High-efficiency Anomalous Reflection Characteristics of an Ultra-thin Gradient Meta-surface Based on SRRs

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Abstract— In this paper, we proposed to redirect the reflected wave to the desired direction based reflective Gradient metasurfaces (GMs). An ultra-thin GM is designed using the square-ring resonators and further demonstrated both numerically and experimentally. The theory and design method of reflective GMs are presented. Both simulated and experimental results demonstrate that a finely designed gradient meta-surface supports high-efficiency anomalous reflections at the designed frequency, which agree quite well with theoretical predictions.

1. INTRODUCTION

Gradient metasurfaces (GMs) have evoked enormous interest recently [1–7]. By delicately design the phase gradient on GMs, the additional parallel wave vector is predefined on the GMs, which can not only redirect the reflection and refraction to the desired directions [3–7], but also convert incident EM waves to surface waves [1, 2]. Hence, GMs can realize anomalous reflection and refraction, negative reflection and refraction, surface wave conversion, and so on. Although intriguing properties of GMs are so attractive, the realization of high efficient GM is not easy. Equal amplitudes and strictly gradient phase changes of scattered waves must be satisfied simultaneously. However, it is comparatively easier to design a reflective GM since equal amplitudes can be realized by a metallic ground plane. In this way, the design of reflective GMs is reduced to the design of phase gradients.

In this letter, we propose to realize high efficient anomalous reflection based on reflective GMs. The theory and design method is presented. Moreover, we designed a sample based on square-ring resonators (SRRs). The GM is composed of an array of 12 SRRs with a phase change step $\pi/6$ per unit cell on the dielectric substrate. Both the simulation and experiment results show that high efficient anomalous reflection can be achieved under normal incidences around the designed frequency, which are good agreement with those predicted by generalized laws of reflection. Our study may pave the way applications such as high directivity antenna, flat focusing etc..

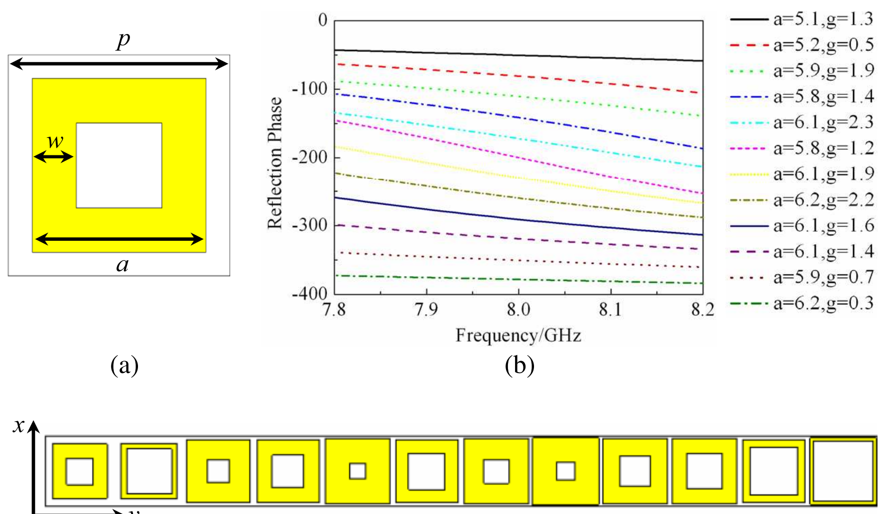
2. THEORY AND DESIGN METHOD

Suppose plane waves are obliquely incident onto a GM with a phase gradient $\xi = d\Phi/dy$ along the interface, and the incidence angle is θ_i. Because of the reflection phase gradient along the metasurface, the parallel wave vector of the reflected beam must be $k_y = \xi + k_0 \sin\theta_i$, where $k_0 = 2\pi/\lambda_0$ (λ_0 is the wavelength in free space). Particularly, the parallel wave vector of the reflected beam is completely equal to the phase gradient ξ under normal incidence, that is $k_y = \xi$. It has been demonstrated by the mode-expansion theory that the normal incident plane waves will be anti-reflected if the condition $\xi < k_0$ is satisfied, and the reflection angle meet generalized laws of reflection, that is $\theta_r = \arcsin(\xi/k_0)$ [4]. This phase gradient at the interface can also be understood as an additional momentum contribution; hence, for the sake of momentum conservation, the reflected wave direction has to change accordingly. It is obvious that the phase gradient ξ is the crucial parameter to determine reflection angle and direction under the normal incidence case.

Since the phase gradient ξ is often discrete in practice, we can using an array of resonant unit cells with constant phase change step but the same periodicity to approximately cover the 2π of phase range along the interface. Therefore, the phase change per each unit cell should be $\Delta\Phi = 2\pi/n$, where n is the number of unit cells in an array. Hence, each n unit cells form a super cell with periodicity $L = np$, where p is the single unit cell periodicity along the phase gradient direction. In this way, we get the phase gradient $\xi \approx \Delta\Phi/p = 2\pi/np = 2\pi/L$. Therefore, once the phase gradient ξ is determined by the super cell periodicity L and the condition $\xi < k_0$ is satisfied, anomalous reflection can be generated and the anomalous reflection angle is also determined. That means we can make the reflected waves to arbitrary direction by varying the periodicity of super cell.

3. SIMULATION RESULTS

As an example, we choose the square-ring resonators (SRRs) as the elementary component for GM, as shown in Figure 1(a). The unit cell consists of a SRR and a metallic sheet separated by a FR4 substrate (with a relative dielectric constant 4.3 and the loss tangent 0.025). We set the thickness of the substrate $h = 1.0\,\text{mm}$. Suppose the GM is illuminated by a transverse-electric (TE) plane wave with y-polarized direction. A magnetic resonance effect can be generated due to the coupling between the SRR and the back metallic sheets, leading to a reflection phase change. By changing the dimension of the SRR, different reflection phases can be yielded. We fix periodicity of the metasurface unit cell $p = 6.53\,\text{mm}$ in the design, but let the length of square ring a and ring width w vary inside a super cell to realize the phase gradient. We choose 12 unit cells to construct a super cell with $(a, w) = (5.1\,\text{mm}, 1.3\,\text{mm})$, $(5.2\,\text{mm}, 0.5\,\text{mm})$, $(5.9\,\text{mm}, 1.9\,\text{mm})$, $(5.8\,\text{mm}, 1.4\,\text{mm})$, $(6.1\,\text{mm}, 2.3\,\text{mm})$, $(5.8\,\text{mm}, 1.2\,\text{mm})$, $(6.1\,\text{mm}, 1.9\,\text{mm})$, $(6.2\,\text{mm}, 2.2\,\text{mm})$, $(6.1\,\text{mm}, 1.6\,\text{mm})$, $(6.1\,\text{mm}, 1.4\,\text{mm})$, $(5.9\,\text{mm}, 0.7\,\text{mm})$, $(6.2\,\text{mm}, 0.3\,\text{mm})$, respectively. Since the 12 unit cells lies one by one with a constant phase change step along y-axis, we only need to consider relative phase change to achieve phase gradient under the same simulation shown in Figure 1(b). In this way, the super cell can discrete the phase gradient with $\Delta\Phi = \pi/6$ at designed frequency 8.0 GHz, as shown in Figures 1(b) and (c). Thus, we get the phase gradient $\xi \approx 0.481k_0 < k_0$.



(c)

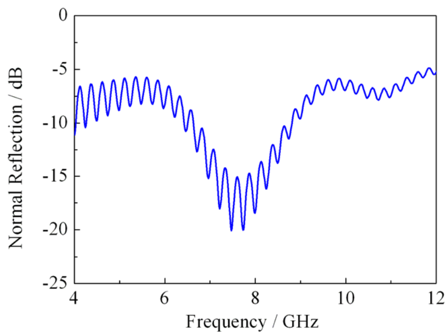
Figure 1: Design of GM composed of SRR super cell: (a) the SRR structure; (b) a reflection phase gradient realized enabled by 12 SRRs; (c) a single super cell composed of twelve SRRs.

In order to verify the design, we simulated a finite-size GM $65\,\text{mm} \times 1560\,\text{mm}$ normally illuminated by a TE plane wave with y-polarization at the middle of metasurface. Figure 2(a) plots the simulated normal reflection versus frequency for the finite-size GM. It is shown that the normal reflection is drastically reduced by 20 dB at the frequency 8.0 GHz.

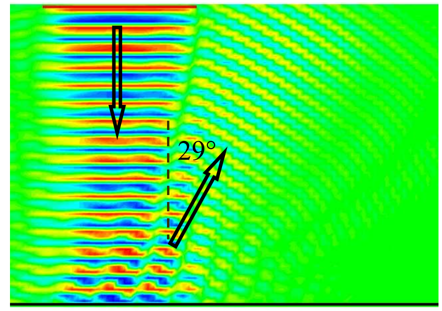
To determine whether the reduced normal reflectivity is resulted from anomalous reflection, the field profiles on y-z plane are monitored. Figures 2(b) and (c) give the snapshots of E_y and H_x on y-z plane, respectively. It can be found that anomalous reflection is generated based on GM and the reflected direction is at the angle 29°, which is in good agreement with the predicted angles calculated by $\arcsin(\xi/k_0) = 29°$. Anomalous reflection characteristics is also can been seen from power flow distributions as shown in Figure 2(d). Since we use 12 SRRs to approximately achieve the phase gradient along the interface in practice, this discreteness implies that there are also regularly reflected waves which follow conventional laws of reflection.

4. EXPERIMENTAL RESULTS

To further verify the design, we fabricated a $390\,\text{mm} \times 390\,\text{mm}$ square GM composed of the super cell and measured its normal reflection spectrum and reflection angle. Figure 3(a) shows the prototype of the fabricated GM sample. Figure 3(b) shows the measured reflection varying with frequency for the GM sample under normal incidence. It shows that the reflection curve shape is in good agreement with the simulated finite-size case. Further more, the reflection angle is also measured



(a)



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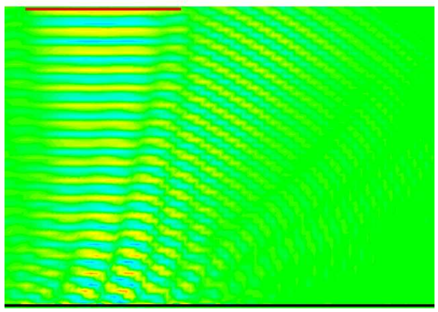

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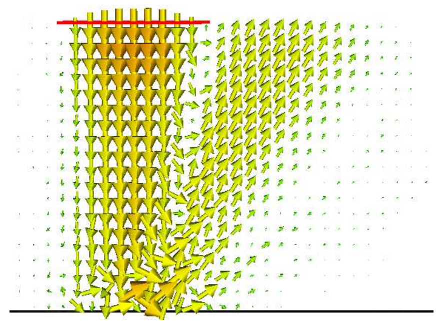
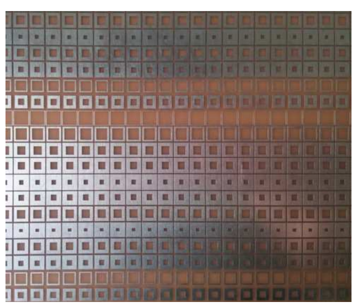
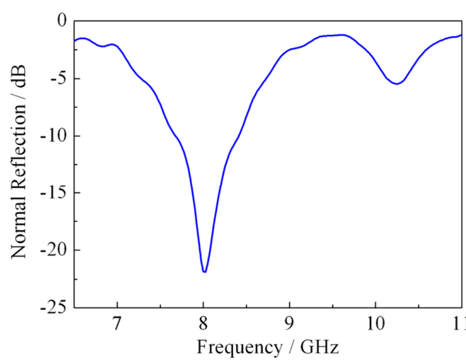


(d)

Figure 2: Simulation results of a finite GM composed of the 12-SRR super cells: (a) normal reflection of the finite GM under normal incidence; (b) E_y, (c) H_x, (d) power flow on y-z plane at 8.0 GHz, respectively.



(a)



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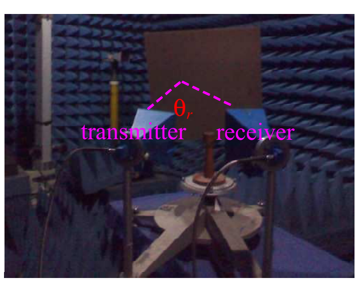

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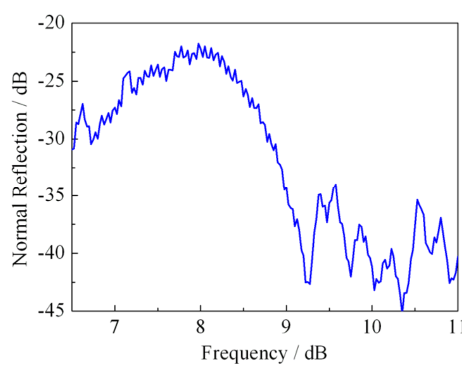

(d)

Figure 3: The fabricated GM sample and measured reflection results: (a) the GM sample (390 mm × 390 mm); (b) measured normal reflection versus frequency under normal incidence; (c) the measuring setup of reflection angle; (d) measured reflection versus frequency under normal incidence at 30° between the two horns.

and the measuring setup is shown in Figure 3(c). We used two horn antenna connected to the same vector network analyzer. Let the left horn fixed as the emitter and illuminate normally on the sample. The right horn can orbit around the sample and acts as the receiver. We found that the reflection reaches the peak around 8.0 GHz when the angle between the two horns is 30 degree, as shown in Figure 3(d). This indicates that the anomalous reflection occurs at 30 degree, in good agreement with simulation and calculation results.

5. CONCLUSION

We demonstrate the anomalous reflection characteristics at microwave frequencies using GMs by simulation and experiment. By adjusting the dimensions of the SRR, it is possible to obtain GMs composed of array of SRR with a constant phase change to approximately cover 2π range. Both the simulation and experiment convincingly demonstrate that the anomalous reflection can achieve high efficiency around the designed frequency. Additionally, the anomalous reflection angle and direction is in excellent agree with those predicted by the generalized laws of reflection. Because of the freedom in manipulation of EM wave reflections, reflective GMs may pave the way towards high directivity antenna, flat focusing, etc..

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