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Gradient metasurface for four-direction anomalous reflection in terahertz

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ABSTRACT

In this paper, a four-direction anomalous reflection metasurface is proposed. The basic cells comprise of squares and circles, which are designed at various sizes and arranged in a super cell at regular spacing. Then, properly combining super cells molds a square phase gradient metasurface (PGM). It is mounted on an optical thickness gold mirror, which inhibits all light transmission. Markedly different from previously reported metasurfaces, the square PGM is characterized by four-direction reflection beams. It takes into consideration the normal incidence and the oblique incidence. For the normal incidence, that the degrees of the four reflection angles are identical is due to the x, $-x$, y and $-y$ directional discontinuous phase gradients, and lies on the symmetric structure in the xoy plane, which is then revealed by the surface current distribution. Incident angles varying from $-20°$ to $20°$, the reflection angles are demonstrated in the oblique incidence. Moreover, the PGM is polarization-independent. The performance is attributed to the symmetry of structure, which is verified by Radar cross section. Simulated results prove that our method offers a simple and effective strategy for metasurface design in terahertz. The proposed PGM can aid in focused beams, steering beams, and shaped beams.

1. Introduction

Recently, a kind of ultrathin or two-dimensional metamaterials, called metasurfaces, have been attracting tremendous attention due to their prominent light manipulation abilities, multi-functionality, low loss, and ease of on-chip fabrication resulting from their planar structures [1,2]. They can be applied in conventional optics as well as in transformation optics and on-chip optics [3,4], such as beam steering or beam shaping [3–5], flat lenses [6], polarization manipulation [7–9], waveplates [10,11], and absorber [12–14], and so on.

Based on the previous mentioned metasurfaces, anomalous reflections or refractions are realized, which in fact tailor the light propagation in nearly arbitrary ways. The milestone work done by Yu et al., uses a PGM made of v-shaped optical antennas [3]. For enhancing efficiency, enlarging bandwidth, expanding functionality, and simplifying fabrication, various researches have sprung up at an increasing rate since then. In 2012 M. A. Kats et al., reported that homogeneous arrays of two-dimensional Y-shaped optical antennas supporting two independent and orthogonally oriented current modes operated as highly birefringent metasurfaces [15]. In the same year, S. Sun et al., demonstrated theoretically and experimentally that a specific gradient-index metasurface consisting of H-shaped antennas led to anomalous reflection/refraction, which converted a propagating wave to a surface wave with nearly 100% efficiency [16]. In 2013, A. Pors and S. I. Bozhevolnyi showed us how a metasurface combining nanobrick elements and nanocross elements allowed one to fully control the phase of reflected light for two orthogonal polarizations simultaneously [17]. In 2015, Fan Ya et al., designed and fabricated a broadband one-dimensional dispersive phase gradient metasurface comprised of six double-circular metallic unit cells periodically arrayed above substrate, which perfectly achieve anomalous reflection [18]. In addition, other basic structural elements of the metasurfaces, such as split-ring resonators [19,20], nanorods [21,22], nanobricks [10], and hybrid structures [17] are demonstrated. To realize anomalous reflections or refractions in desired directions, therefore, one key aspect is to appropriately design a super cell (i.e., the basic structural element of the metasurface) to satisfy the required phase shift profile along the interface.

In this paper, basic cells comprising of squares and circles with different sizes are designed and arranged with appropriate spacing in a super cell. Then, the proper combination of super cells forms a new type of PGM profile. It is mounted on an optically thick gold mirror, which inhibits all light transmission. The design was simulated using CST Microwave Studio. The simulated results show that the exhibited anomalous reflection is characteristic of four-direction reflection beams in terahertz and follows polarization-independent in terahertz. Moreover, the mechanisms of the four-direction reflection and polarization independence are illuminated by field distribution.

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Table 1
Structural parameters of six basic cells.

Basic cell index	p (μm)	h (μm)	w (μm)	r_1(μm)	r_2(μm)	ϕ (°)
1			22.6	6.3	1.3	270
2			46.6	18.3	13.3	210
3	85	30	53.6	21.8	16.8	150
4			59.8	24.9	19.9	90
5			67	28.5	23.5	30
6			82.4	36.2	31.2	−30

2. Design of four-direction anomalous reflection PGM

2.1. Fundamental theory

The PGM is capable of governing reflected beam directions. This performance is attributed to the discontinuous phase shift on the interface and can be interpreted by the generalized Snell's law [3]. Mathematically, the generalized reflection law is described as

$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_0}{2\pi n_i}\frac{d\phi}{dx} \tag{1}$$

where θ_r and θ_i are the angles of reflection and incidence, respectively; n_i are the refractive index of the medium; λ_0 is the vacuum wavelength; $d\phi/dx$ is a phase gradient along the interface between two media. Eq. (1) implies that for a given θ_i, θ_r are tailored by $d\phi/dx$. If the metasurface is illuminated by vertically incident plane wave from vacuum, then n_i is one and θ_r is zero, Eq. (1) is therefore simply stated as

$$\sin(\theta_r) = \frac{\lambda_0}{2\pi}\frac{d\phi}{dx} \tag{2}$$

2.2. Layout for four-direction PGM

The inset of Fig. 1 schematically depicts a basic cell, which is mounted on a full reflective gold ground plane. The gold plane thickness is negligible and does not allow the transmission of incident light. The dielectric layer (cyan) thickness h is 30 μm and the width p is 85 μm, whose refractive index is 1.53. r_1 and r_2 are radii of two circles respectively. The circle with radius r_2 is made of gold (yellow). The top gold square side-length is w. A super cell consisting of six basic cells, labeled with 1, 2, 3, 4, 5 and 6, is shown in Fig. 1, in which dx is 510 μm leading to phase gradient $|d\phi/dx| = 2\pi/510$. The parameters relating to these six basic cells are listed in Table 1, in which ϕ is the phase. Mathematically stated, the correlations between w, r_1 and r_2 are expressed as follows:

$$w - 2 \times r_1 = 10 \tag{3}$$

$$r_1 - r_2 = 5 \tag{4}$$

$$w = 2 \times r_2 + 20 \tag{5}$$

Based on the periodic boundary condition and normal incidence, the reflection coefficients and phases of basic cells are shown in Fig. 2. We can draw a conclusion that the simulated efficiency is over 90% and the phase gradient keeps constant.

A four-direction PGM made of super cells tailors the propagation of plane wave along four directions and schematic is shown in Fig. 3 (the numbers corresponding to that in Fig. 1), which is a multi-order structure. Each order of the PGM covers a square ranging from 1 to 6.

3. Results and discussion

In this part, open and space boundary conditions were used in the x, y and z directions. It should be noted that the following discussions are based on the incident plane wave with x polarization if there is no specific mention.

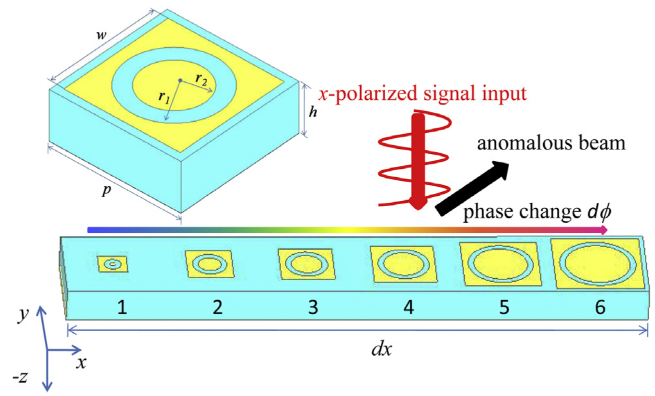

Fig. 1. Schematic of the anomalous beam for an x-polarized incident beam propagating in the $-z$ direction. The inset shows the structural details of the basic cell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

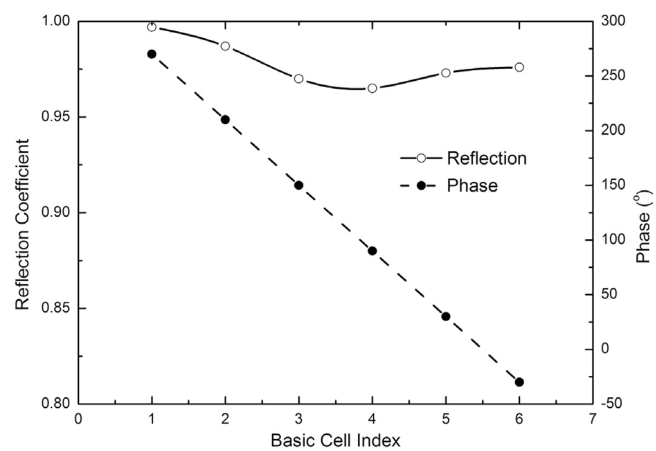

Fig. 2. Reflection coefficients and phases of basic cells at 1THz.

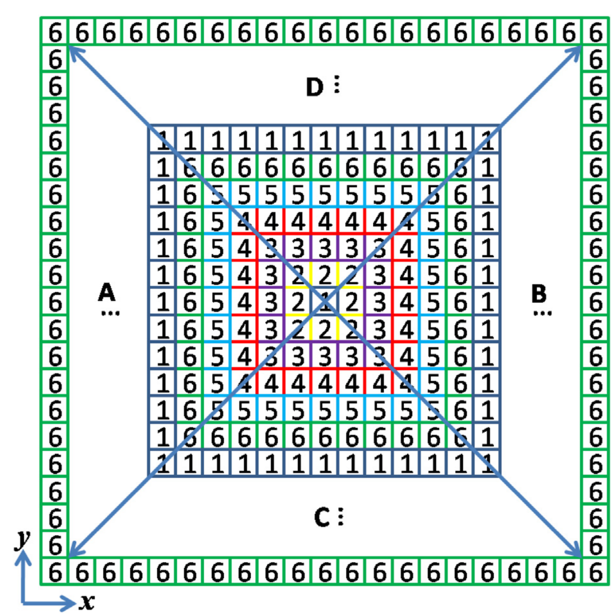

Fig. 3. Basic cells distribution schematic of the four-direction metasurface, which is divided into four regions such as A, B, C, and D.