidence. Through full-wave electromagnetic simulation, it has been shown the proposed metasurface deflects the normal incident plane wave by $-35°$, and the desired diffracted mode contains more than 80% of the total transmitted power. In near future, we will explore additive manufacturing for its fabrication and will look into more practical applications at mm-wave and THz band.

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