A Coarsely Discretized Huygens' Metasurface for Anomalous Transmission

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***Abstract*—Metasurfaces composed of subwavelength elements usually require complicated design and a large number of elements. Coarse discretization in metasurface design – having as few metasurfaces cells as possible within a wave length or period – leads to reduced number of elements in a period, resulting in lower requirement for phase coverage as well as surface impedance coverage. Additionally, coarsely discretized metasurfaces may provide possibility for larger unit cells. Therefore, coarsely discretized metasurfaces show advantages of easy design and may find applications in high frequency range. In this work, we propose a transmitting Huygens' metasurface with a discretization level of 3 elements in a period. Simulation result shows efficient anomalous transmission achieved.**

Keywords—Huygens' metasurface, discretization, anomalous transmission

I. Introduction

Metasurfaces are structures composed of subwavelength elements which can provide various electromagnetic (EM) wave manipulation functionalities, including wave refraction and reflection, polarization control, antenna beamforming, etc.[1-3]. However, the subwavelength unit cell size of metasurface often causes complication in design and fabrication. Also, a deeply subwavelength element size may limit the application potential of metasurface in high frequency regime due to the difficulty in fabrication precision guarantee.

In recent years, Huygens' metasurfaces have been attracting increasing attention because of their simultaneous electric and magnetic response to an incident EM wave. It has been demonstrated that a transmitting Huygens' metasurface can realize efficient EM wave refraction[4, 5]. More recently, some researchers have proposed an aggressively discrete reflecting Huygens' metasurface with only two elements in a period which can realize near-perfect anomalous reflection[6, 7]. By applying a higher level of discretization, the number of elements in a period will be decreased. The reduced number of elements leads to lower requirement for phase and/or surface impedance coverage, resulting in simpler design. Furthermore, the discretization of a metasurface will provide possibility for larger unit cells, which may benefit its application in high frequency range.

In this work, we propose a transmitting Huygens' metasurface with a discretization level of 3 elements in a period. As a proof of concept, each element is composed of 3 identical unit cell. The metasurface is designed to realize efficient anomalous transmission. Future work will focus on the investigation of larger unit cell in metasurface design to realize efficient EM wave manipulation.

II. Metasurface Discretization

Consider a periodic metasurface in free space, upon an incident plane wave, the output will consist of an infinite numbers of diffraction modes. Fig. 1 shows the *k*-space operation of a periodic metasurface with period Λ_g and wave number $k_g = 2\pi / \Lambda_g$. It can also be expressed using the following equation:

$$S_{out}\left(k_y\right) = \sum_n a_n \delta\left(k_y - k_{out,n}\right) = \sum_n a_n \delta\left(k_y - \left(k_{in} + n \cdot k_g\right)\right) \quad (1)$$

where $S_{out}\left(k_y\right)$ is the *k*-space spectrum determining the tangential wave number of the output plane wave, k_{in} is the tangential wave number of the input plane wave, *n* is an integer and $k_{out,n}$ is the *n*-th diffraction mode of the output with an amplitude of a_n. The light blue region in Fig. 1 denotes the free space propagation range of $k_y \in \left[-k_0, k_0\right]$, where k_0 is the free space wave number. The diffraction modes falling into the propagation range can scatter into the far field while the diffraction modes out of it will become evanescent. Our previous work [7] has shown that a metasurface with *N* independent degrees of freedom is sufficient for tuning an output with *N* propagating diffraction modes, and that these *N* degrees of freedom can be realized using an array of *N* elements along the variation direction, resulting in a discretization level of *N* elements in a period. Based on this principle, we can realize efficient EM wave manipulation with an aggressively discretized metasurface.

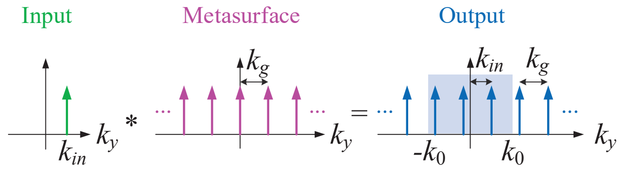

Fig. 1. *k*-space operation of a periodic metasurface which variates along y-direction. Arrows indicate the existence of an infinite number of diffraction modes, the light blue box denotes the free space propagation range from $-k_0$ to k_0.

For a periodic metasurface under normal incidence, a coarse discretization level of *N*=3 can be sufficient to realize efficient anomalous reflection/transmission. Moreover, an insufficient discretization level of *N*=2 can realize spitting effect. Figs. 2 (a) and (b) are the *k*-space operation and a schematic diagram showing the perfect anomalous transmission of a transmitting metasurface with a discretization level of *N*=3. In this case, the metasurface should have a wave number k_g larger than $k_0 / 2$. Figs. 2 (c) and (d) show the *k*-space operation and a schematic diagram of a transmitting metasurface with a discretization level of *N*=2. This discretization is insufficient and leads to a splitting effect. In this case, the metasurface should have a wave number k_g larger than $k_0 / 3$.

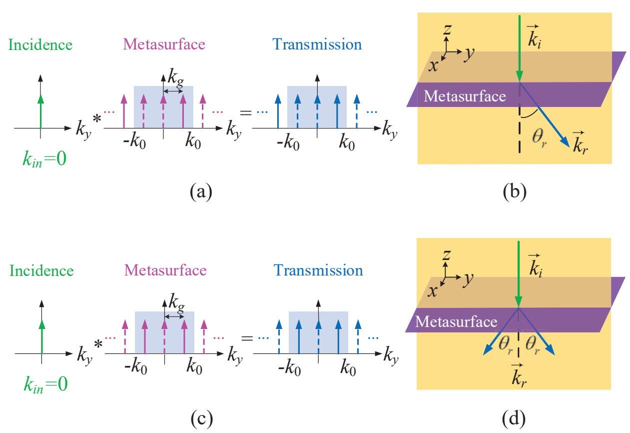

Fig. 2. (a) The *k*-space operation of a periodic metasurface with a discretization level of three elements in a period under normal incidence. Arrows with solid line represent diffraction modes with non-zero amplitude, arrows with dashed line represent diffraction modes with zero amplitude. (b) A schematic diagram of a metasurface showing perfect anomalous transmission. (c) The *k*-space operation of a periodic metasurface with a discretization level of two elements in a period under normal incidence. (d) A schematic diagram of a metasurface showing the splitting effect.

III. Discrete Huygens' Metasurface for Anomalons Transmission

To demonstrate the concept, we design a transmitting metasurface with *k*-space property shown in Fig. 2(a). For comparison, we used the same Huygens' unit cell structure as in [4], but *double* the unit cell dimension along the direction of feature variation, and attempt to generate a similar refraction functionality using the concept of discrete Huygens' metasurface. As shown in Fig. 3(a), the unit cell consists of three metallic layers and vias, with size of U_x and U_y along x-direction and y-direction respectively, and thickness *T*. The electric dipole is on the middle layer, with dipole gap width of g_e and dipole width of w_e, the magnetic dipole is realized by an electric loop with width of w_m.

The metasurface is designed at 10 GHz with unit cell size of $U_x = U_y = 0.2\lambda_0$ and $T = 0.1\lambda_0$, in keeping with [4], we use a Rogers RO3003 substrate with $\varepsilon_r = 3.0$ and $\delta_t = 0.0013$ [8]. The refraction angle under normal incidence can be calculated using:

$$\sin\theta_r = \frac{k_g}{k_0} = \frac{\lambda_0}{\Lambda_g}, \tag{2}$$

or conversely Λ_g can be designed as a function of the desired refraction angle. Fig. 3(b) is a schematic diagram showing a period of the metasurface. This metasurface has 3 elements, each element is composed of 3 identical unit cells. (In a future work, each element can be redesigned as a unit cell on its own, which should further enlarge the feature size of the metasurface element.) Hence the total metasurface period is Λ_g=1.8λ_0; using (2), one readily see that this corresponds to an anomalous transmission angle of θ_r=33.7° under normal incidence.

The commercial software Ansys HFSS is used for simulation, a period of the designed metasurface is shown in Fig. 3(c), the geometric parameters are given in Table I. Fig. 4 shows the electric field magnitude distribution of the designed metasurface under a normally incident Gaussian beam with the beam width of 64 mm at focal point.

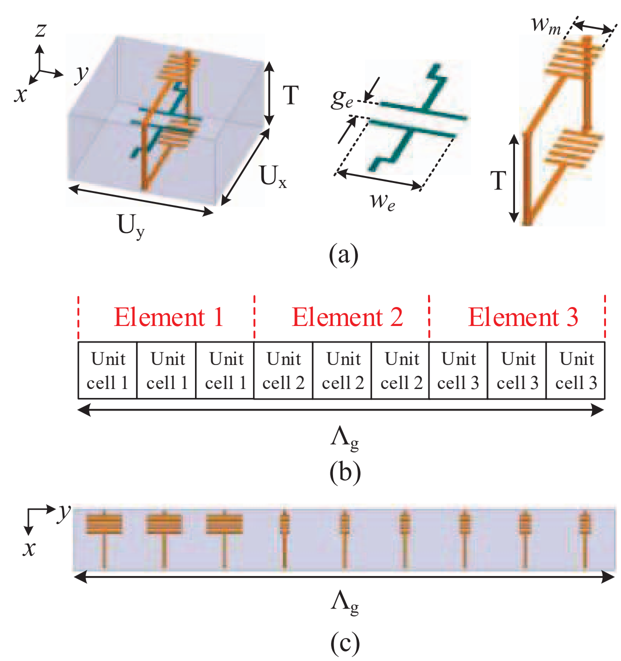

Fig. 3. (a) Geometric structure of a unit cell. The three metallic layers consisting electric and magnetic dipoles are all perfect conduct. (b) A schematic diagram of a period of the metasurface. (c) Top view of a period of the designed metasurface, with only the top metallic layer visible.

I. GEOMETRIC PARAMETERS OF THE UNIT CELLS

	g_e (mm)	w_e (mm)	w_m (mm)
Unit cell 1	2.26	5.28	3.49
Unit cell 2	1.59	0.38	0.89
Unit cell 3	2.37	4.46	1.07

Simulation result shows efficient anomalous transmission of the metasurface with more than 70% of the incident power being deflected to the designed direction. Some undesired reflection and transmission may be caused by the design method. We used phase gradient approach in this design by choosing three unit cells with near-perfect transmission and equidifferent transmission phases. In the future, higher efficiency may be achieved by considering more design parameters such as surface impedances as well as coupling among unit cells.

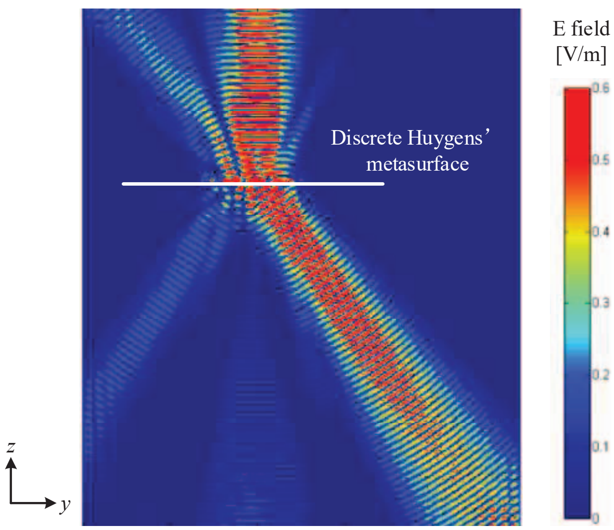

Fig. 4. The electric field magnitude distribution of the designed metasurface upon normally incident Gaussian beam.

Compared to the work in [4], the unit cell size along the variation direction is doubled, and the discretization level is increased from 20 elements to 3 elements in a period. Additionally, for our proposed design, the required unit cell transmission phase coverage is about 240 degrees, which is much less than the phase coverage requirement of more than 340 degrees in the compared design.

IV. CONCLUSION

In conclusion, we have demonstrated that coarse discretization – decreasing the number of elements in a period as much as possible – can benefit metasurfaces design. We proposed a transmitting Huygens' metasurface with the discretization level of 3 elements per period which can realize efficient anomalous transmission. In this work, each element of the proposed metasurface is composed of 3 identical unit cells. Simulation result shows efficient anomalous transmission of the metasurface by deflecting a normally incident Gaussian beam by 33.7 degrees. In the future, we will investigate larger unit cells in a highly discretized metasurface.

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