Terahertz Broadband Low-Reflection Metasurface by Controlling Phase Distributions

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1. Introduction

Recently, reflectionless or low-reflection surfaces made of subwavelength structures have been of broad interest in practical engineering. Here, a single-layer terahertz metasurface is proposed to produce ultralow reflections across a broad-frequency spectrum and wide incidence angles by controlling the reflection phases of subwavelength structures. To enable full control of the phase range in a continuous band, a combination of two different subwavelength elements are employed, both of which exhibit weak interactions with the incident terahertz waves, thereby showing high local reflectivities near the operating frequency. An optimization method is utilized to determine the array pattern with the minimum overall reflections under the illumination of plane waves. Both numerical simulations and experimental results demonstrate ultralow reflections of terahertz waves by the metasurface over a broad frequency band and wide incidence angles. By using the proposed metasurface, the far-field scattering patterns of metallic objects can be efficiently controlled, which opens up a new route for low-reflection surface designs in the terahertz spectrum.

Recently, reflectionless or low-reflection surfaces made of subwavelength structures have been of broad interests in practical engineering. Here, we propose a single-layer terahertz metasurface to produce ultralow reflections in broad frequency spectrum and wide incidence angles by controlling the reflection phases of subwavelength structures. To enable full control of the phase range in a continuous band, we propose to employ a combination of two different subwavelength elements, both of which exhibit weak absorptions to the incident terahertz waves, thereby showing high local reflectivities near the operating frequency. An optimization method is utilized to determine the array pattern with the minimum overall reflections under the illumination of plane waves. Both numerical simulations and experimental results demonstrate ultralow reflections of terahertz waves by the metasurface in broad frequency band and wide incidence angles. By using the proposed metasurface, the far-field scattering patterns of metallic objects can be efficiently controlled, which opens up a new route for low-reflection surface designs in the terahertz spectrum.

Recent advances in artificial metasurfaces have enabled rapid development of ultrathin flat optical devices which can modify the wavefront of light by altering its phase and amplitude. The metasurface is a 2D equivalence of metamaterials, which are usually constituted by inhomogeneous arrays of subwavelength resonators and easy to be integrated into nanophotonic systems. The abrupt phase discontinuities can be introduced owing to the presence of resonators, making it possible to manipulate the wavefronts of electromagnetic waves at will. So far, a number of planar devices based on metasurfaces have been proposed and fabricated to demonstrate the unique electromagnetic properties, showing a promising future for the emerging applications, ranging from the vortex plates and polarizers to flat lenses.

Since the metasurface allows a new route to redirect wavefronts around an object, a variety of approaches have been put forward and experimentally characterized to reduce the reflection and scattering of objects, resulting in invisibility or camouflage as desired. One is based on the scattering cancellation of the reflected waves, which can greatly suppress the backward scattering within broad angles. Other approaches include the mantle cloaks, ultrathin metamaterial absorbers, zero refractive-index materials, and transformation optics devices. Recently, metasurfaces composed of randomly distributed...
elements have been demonstrated in the microwave frequency to provide an important path toward the design of reconfigurable low-scattering coatings, due to the possibility to synthesize the scattering patterns based on the practical environment.\[21,22\] By tailoring the spatial profile of metaatoms, electromagnetic diffusions are invoked, which can be attributed to destructive interference of the reflected waves from each elements, resulting in extremely low backward scattering. By using the coding and programming metasurfaces, electric tuning of the scattering patterns can be easily achieved with the external bias voltages.\[23\]

Here we propose a method to design a single-layer terahertz metasurface that possesses ultralow reflections in broad frequency spectrum and wide incidence angles by controlling the local reflection phases of subwavelength structures. To realize full controls of the phase range in a continuous terahertz frequency band, two different subwavelength elements are employed in our design, which exhibit weak absorptions to the incident terahertz waves, and hence provide high reflectivities near the working frequency. We employ an optimization method to determine the final arrangement of subwavelength elements, reaching the minimum backward scattering under the illumination of plane terahertz waves. The proposed method provides an efficient way to control and manipulate the scattering patterns of objects in the terahertz regime, which can also be extended to the infrared and optical spectra.

2. Theory and Design

The schematic diagram of the proposed terahertz metasurface for extra-low reflections is illustrated in Figure 1a, where two kinds of subwavelength metaelements (or metaatoms) are considered to provide a large reflection phase range over a wide frequency band. Both elements are composed of an internal square patch and an outer closed ring, as depicted in Figure 1b,c, denoted as elements A and B. The considered metaatoms are fabricated on the polyimide substrate with a gold mirror at the bottom. At the presence of the backside metal, the transmittance of this structure will be totally eliminated in the considered terahertz spectrum. To broaden the bandwidth of the metasurface, a relatively large substrate thickness is selected to lower the quality factor of the unit elements\[24\] since the radiation loss is enhanced due to the low permittivity of the substrate for both elements. The periods of such two elements are fixed at 100 µm throughout the design, and the incident wave is propagating along the normal of the surface. Due to the symmetry of the proposed elements, their phase responses are independent to the polarization state.

To better understand the electrical properties of the basic elements and gain more physical insights into the underlying mechanism of the metasurface, numerical simulations are performed based on commercial full-wave electromagnetic software, Computer Simulation Technology (CST) Microwave Studio. The Floquet’s boundaries are used in the simulation to take the mutual coupling of adjacent elements into account. In the realistic scenario, this type of boundary is not very strict since the whole metasurface is composed by elements with various dimensions. However, such local periodicity approach has demonstrated good accuracy for the designed metasurface, which is also widely used in the design of reflectarray antennas in microwave frequencies.\[25\] The dimensions of elements A and B are \(d_1 = d_2 = 5\, \mu m\), \(a_1 = a_2 = 100\, \mu m\), and \(b_1 = b_2 = 5\, \mu m\). The length of the internal patch \(b_1\) is varied from 5 to 20 µm, and \(b_2\) is varied from 12 to 21 µm, to get the desired linear reflection phase responses. In general, it is sufficient to obtain a linear variation of the phase shift in a large range \(>360°\) only by tuning the patch length \(b_1\) of element A (see Figure 1b). However, due to the resolution limit in the lithography system, the patch length \(b_1\) in Figure 1b is chosen to be no less than 5 µm to ensure the accuracy of fabrication, resulting in the reduction of phase coverage. Therefore, as a complement, element B is used to compensate the loss of phase range.

The reflection phases of the elements can be adjusted in a large range at 1 THz by simply varying the dimensions \(b_1\) and \(b_2\), as demonstrated in Figure 2a,b. The shadow region in Figure 2a represents the unavailable phases due to the fabrication limit, which can be made up by element B, as illustrated in the shadow region in Figure 2b. In the meantime, the simulated reflection spectra of both elements are plotted in Figure 3a,b to...
show phase properties of both elements. In the simulation, the dimensions of the internal patch in both elements are chosen as \( b_1 = 8 \text{ µm} \) and \( b_2 = 20 \text{ µm} \). It is obvious that the proposed element configurations have a remarkable feature that the reflection phases change smoothly with the increase of frequency while maintaining a relatively high reflectivity (>0.75) below 2 THz. Unlike the metamaterial absorber which strongly absorbs the incident waves, the proposed elements demonstrate weak absorptions and poor field confinements at the resonant frequencies, giving rises to small reflection dips as desired in the terahertz spectrum. Actually the reflection dips come from the hybridized mode between the antenna and metal ground. The reflection dips in Figure 3a,b stand for the resonant modes in elements A and B, where both the current distributions and electric-field distributions at resonance are simulated, as depicted in Figure 3c. Taking the resonant mode in element A at 1 THz as example (I in Figure 3c), two circulating current loops are observed at the top and bottom of the structure, and electric fields are concentrated at the margin of outer ring, which are responsible for the electric resonance together with the image currents on the metal ground. Similar current distributions are also displayed in II and III in Figure 3c, representing the mode of element A \( (f = 1.735 \text{ THz}) \) and the mode of element B \( (f = 1.91 \text{ THz}) \). Moreover, the phase responses of element A and B are nearly independent at various incident angles (up to 70°) for both polarizations, as shown in Figure 4, indicating that the proposed metasurface will be insensitive to oblique illuminations in the real circumstances.

Then we proceed to design the array pattern of the metasurface once the elements are determined, aiming for significant reduction of reflected and scattering fields under the illumination of plane terahertz waves. In contrast to the sharp radiation pattern of reflectarray antennas with ultrahigh gain, the scattering pattern of the proposed metasurface should be as omnidirectional as possible to redistribute the reflected terahertz energy into the whole backward space and therefore mimic the diffusion effect in nature. The detailed design flow includes two steps. First, we generate a 2D matrix filled with random integers ranging from 0 to 360, representing the phase delay for each element of the metasurface. Therefore, a random phase gradient will be generated along the metasurface due to the presence of phase discontinuities, resulting in various reflection angles on each element according to the general law of reflection. From the relationship between the phase shift and element geometry at the central frequency shown in Figure 2, the corresponding array pattern can be preliminarily obtained as the starting point of optimization in the second

![Figure 3.](image-url)  
(a) The reflection amplitude (blue line) and phase (red line) spectra of element A. (b) The reflection amplitude (blue line) and phase (red line) spectra of element B. (c) The current distributions and corresponding electric distributions at reflection dips I and II in (a) and III in (b).

![Figure 4.](image-url)  
The reflection phase spectra of elements A and B at different incident angles.
To manipulate the scattering pattern of the metasurface and achieve the excellent reflection suppression in a maximum bandwidth, the particle swarm optimization (PSO) method is used for array synthesis based on the far-field pattern prediction method. During the optimization, the scattering pattern of the metasurface can be expressed as the far-field contributions of all metaatoms:

$$E_{\text{total}} = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{m,n}(\theta, \phi) \cdot e^{j\lambda m,n}$$

in which $E_{m,n}$ can be determined from the conducting current, equivalent electric current, and equivalent magnetic current extracted through the full-wave simulations, which stands for the radiation pattern for the element ($m$, $n$) in the metasurface. The optimization aims to reduce the reflection at normal incidence below $-10$ dB (or 0.1) in a large terahertz frequency band.

We use a subgroup made of $4 \times 4$ identical elements as a whole in the optimization process. Such configuration will maximize the geometrical similarity for each element, which complies with the periodic boundary hypothesis in simulation. There are totally $80 \times 80$ elements included in the metasurface. Full-wave simulations are conducted to check performance of the designed metasurface. The reflection coefficient of the metasurface is presented in Figure 5a (red line) when illuminated by plane terahertz waves at normal incidence. At the same time, an unpatterned metallic control plate with the same dimension is also simulated for comparison (black line). From Figure 5a, we observe excellent reflection depressions from 1 to 1.8 THz under the normal illumination, indicating that the proposed metasurface paves a way for developing novel broadband low-reflection metasurface.

The inset of Figure 5a shows the random phase distributions for all elements in the designed metasurface, which are responsible for wave diffusions as expected. The scattering patterns for the control plate and metasurface at normal incidence are also demonstrated in Figure 6 at 1, 1.4, and 1.7 THz for comparisons. We clearly see sharply directive terahertz scattering for the metallic plate due to the constructive interference from the electric currents along the surface. However, at the presence of metasurface, the scattering pattern becomes more diverse, which means that the scattered terahertz energy is redistributed into other directions, and therefore the reflection is greatly reduced.

Due to the nonuniform distributions of phase gradient between neighboring elements, the specular reflections will no longer dominate within the whole scattered waves. However, to avoid significant increase of scattered waves to other directions, the scattering patterns of the proposed metasurface and control plate are presented in Figure 6 for a quantitative comparison. By comparing the second and fourth rows in Figure 6 at three frequencies, there is no significant elevation of side lobes in the $xoy$-plane pattern for both configurations, which is especially important for real applications in the future.

Figure 5. a) The reflection amplitude spectra for the designed metasurface and the control metallic plate. b) The measured reflection amplitude spectra of the fabricated metasurface sample and the control metallic plate.

Figure 6. a–c) The scattering patterns of the metasurface for normal incidence at 1, 1.4, and 1.7 THz, respectively. d–f) The scattering patterns of the metasurface for normal incidence at the $xoy$-plane at 1, 1.4, and 1.7 THz, respectively. g–i) The scattering patterns of the control plate for normal incidence at 1, 1.4, and 1.7 THz, respectively. j–l) The scattering patterns of the control plate for normal incidence on the $xoy$-plane at 1, 1.4, and 1.7 THz, respectively.
3. Experiment and Discussion

To demonstrate the proposed low-reflection properties of terahertz waves experimentally, the metasurface is fabricated using the conventional photolithography techniques. A gold ground layer is first evaporated on the silicon wafer. Then a dielectric layer (polyimide) is coated upon the ground with the thickness of 30 µm. The array of the elements is then patterned on the dielectric layer, resulting in the metasurface sample, as shown in Figure 7. The available area of the sample is 64 mm², and the elements have the same geometries as those in the numerical simulations.

The reflection coefficients of the fabricated sample are measured using the terahertz time-domain spectroscopic system, with the experimental configurations illustrated in Figure 8. To check the angular dependence of the scattering pattern, both the incident and reflected angles can be adjusted independently, by tuning the positions of two off-axis parabolic mirrors on the guided rails. Two photoconductive antennas are used as emitters and detectors of terahertz waves, which are driven by

Figure 7. Part of the fabricated metasurface sample with the fabrication details illustrated in the inset.

Figure 8. Experimental configurations to measure the reflection coefficients of the fabricated sample at the terahertz band.

Figure 9. The scattering amplitude spectra of the fabricated metasurface and control plate at 200, 300, 400, 500, 600, 700, and 800, respectively. The first row stands for the scattering amplitude spectra of the fabricated control plate, and the second to eighth rows represent the scattering amplitude spectra of the fabricated metasurface. a) The incident angle is $\theta = 200$. b) The incident angle is $\theta = 300$. c) The incident angle is $\theta = 400$. 
a laser source. The bandwidth of the radiated pulses is nearly 2 THz, which is broad enough to satisfy the frequency requirement of the designed metasurface. However, for the normal incidence, the rails are removed and both antennas are placed in opposite directions. The Fourier transformations of the time-domain waveforms are used to extract the frequency responses of the sample.

Both the metasurface and control plate are measured in the experiment for comparison. For the normal incidence, the measured reflection amplitude spectra are illustrated in Figure 5b, from which we observe that the metasurface can greatly reduce the reflections, as expected. The experimental data agree very well with the simulation results shown in Figure 5a. At oblique incidence, three incident angles (20°, 30°, and 40°) are considered in experiments, as illustrated in Figure 9. The scattering profiles are plotted to investigate the energy distributions near the specular reflection directions. Broadband reflection suppressions are clearly visualized, which agrees well with the theoretical predictions. At the presence of metasurface, the specular reflection is greatly reduced from 1 to 1.8 THz. It is worth noting that some sharp scattering peaks are observed for both normal and oblique incidences in Figure 9, which originates from the electromagnetic diffusions as we discussed earlier. However, all the peaks are small enough to avoid the significant increase of reflections in those directions. The low-scattering profiles indicate that the current metasurface could be used as an efficient platform to realize stealth applications at terahertz frequencies.

4. Conclusion

In summary, we show the design and fabrication of a terahertz metasurface with ultralow reflections. Numerical simulations confirm that terahertz diffusions can be invoked at the metasurface due to the randomly distributed phase gradient among the metamaterial structures. The broadband and angular independent properties of the metasurface are demonstrated from both simulation and measured results. Such mechanism opens the door to the possibility of creating low-reflection terahertz metasurfaces.

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