Wideband microwave radar cross section reduction by orientation distributed digital metasurfaces

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***Abstract*—This paper presents a novel design of orientation distributed digital metasurface for suppressing backward radar cross section (RCS) with a broad working bandwidth. A corrugated meander line is proposed as the constitutive unit cell which is capable of creating 1-bit (with two orientations of 0° and 90°), 2-bit (with four orientations of 0°, 45°, 90° and 135°) and multi-bit elements by different orientations with respect to the geometrical center. Each element shows a different reflected phase response to the incident electromagnetic waves, thus metasurface arranged with disordered digital elements will have randomly distributed phase shifts at the interface, leading to a diffusion of backscattering. Thereby, the RCS of the metasurface is substantially suppressed. As verification, full wave simulations have been carried out.**

Keywords—digital metasurface; orientation; RCS reduction

I. INTRODUCTION

Metamaterials made of subwavelength artificial inclusions have attracted much attention due to their striking abilities to create novel electromagnetic (EM) devices such as superlens [1], directive radiator [2] and wave-plate [3], to name only a few. Among these metamaterial-based applications, radar cross section (RCS) reduction aiming to diminish the backscattering of dielectric or metallic targets have gained growing interests, owning to their great potential use in stealth technique. Previous works have proposed several approaches to suppress the RCS, for example, the well-known metamaterial absorber [4], invisibility carpet [5], and chessboard surfaces [6].

Traditional bulk devices for EM wave manipulation often require significant thickness comparable to or even much larger than the working wavelength to achieve necessary accumulation of phase retardations during the wave propagation. However, metasurface, a planar version of metamaterial, circumvents this fundamental limitation of the reliance on propagation length and demonstrates a great advantage of ultrathin flat device profile. By introducing spatially varying elements to create phase-discontinuities on the interface, metasurface has the ability to manipulate the incident EM waves into arbitrary wavefronts. Examples including anomalous refractions [7-10] and reflections [11] have been demonstrated and result in the Generalized Snell's laws [7] or the so-called Huygens' metasurface [9-10]. Different to these ordered spatially varying arrangements, a class of metasurfaces with random distribution of reflected phase responses can distort the wavefront of incidence, resulting in a diffusion of scattering energy [12-16], thus leads to a reduction of backward RCS. Actually, the scattered wave from each element experiences destructive interferences in the far field region. In practice, several elements are independently designed with careful optimization to achieve a large coverage of phase shifts while maintain uniform scattering amplitudes, and then they are randomly combined together in a finite planar slab. In the designs strong resonant modes in the elements have been avoided, and smooth frequency-dependent phase responses can be obtained to enable a wideband behavior.

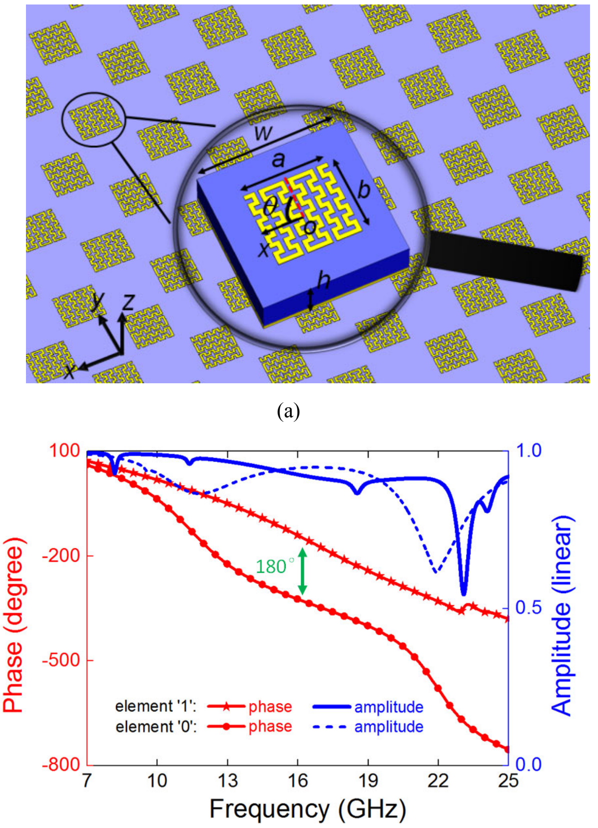
Recently, digital metamaterials have been emerged as new paradigms for controlling over the wave propagation. This type of metamaterials is defined by ''digital metamaterial bits' through certain spatial mixtures of material entities that possess distinct material properties [17], for example, a mixture of Si (material with a positive permittivity) and Ag (material with a negative permittivity at certain frequency band), or through the phase responses of metamaterial particles [16], for example, reflected phase shift of zero or 180 degrees is used to mimic the digital "0" or "1" element, respectively. The concept of digital metamaterial provides a way to create novel devices by applying coding sequences, which is distinguished differently from previous works and may have great potential in EM wave manipulation.

In this paper, we propose an orientation distributed digital metasurface for wideband RCS reduction. Different to previous works [12-15] which experience complex and time-consuming optimizations of geometrical parameters of several constitutive elements, we only use a single structured unit cell to achieve full phase coverage of 2π by rotating its orientation. We further propose the digital metasurface by discretizing the orientation as the metasurface bit (eg. in the case of 1-bit, zero orientation is defined as the digital element "0" while $\pi/2$ as the element "1"). Based on such definition, by applying randomly distributed elements in a finite sheet, digital metasurface for backward RCS reduction has been obtained. In addition, the digital concept have also been extended to 2-bit (incorporates four digital elements) and 3-bit (incorporates eight digital elements) cases, where full wave simulations have verified that the proposed orientation distributed digital metasurfaces are capable of suppressing the backward RCS in a broad bandwidth.

II. DESIGN PROCEDURE AND SIMULATION

The designed unit cell is illustrated in Fig. 1(a), a corrugated meander line pattern is etched on a substrate backed by a metallic ground. The substrate has a thickness of h = 2 mm with a relative permittivity of 4.3 with a loss tangent of 0.025. Due to the structured metallic pattern, the element shows a bi-anisotropic property, leading to different phase responses of reflection as the polarization of the incident wave varies.

We start the digital metasurface design with case of 1-bit. The realization of digital metasurface requires distinct phase responses to feature the constructive element. In the binary case, two discrete elements are required. Here, we define the digital element '0' by an orientation of zero and digital element '1' by an orientation of $\pi / 2$, as shown in Fig. 2, the angle θ is defined as the orientation with respect to the x direction. By optimizing the geometric parameters, the phase retardation between two digital elements can be tuned to be π with amplitudes nearly to unity in a broad bandwidth. Fig. 1(a) shows the performance of reflection of the digital elements under the illumination of x-polarized EM wave. For a y-polarized wave, a flip of these performances will be achieve between the element '0' and '1', due to the rotation symmetry. We will show the details in the presentation.



(a)

(b)

Fig. 1. (a) Local view of the proposed metasurface with a 1-bit randomly distributed elements, the enlarged part shows details of the unit cell with parameters of, in millimeter, a = 4.6, b = 4.25, w = 8, h = 2. The width of cut wires is 0.3 mm. (b) The frequency-dependent phase shift and amplitude of the digital metasurface elements with the incident wave polarizes along x direction.

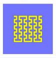
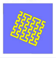
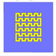
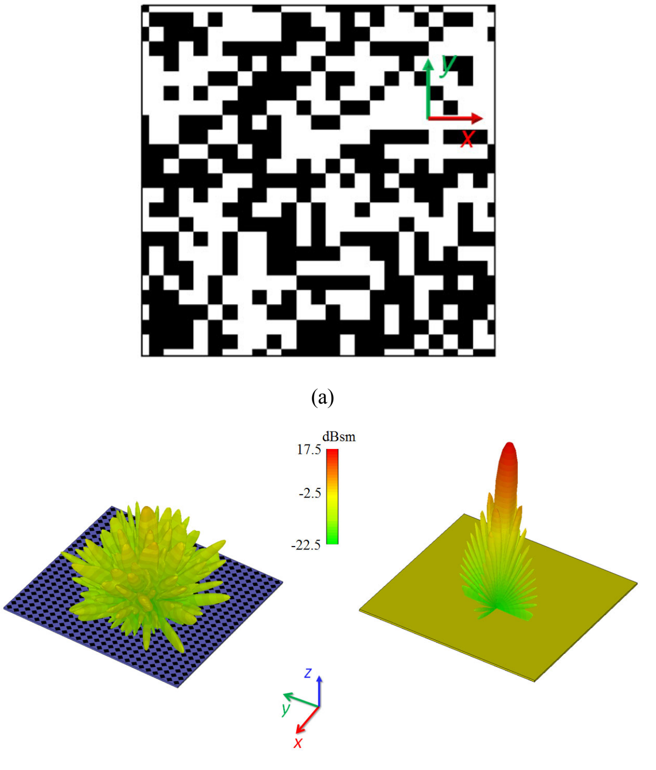
θ & Shape Bit	0° 	22.5° 	45° 	67.5° 	90° 	112.5° 	135° 	157.5° 
1-bit	**0**				**1**			
2-bit	**00**		**01**		**10**		**11**	
3-bit	**000**	**001**	**010**	**011**	**100**	**101**	**110**	**111**

Fig. 2. Definitions of digital elements at the case of 1-bit, 2-bit and 3-bit.

To obtain a random distribution digital metasurface for RCS reduction, a slab of $200\,mm\times200\,mm$ with randomly distributed elements has been investigated by full wave simulation. The random distribution shown in Fig. 3(a), where black blocks represent the element '0' and the white ones represent element '1'. The simulated backward far field radiation pattern (3D) at 16 GHz is shown in Fig. 3(b), as depicted, the energy randomly spread over numerous directions. Such diffusion of scattering energy enables the metasurface to achieve substantially lower RCS compared to that of bare metallic plate with same dimensions which is also shown in Fig. 3(b).

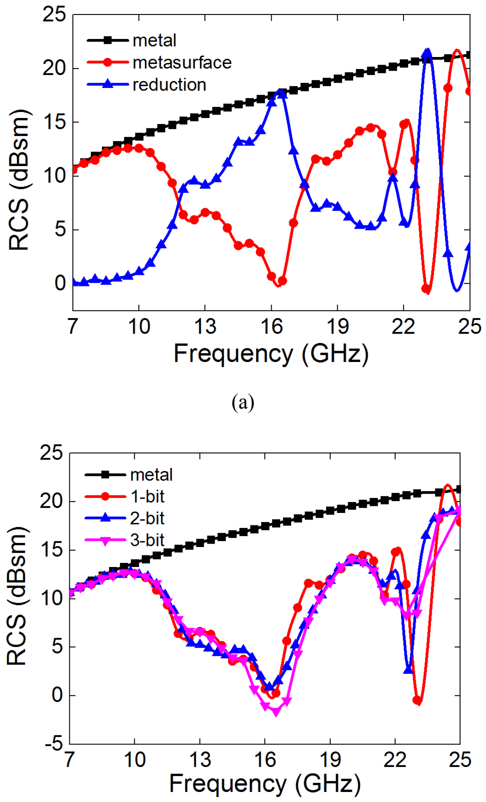


(a)

(b)

Fig. 3. (a) The random distribution of 1-bit digital elements in a 2D plane (625 elements). Black blocks represent digital element '0' while the white ones represent '1'. (b) Far field radiation pattern at 16 GHz of the proposed metasurface (left) and bare metallic plate (right) under the illumination of x-polarized linear EM wave, respectively.

Fig. 4(a) gives the comparison of boresight RCS (z direction) versus frequency, which verifies a RCS reduction of nearly 10 dB from the metasurface in a broad bandwidth. In addition, metasurfaces consist of 2-bit and 3-bit (definitions of the digital elements are shown in Fig. 2) with random distribution of digital elements have been simulated as well, which also show broadband RCS reduction, as shown in Fig. 4(b). We will show the experimental results in the presentation.



(a)

(b)

Fig. 4. (a) Boresight RCS versus frequency of the metasurface and the metallic plate, along with the reduction property. (b) Boresight RCS versus frequency of the metallic plate and the metasurfaces with 1-bit, 2-bit and 3-bit random distributed elements.

III. CONCLUSION

In summary, an optimized corrugated meander line unit cell has been proposed and discretized into 1-bit, 2-bit and 3-bit digital elements by applying distinct orientations. By randomly arranging the elements in a 2D plane, we have obtained orientation distributed digital metasurface working for wideband RCS reduction. The proposed metasurface may have potential applications in stealth technique in the future. The designed principle can also potentially extend to other microwave frequency bands or even scaled at much higher frequency such as terahertz and optics.

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