Binary Huygens' Metasurface: A Simple and Efficient Retroreflector at Near-Grazing Angles

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Abstract— **In this work we report the design and simulation of a metasurface retroreflector for near-grazing incidence. The retroreflector is a Huygens' metasurface that is coarsely discretized to just two cells per grating period. The coarse discretization leads to a relatively large element size, which in turn enables one to realize the metasurface unit cells using a simple, single-layered metasurface structure of a dipole backed by a ground plane. A full-wave Floquet simulation of the metasurface demonstrates retroreflection at 94% power efficiency for an incident TE plane wave at 82.87°. A simulation of the finite-length metasurface also shows efficient retroreflection in the far-field.**

I. Introduction

Recent works on metasurfaces have shown their ability to modify the phase, direction and polarization of an electromagnetic wavefront [1-5]. Specifically, Huygens' metasurfaces [3-5] – surfaces of sub-wavelength elements which generate co-located but orthogonal electric and magnetic currents – can be tuned to achieve a wide range of reflection properties, which make them a versatile tool for wavefront manipulation. However, the use of metasurfaces at near-grazing angles remains a challenge, in part because at near-grazing incidence angles, the electromagnetic wave oscillates quickly along the direction of the metasurface. Nonetheless, the ability to modulate waveforms at near-grazing incidence can find important applications. In this paper we present a simple Huygens' metasurface which serves as a retroreflector for near-grazing incidence. We report our design process and present full-wave simulation results which demonstrate the achievement of retroreflection. We aim to highlight our adopted approaches and gained insights which apply generally to designing metasurfaces for wide-angle operation.

II. Retroreflection Metasurface

Fig. 1a depicts the geometry of the incident wave and the metasurface. The metasurface lies on the xy-plane. A 24 GHz TE-polarized beam from a near-grazing angle of 82.87° impinges on the metasurface. We wish to design a metasurface which retroreflects the beam and minimizes scattering in all other directions, including the specular direction. We aim to design the metasurface with high efficiency and utmost simplicity.

We seek to synthesize a reflection profile which has a grating period in the y-direction that satisfies the Bragg condition:

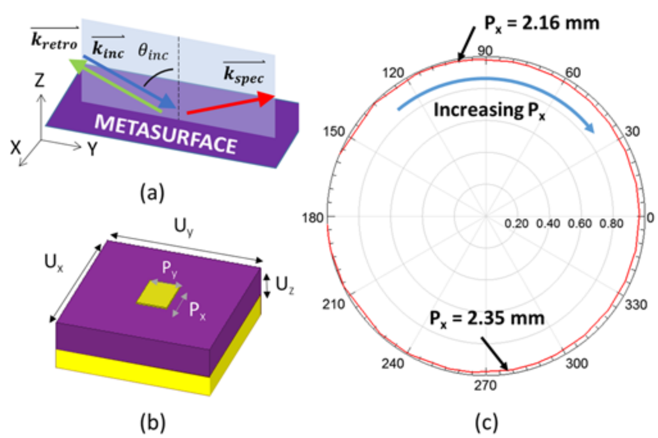

Fig. 1. Retroreflection metasurface: concept and unit cell design. (color online) (a) A conceptual drawing showing directions of the incident wave (blue), the specularly reflected wave (red) and the retroreflection (green). The ideal metasurface should suppress specular reflection and maximize retroreflection. (b) A diagram showing the metasurface unit cell. Dimensions are: $U_x = U_y = s =$ 3.149 mm; $U_z = 1.575$ mm, $P_y = 1.5$ mm and P_x is swept from 1mm to 3mm. (c) A plot showing the variation of the reflection coefficient as a function of dipole length.

$$\Lambda = \frac{\lambda}{2\sin\theta_{inc}}. \tag{1}$$

Since the Huygens' metasurface will implement a discretized version of this reflection profile, we investigate the degree of discretization which will be tolerable for this metasurface. From Fourier theory, an arbitrary surface with grating period Λ will generate spectral harmonics at increments of

$$\Delta k_g = \frac{2\pi}{\Lambda} = 2k_0 \sin\theta_{inc}\,. \tag{2}$$

The number of such harmonics which lie within the propagation spectrum ($|k_y| \leq k_0$) is given by:

$$N = 2 \times \text{round}\left(\frac{1}{2 \sin \theta_{inc}}\right). \quad (3)$$

One can show that to fully control these N harmonics one needs to discretize the grating into N segments per grating period. This hence establishes the lower bound in the allowable discretization granularity of the metasurface.

The somewhat surprising conclusion of this analysis is that *larger* incidence angles actually allow *coarser* discretization. Particularly, for $\theta_{inc} \geq 19.5°$, $N = 2$, which means only the specular and retroreflection plane waves remain in the propagation region. (This case for minimum discretization concurs with an earlier work [6] on blazed gratings, and validates a more recent work on blazed metasurfaces [7].) Hence for our case of near-grazing incidence, a binary grating with two elements per grating period, separated by a distance

$$s = \frac{\Lambda}{2}, \quad (3)$$

and differing in reflection by a 180° phase shift, suffices in eliminating specular reflection and optimizing retroreflection.

III. Unit Cell Design and Simulation

We used as our metasurface element the ground-backed dipole structure shown in Fig. 1b. We showed in an earlier work [8] that this structure can constitute a Huygens' source, and that by tuning the dipole length along the direction of the electric field, one can modify the reflection phase by a range approaching 360°. Fig. 1c shows the reflection coefficient of an infinite 2D array of the unit cell, as found from full-wave simulation using Ansys HFSS. For this design we used a Rogers Duroid 5880 substrate with 1.575 mm thickness and 1 oz. (17μm) copper. As we tuned p_x from 1 mm to 3 mm, the reflection phase varied monotonically. The dipole lengths $p_{x1} = 2.16$ mm and $p_{x2} = 2.35$ mm generate reflection phases which were 180° shifted from one another. They were chosen as operation points for this metasurface.

IV. Metasurface Design and Simulation

We placed the aforementioned elements beside one another to form a diffraction grating in the y-direction. We then performed a Floquet analysis to simulate the reflection response of a metasurface formed by the 2D infinite periodic repetition of the aforementioned grating. We found that (a) individual unit cell behaviors remained largely similar even though the neighbouring cells were different, and (b) 94% of the power was retroreflected by the metasurface.

We proceeded to simulate a metasurface that was finite in one direction. To conserve computation resource, we left invariant the simulation in the x-direction using a pair of periodic boundaries in the $+x$ and $-x$ directions, but in the y-direction we truncated the metasurface to 80 grating periods (503.8 mm). Upon plane-wave illumination, the scattered waves along the yz-plane are shown in Fig. 2b. In this finite simulation, a specular lobe emerged, but clearly most of the power has been diverted into the retroreflection lobe.

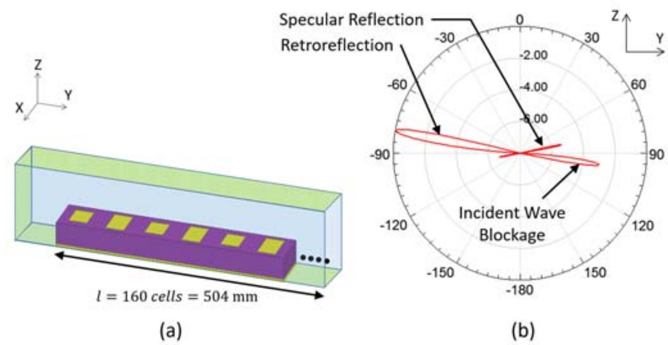

Fig. 2. Retroreflection metasurface simulation. (color online) (a) A diagram showing the simulation of the 1D infinite metasurface. The x-directed (blue) faces are periodic boundaries; the y- and z-directed faces are radiation boundaries. (b) The corresponding scattered pattern in dB scale, showing a strong retroreflection lobe along with a much weaker specular reflection lobe. The back lobe represents the forward scattering pattern.

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