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Design of 1-Bit Coding Engineered Reflectors for EM-Wave Shaping and RCS Modifications

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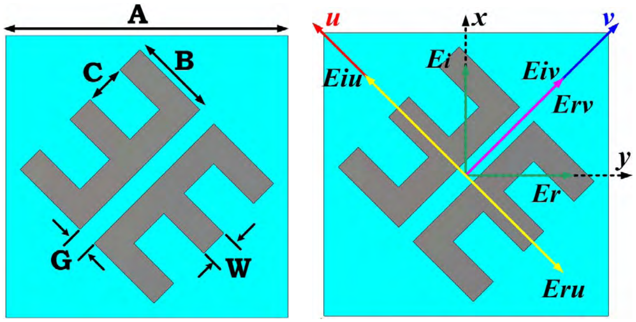
ABSTRACT In this paper, the engineered reflectors are designed and characterized for cross polarization rotation, RCS modification, and EM-wave shaping at W-band. The multiple plasmon resonances, cross-polarization rotation, reflection phase cancellation, and coding sequence principles are combined together to design the presented reflectors. First, an anisotropic unit cell consisting of a two E-shaped metallic resonators on the top side of a PEC-backed dielectric substrate is precisely designed and optimized. The unit cell operates in a linear cross-polarization scheme from about 86 GHz to 94 GHz and has multiple plasmon resonances at 86.5 GHz, 89.2 GHz, 92.2 GHz, and 93.2 GHz with 100% cross-polarization conversion efficiency at these frequencies. Then this unit cell and its mirrored unit cell are used to compose a number of 1-bit coding reflective engineered reflectors to generate the “1” and “0” elements of the coding sequence required for EM-wave shaping. Four engineered reflectors of various coding sequences are designed to shape the backscattered energy to achieve one lobe, two lobes, three lobes, and four lobes. Furthermore, the low-scattering diffuse reflection pattern is also achieved under both normal and oblique incidence by using a random distribution (random coding sequence) of the unit cells across the engineered reflector aperture. Both 3D full wave simulations and measurement results verify the capability of the presented surfaces in shaping the backscattered EM-wave.

INDEX TERMS EM-wave, millimeter waves, metasurface, diffuse reflection, reflective surface, scattering.

I. INTRODUCTION

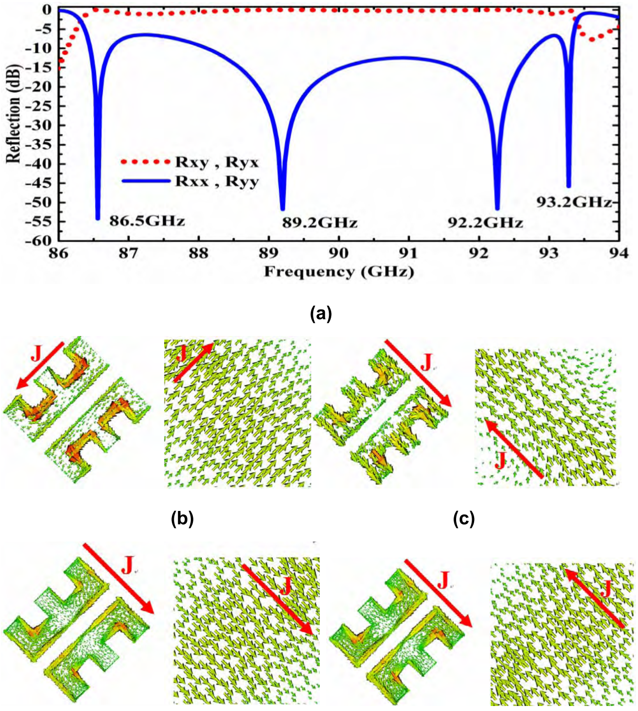
Engineered surfaces (reflectors) or man-made artificially reflectors usually comprise periodic or non-periodic dielectric/metallic unit cells that enable the manipulation/shaping of transmitted or reflected electromagnetic (EM) wave [1]–[5]. Recently, engineered reflectors have drawn much attention due to many fascinating properties in manipulating (shaping) of EM-waves, for instance, invisibility cloaking [6], focusing lens [7], polarization conversion [8], radar cross section (RCS) modification [9], reduction [10]–[15], and enhancement [16], [17]. The concept of 1-bit and 2-bit coding engineered reflectors (metasurface) was originally proposed at microwave frequency band in [18]. In 1-bit coding engineered reflector, binary states “1” and “0” of the1-bit coding sequence is implement by using two unit cells with reflection phases 0° and 180°. In other words, the reflection phase difference between the two unit cells should be kept as 180°±37° and their absolute reflection phases are unimportant [18], [19]. A 1-bit metasurface for RCS reduction around 10GHz was proposed in [18] based on square patches metallic inclusions. In [20] RCS reduction at THz frequencies was achieved using 2-bit coding metasurface and the digital states of the coding sequence are realized using four metallic double cross line structure. In [21] a 3-bit coding metasurface is designed for RCS reduction using a unit cells operates in a linear cross-polarization conversion scheme around 12GHz was reported using unit cell composed of a symmetric split ring and a cut wire and 3-bit metasurface was designed based on this unit cell for frequencies from 6 GHz to 20 GHz.

In this article, engineered reflectors are designed and characterized for cross polarization rotation, RCS modification, and EM-wave shaping at millimeter wave. Multiple plasmon resonances, cross-polarization rotation, reflection phase



(a) (b)

FIGURE 1. Schema of the proposed unit cell in (a): A=2mm, G=0.1mm, B=0.4 mm, W=0.2mm, and C=0.2mm. (b) Incident and reflected field components. Please note the gray color is copper part.



(a)

(b) (c)

(d) (e)

FIGURE 2. (a) The co- and cross-polarization reflections. (b), (c), (d) and (e) are the current distribution on the metallic parts at: 86.5GHz, 89.2GHz, 92.2GHz, and 93.2GHz, respectively.

cancellation, and 1-bit coding sequence principles are combined together to design the presented reflectors. The simulation and measured results are presented.

II. UNIT CELL DESIGN

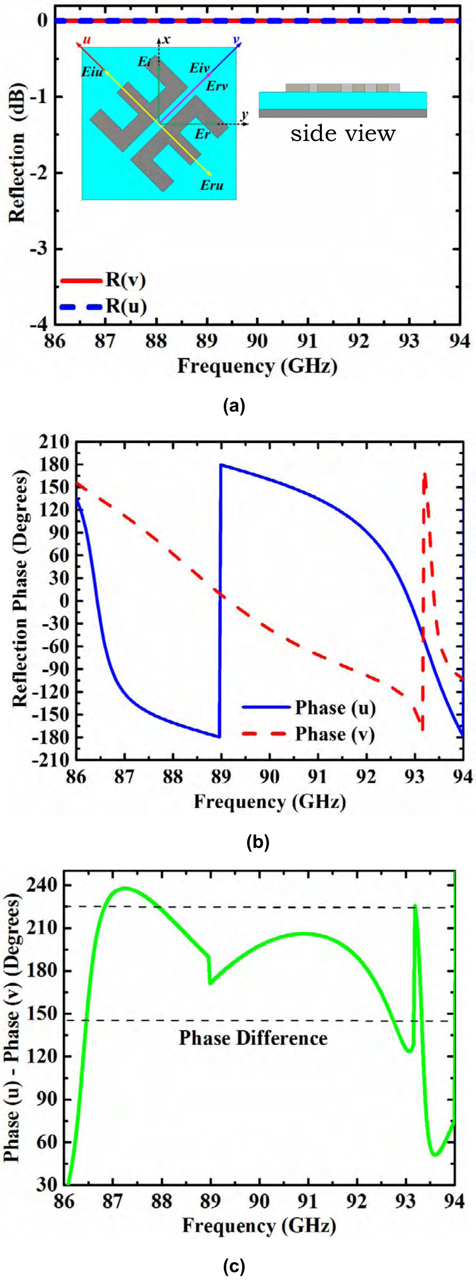
The front face of the proposed unit cell is depicted in Fig. 1 and has a sandwich-like structure, i.e., metal-dielectric-metal. The upper metallic layer consist of two E-shape like metallic resonators etched on the upper side of a PEC backed dielectric substrate with a thickness of 1.27 mm and a dielectric constant of 10.2. Other geometrical dimensions of the unit cell are listed in the caption of Fig.1. To obtain both the magnitude and phase of the reflection coefficients, the unit cell is simulated using F-solver of CST microwave studio, with periodic boundary conditions in ±x and ±y directions and floquet ports in z-direction. Figure 2 (a) shows the simulated co-polarization (R_{xx}, R_{yy}) and cross-polarization (R_{xy}, R_{yx}) reflection coefficients of the unit cell under normal incidence of x- and y-polarized EM-waves and as can be seen that R_{xy}, R_{yx} (cross-pol) reflection is strong over frequencies from 86.2GHz to 93.4GHz and the unit cell has a multiple plasmon resonances at 86.5GHz, 89.2GHz, 92.2GHz, and 93.2GHz with 100% cross-polarization conversion efficiency at these frequencies. In order to judge whether those four resonances are electric or magnetic resonances, the induced current distribution on the metallic parts of the unit cell is investigated and presented in Fig.2 (b) 86.5GHz, (c) 89.2GHz, (d) 92.2GHz and (e) 93.2GHz. At plasmon resonance 86.5GHz, 89.2GHz, and 93.2GHz, the surface currents on the E-shape resonators and the metallic ground plane have opposite direction when compared to each other and forming a magnetic dipole. On the other hand for the plasmon resonance 92.2GHz the currents on both the E-shape resonators and the ground plane are in the same direction and forming electric dipole.

The magnitude and phase of the reflected components (E_{rv} and E_{ru}) along u- and v-axis are computed as shown in Fig.3. As can be seen in Fig.3 (a), both components have almost unity reflection, however, there is a clear reflection difference between their reflection phases as shown in Fig.3 (b) and this phase difference is mainly because of the anisotropy of the unit cell geometry. The phase difference (Phase(u)-Phase(v)) is about $180^{o}\pm37°$ over frequencies from 86.2GHz to 93.4GHz as shown in Fig.3 (c). These results show that the incident EM-wave will be rotated to its orthogonal component and reflected back.

III. ENGINEERED REFLECTORS DESIGN

To realize the required phase difference for efficient manipulation of EM-waves across the 1-bit engineered reflectors, the unit cell which has 180°±35° reflection phase difference between its E_{rv} and E_{ru} reflection components is used to realize the digital states of the 1-bit coding sequence as "0" element while its mirrored unit cell is used as "1" element. Based on the unit cell – mirrored unit cell arrangement four 1-bit engineered reflectors of various "1" and "0" distributions are designed as shown in Fig.4 and their ability in manipulate the EM-wave is investigated. The three-dimensional RCS patterns of the four 1-bit surfaces under normal incidence are computed using T-solver of the EM simulation software CST Microwave Studio and presented in Fig.4. All 1-bit engineered reflectors consist of 8×8 unit cells and the overall dimensions are 16mm×16mm.

The four 1-bit surfaces are designed in such a way to achieve one, two, three, and four reflected lobes in the half space in front of the 1-bit engineered reflectors based on their unit cell distribution. Its important to mention that other

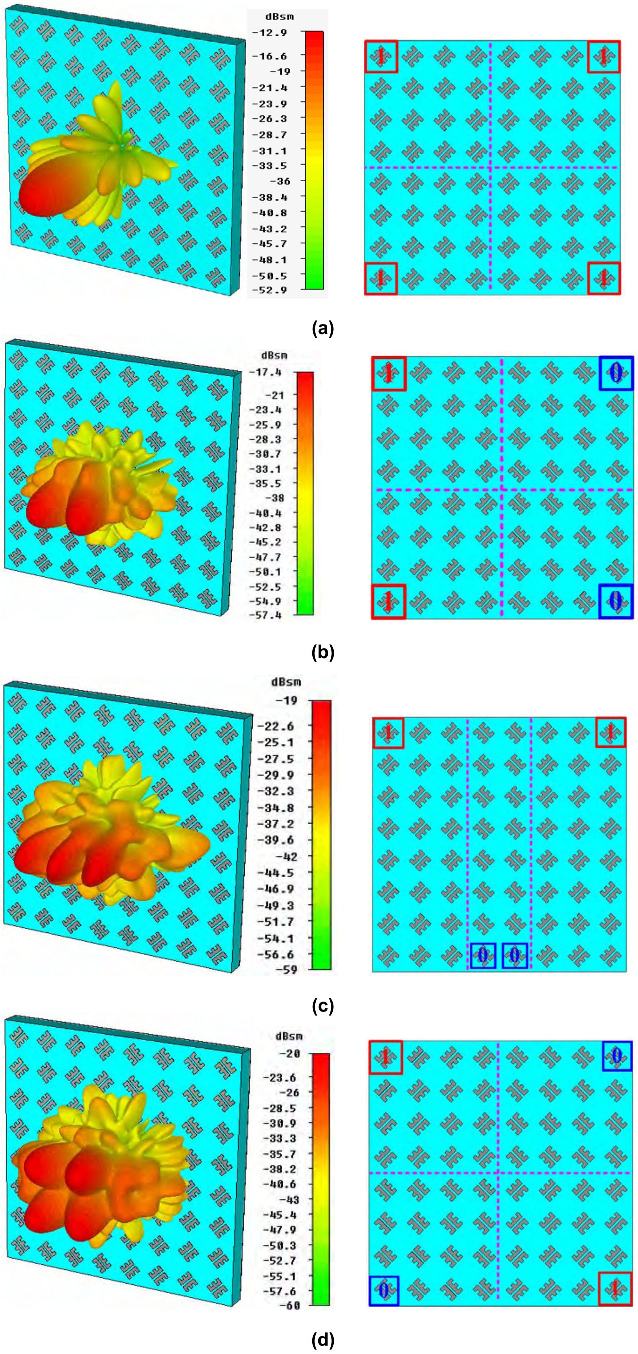


(a)

(b)

(c)

FIGURE 3. Reflection characteristics of E_{rv} and E_{ru} : (a) Magnitude and (b) Phase. (c) Reflection phase difference (Phase (u) − Phase (v)).



(a)

(b)

(c)

(d)

FIGURE 4. Layout of 1-bit engineered reflectors and their unit cell distribution maps for (a) single lobe, (b) two lobes, (c) three lobes, and (d) four lobes.

kinds of backscattered patterns are also possible to achieve if other unit cells distribution maps are used. The backscattered characteristics of those four surfaces are more investigated by carefully looking at the E-field distribution of the single lobe and four lobes 1-bit engineered reflectors (as example) and bare PEC plate of same size as shown in Fig.5 where the single and four lobes are very clear from the distribution of the E-field in front of the surfaces.

Another 1-bit engineered reflector based on the random distribution of "1" and "0" unit cells are designed to achieve low-level diffusion far-field scattering, i.e., RCS reduction. The designed reflector and its unit cells distribution map are presented in Fig.6 (a) and (b). The unit cells distribution map is achieved using a special MATLAB code. The operating mechanism of this 1-bit random phase distribution engineered reflector is to diffuse the backscattered energy into many directions, and as a result, the RCS would dramatically reduced compared to that of a bare PEC plate. To validate this, far-field scattering 3D patterns at 86.2 GHz, 87 GHz and 91.2GHz are computed using T-solver of CST Microwave

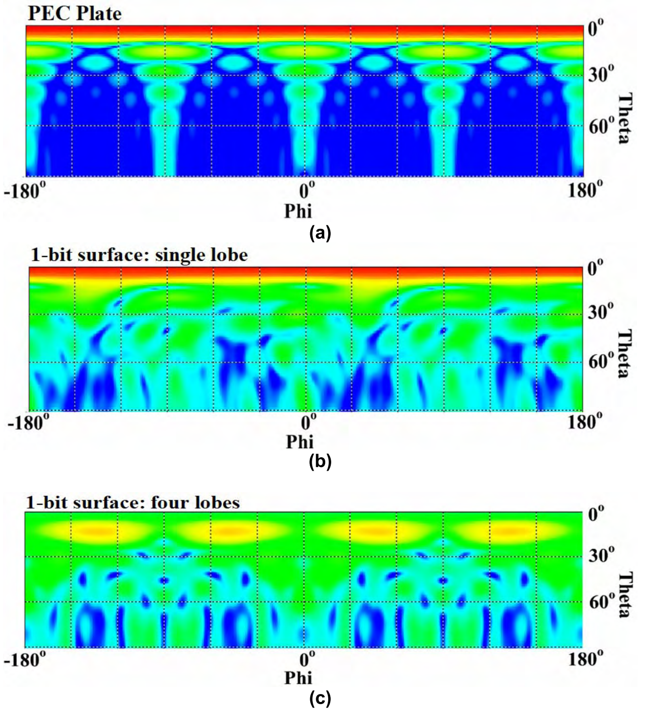
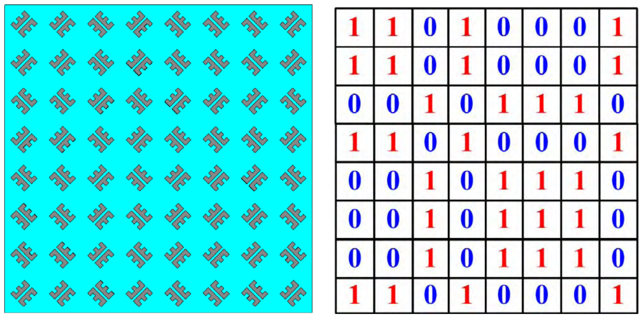


FIGURE 5. Backscattered E-field distribution in front of (a) bare PEC plate, (b) Single-lobe 1-bit surface, and (c) Four-lobes 1-bit surface. Here Phi and theta are corresponding to the azimuthal and polar angles of spherical coordinates.



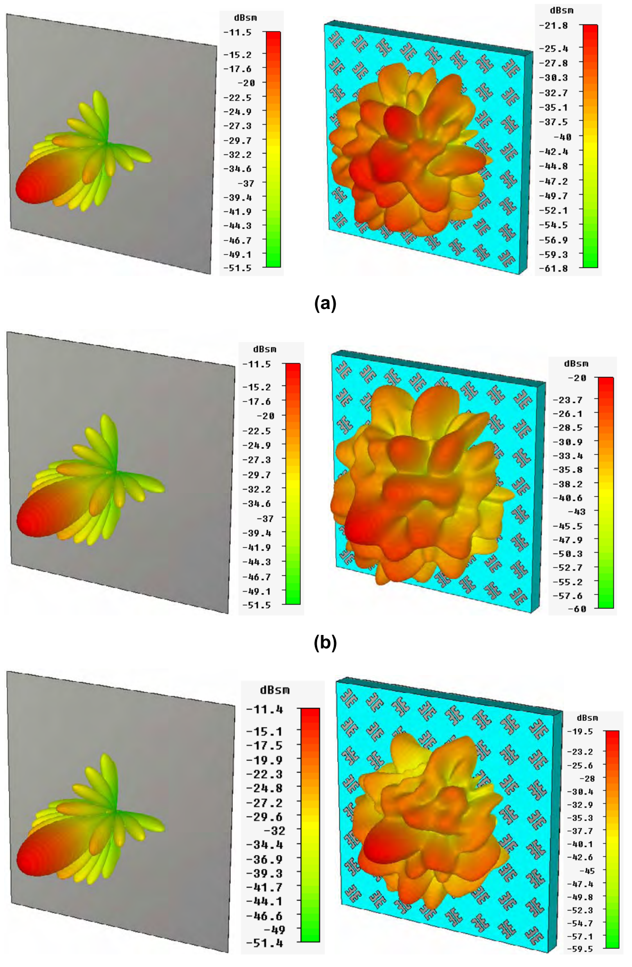
1	1	0	1	0	0	0	1
1	1	0	1	0	0	0	1
0	0	1	0	1	1	1	0
1	1	0	1	0	0	0	1
0	0	1	0	1	1	1	0
0	0	1	0	1	1	1	0
0	0	1	0	1	1	1	0
1	1	0	1	0	0	0	1

(a) (b)

FIGURE 6. (a) Layout of the 1-bit random engineered reflector. (b) Unit cells distribution map.

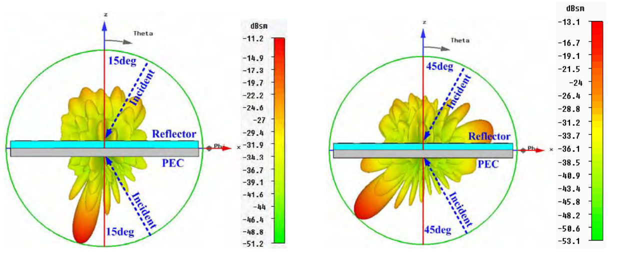
Studio under normal incidence and the results are shown in Fig.7. For comparison purposes, scattering 3D patterns of a metallic plate are also presented. The backscattered energy is re-distributed in the space angular domain, forming the diffuse reflection pattern with large number of low level lobes in many directions with low backscattered level from about 86.4GHz to 93.2GHz. On the other hand, for the bare PEC plate the backscattered energy has only single lobe according to Snell's law of reflection [22].

The backscattered levels in Fig.7 show that the level is much lower for the 1-bit engineered reflector compared to a PEC plate and this RCS level reduction is mainly resulted from the random distribution of phases which leads to diffusion scattering and redirecting the backscattered energy in many directions. Furthermore, the three-dimensional scattering patterns under oblique incidence is computed as well and presented in Fig.8. Here two cases are considered when $\theta_{\text{inc}}=15^\circ$ and 45° and in both cases the backscattered energy is low compared to that of a bare PEC plate. The E-field distribution of this 1-bit random surface under oblique



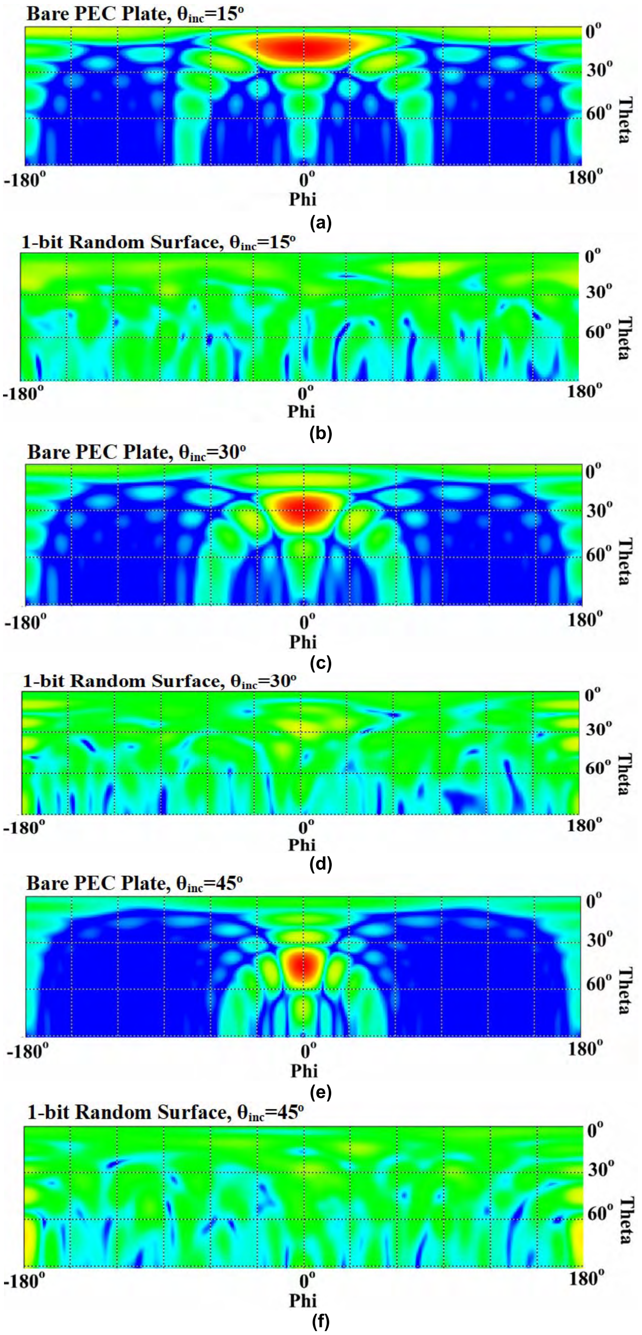
(b)

FIGURE 7. Far-field 3D scattering patterns of the 1-bit random engineered reflector and a bare PEC plate of same dimensions at: (a) 86.2 GHz, (b) 87 GHz, and (c) 91.2 GHz.



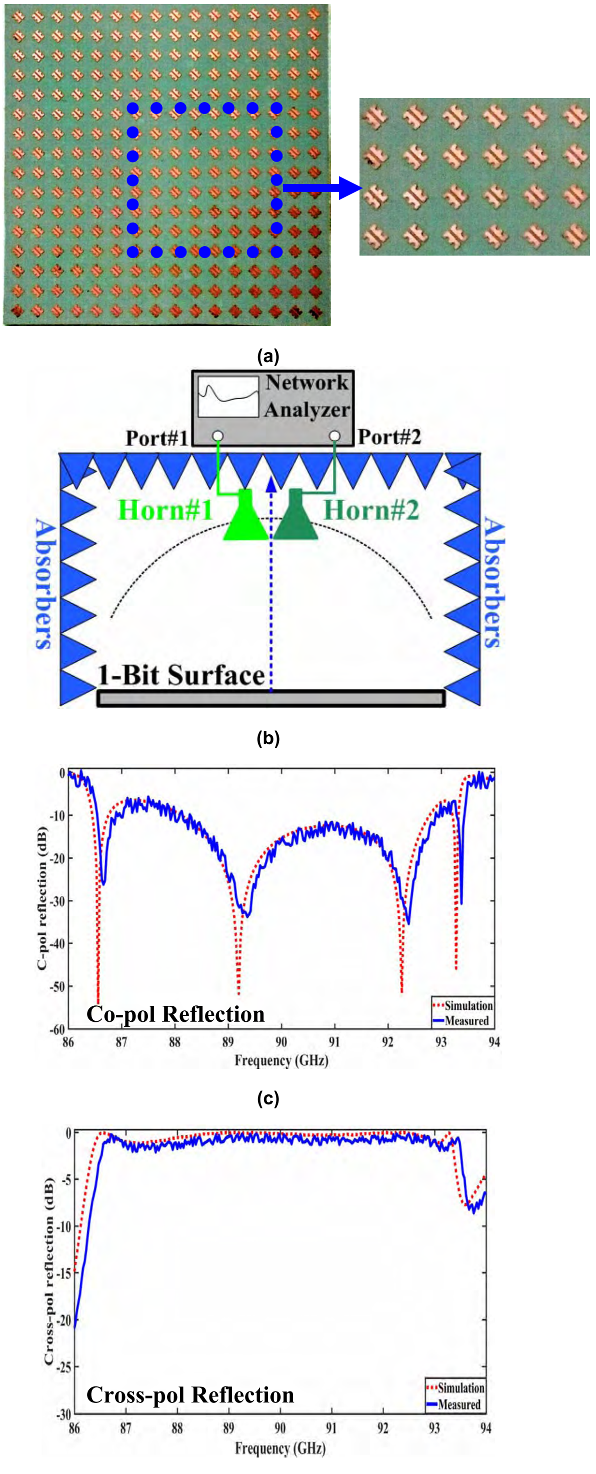
(a) (b)

FIGURE 8. Far-field 3D scattering patterns of the 1-bit random engineered reflector and bare PEC plate of same dimensions under oblique incidence: (a) 15° and (b) 45°.



(a)
(b)
(c)
(d)
(e)
(f)

FIGURE 9. Backscattered E-field distribution under oblique incidence.



(a)
(b)
(c)
(d)

FIGURE 10. (a) Photograph of the fabricated sample. (b) Measurement setup. (c) Measured (c) co-pol and (d) cross-pol reflection coefficients.

incidence is also computed and presented in Fig.9 when θ_{inc}=15°, 30° and 45°. In all cases the 1-bit random surface still have a low-level diffused backscattered radiation.

IV. FABRICATION AND MEASUREMENT

To validate the reflection characteristics of the engineered reflectors, a cross polarization converter surface (33mm × 33mm) with unit cell distribution similar to that in Fig.4 (a) is manufactured using printed circuit board technology as shown in Fig.8 (a). The experimental measurement of reflection coefficients is performed inside an anechoic chamber based on free space method as shown in Fig.8 (b). The experimental measurement setup is consisting of a network analyzer and two millimeter wave standard-gain horn antennas.

In measurements one horn antenna is used to illuminate the sample under test while the other horn antenna is used as a receiver to collect the backscattered energy and both antennas are connected to the ports of a calibrated network analyzer. The distance between the antennas and the sample under test is chosen according to the far-field formula in [23]. To avoid coupling between the horn antennas, small pieces of absorbing material is added between them. The measured co-pol and cross-pol reflection coefficients are presented in Fig.10 (c) and (d) both measured and simulated results are in good agreement and the discrepancy between the two results can be attributed to fabrication error of the surface, misalignments between the horn antennas and the surface under test, the difference between the real and assumed dielectric constant of the dielectric substrate.

V. CONCLUSION

In conclusion, 1-bit engineered reflectors for cross polarization rotation, EM-wave manipulation, and RCS modifications are proposed in this article and investigated both numerically and experimentally at mmWave. The proposed engineered reflectors consist of anisotropic unit cell which has four plasmon resonant frequencies at 86.5 GHz, 89.2 GHz, 92.2 GHz, and 93.2 GHz. Based on the unit cells distribution, efficient manipulation of the scattered energy is achieved and various kinds of scattering 3D patterns from one lobe to four lobes are obtained. Furthermore, RCS modification and reduction and diffuse reflection patterns are achieved using optimized 1-bit coding sequence based on the unit cell – mirrored unit cell arrangement. Both simulated and measured results are presented for verification.

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