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Achieving Wideband Beam-Splitting with an Ultrathin Discrete Huygens' Metasurface

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Abstract—**We propose the design of a Huygens' metasurface whose elements can realize stable reflection characteristics from 21 GHz to 30 GHz (37% bandwidth). The proposed metasurface features two markedly different elements which provide a reflection phase difference of $180° \pm 37°$ over the aforementioned band. This design methodology allows one to broaden the bandwidth of various metasurface designs that rely on a variation of reflection coefficients. As a simple example, we demonstrate a metasurface that reduces the reflectance of a normally incident electromagnetic (EM) wave by redirecting the energy into oblique scattering directions. A wideband beam splitter is hence designed with very thin substrate thickness and utmost simplicity. This work paves way to the design of wideband Huygens' metasurfaces.**

Keywords—metasurface; beam splitter; harmonics; reflection coefficient.

I. INTRODUCTION

A beam splitter is a passive device that is widely used in optical devices such as interferometers and spectrometers to split the incoming beam into multiple beams with a certain power ratio. However, its design in the lower frequency band is seldom reported. The design of beam splitter at low frequencies can also find applications in wireless power transfer and millimeter wave interferometers. In this work, we designed a beam splitter with the help of a Huygens' metasurface which is ultra-thin ($0.046\lambda_o$) and wideband. Metasurfaces are basically artificial surfaces consisting of subwavelength engineered elements which give them designer-responses to EM waves. They have gained enormous attention due to their ultimate wave manipulation abilities. Novel applications such as anomalous and multichannel reflections [1-2], beam splitter [3], etc. have recently been realized by the researchers in the recent past.

In this work, we propose a method to design an inherently wideband ultrathin Huygens' metasurface. Our metasurface consists of two basic cells that feature a reflection phase difference of 180°. Through using two types of metasurface elements with compensatory dispersion characteristics, the reflection phase difference is controlled at $180° \pm 37°$ over a wide bandwidth of 37%. We then combine them to form an ultrathin metasurface beam splitter that realizes a reduction in reflectance for a normally-incident plane wave over a bandwidth of 37%. Beyond the demonstration of beam-splitting, our work paves way to the design of metasurfaces with phase-stable performance over a wide bandwidth. The design analysis along with full-wave simulation results are demonstrated in the paper which validates the wideband splitting ability of our ultrathin Huygens' metasurface.

II. THEORY AND ANALYSIS

When a plane wave impinges on a periodic metasurface in free space, it generates an infinite number of diffraction modes, as shown in Fig. 1(a). The tangential and normal wavenumber of the n[th] diffraction modes at the output can be expressed as

$$k_{out,t} = k_{in} + nk_g \tag{1}$$

$$k_{out,n} = \sqrt{k_i^2 - k_{out,t}^2} \tag{2}$$

From (1), the $k_{in} = k_i \sin\theta$ is the tangential wave number of the incident plane wave, $k_g = 2\pi/D$ is the spatial frequency of the metasurface, D is the spatial period and n is the diffraction order representing the spatial harmonic modes. Out of infinite diffraction modes, only a finite number of diffraction modes fall within the propagation range of $k_y \in [-k_0, k_0]$ which scatter into the far-field and rest will become evanescent.

We begin by designing a metasurface that would split the incoming plane wave to directions other than the incident. Under normal beam incidence, the metallic surface strongly reflects the incoming beams to the direction of incidence. Therefore, no reflection along the axis of the incidence beam is required for the design of efficient beam splitter. Based on this idea, we design an ultrathin Huygens' metasurface which allows the propagation of the 1[st] and -1[st]-order modes and suppresses the normal retroreflection over wideband. The schematic diagram of the metasurface with the design concept is demonstrated in Fig. 1(b). According to [1],[2], a metasurface structural period of $\lambda_o < D < 2\lambda_o$ is required to generate three spatial harmonics (1, 0, -1). Fig. 1(c) shows the k-space operation of the proposed metasurface. The proposed metasurface suppresses the mirror reflection ($n = 0$, dotted arrow), and allows the anomalous reflection into θ_r and $-\theta_r$, (harmonics $n = 1$ and $n = -1$). The suppression of the zeroth order is achieved by introducing destructive interference between the metasurface unit cells, as discussed in the subsequent section. The reflection angle and the structural period of the metasurface are related as:

$$\sin\theta_r = \frac{nk_g}{k_0} = \frac{n\lambda_0}{D} \tag{3}$$

From (3), at the fixed frequency, the reflection angle of the propagating diffraction modes only depends on the structural period of the metasurface.

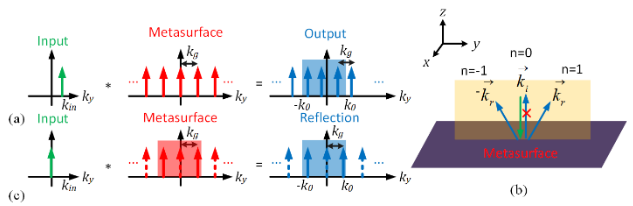

Fig. 1. (a) K-space operation of the periodic metasurface that varies along the y-axis. Arrows depicting the presence of the diffraction modes. The blue shaded box shows the propagation range $-k_0 \le k_y \le k_0$. (b) Schematic diagram of the proposed discretized Huygens' metasurface. (c) K-space operation of the proposed metasurface with propagation range $-k_0 \le k_y \le k_0$.

III. Unit Cell Design and Simulations

We achieved the suppression of specular reflection by constructing two different unit cells with a phase difference of $180^{\circ} \pm 37^{\circ}$. The 180°phase difference provides destructive interference between the unit cells and eliminates the specular reflection. However, it is difficult to achieve a 180° phase over wideband. Following [4], which shows that the phase difference of $180^{\circ} \pm 37^{\circ}$ is sufficient to suppress the mirror reflection up to 10 dB, we applied $180^{\circ} \pm 37^{\circ}$ phase difference as a criterion to suppress the normal reflection in a wideband. We used as our metasurface element two different unit cells which consist of rectangular and circular metallic patterns, as shown in Figs. 2(a) and 2(b), which are etched on the ultrathin FR4 substrate with the dielectric constant of 4.4, $\tan\delta = 0.02$, and thickness of 0.5 mm. Fig 2(c) depicts the reflection phase profile of the infinite 2D array of the unit cells, as found from full-wave simulation using Ansys HFSS. To observe the compensatory dispersion characteristics, we tune the rectangular dipole length (P_x) from 0.5 mm to 1.785 mm and the radius (R_1) of unit cell 2 from 0.5 mm to 1 mm. We found that the lengths $P_x = 1.68$ mm, $P_y = 0.90$ mm, and $R_1 = 0.835$ mm provide the dispersive phase responses which yield a phase difference of $180^{\circ} \pm 37^{\circ}$ among the unit cells. They were selected as operation points for the design of unit cells. It can be seen from Fig. 2(c) that the proposed unit cells exhibit stable relative reflection coefficients from 21 GHz to 30 GHz. Therefore, we proceeded to design a beam splitter with a structural period $\lambda_0 < D < 2\lambda_0$, which allows only spatial harmonics of $n = \pm 1$. To prove the concept, we simulated a beam splitter at 28 GHz which reflects a normally-incident beam into $\theta_r = \pm 30^{\circ}$.

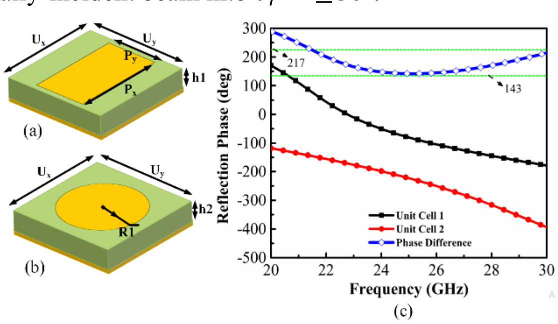

Fig. 2. Designing of the unit cells. (a) Unit cell 1, with $U_x = U_y = 1.785$ mm, $P_x = 1.68$ mm and $P_y = 0.9$ mm. (b) Unit cell 2, with $R_1 = 0.835$ mm. (c) Reflection phase of the unit cells.

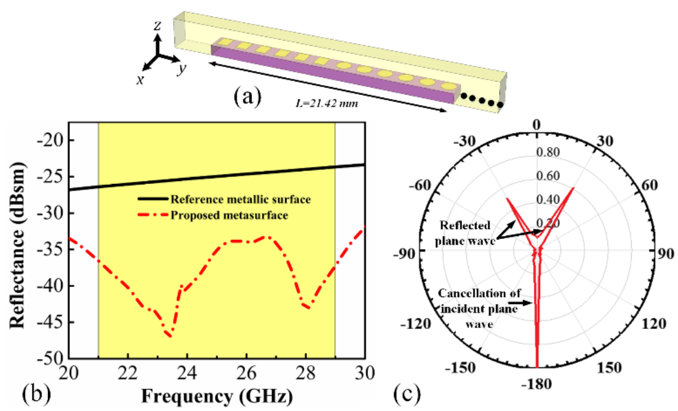

Fig. 3. (a) An ultrathin Huygens' metasurface design at 28 GHz. (b) Retroreflection under normal incidence. (c) Radiation pattern at 28 GHz.

IV. Beam Splitter Design and Simulations

We obtained the supercell design for the beam splitter by repeating the basic unit cells up to six periods and placing them beside one another. The size of the supercells is 21.42 mm which is considered by utilizing the equation (3). From (3), to split the beam at $\theta_r = \pm 30^{\circ}$ directions at 28 GHz, the size of the period should be 21.42 mm. Fig 3(a) shows the structure of a supercell for the metasurface. We simulated the beam splitter as a finite structure in the direction of variation. We applied the periodic boundary condition in the $\pm x$ direction, but in the $\pm y$ direction we repeated the supercells for 20 periods (428.4 mm). Fig. 3(b) shows the reflectance performance of the reflection beam propagating in the $-z$ direction, which depicts a prominent suppression of mirror reflection as compared to the same sized metallic surface. It is evident from Fig. 3(b) that the proposed metasurface reduces the normal reflection for more than 10 dB from 21 GHz to 29 GHz, and allows only $n = \pm 1$ spatial harmonics. Fig. 3(c) shows the 2D radiation pattern of the proposed metasurface. It can be seen that the incident plane wave is split towards the $\theta_r = \pm 30^{\circ}$ directions with minimal normal reflection, which validates the design method.

V. Conclusion

This work presents the design of an ultrathin Huygens' metasurface which constitutes a stable reflection response over a relative bandwidth of 37%. A beam splitter device at 28 GHz is designed which splits the incoming beam to the $\theta_r = \pm 30^{\circ}$ direction. Due to the wideband suppression of the mirror reflection, the proposed device will not have any retroreflection.

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