Coding Engineered Reflector for Wide-Band RCS Reduction Under Wide Angle of Incidence

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Abstract—This article presents the design of 1-bit coding engineered reflector for wideband monostatic/bistatic radar cross section (RCS) reduction under wide-angle of incidence by redirecting the backscattered electromagnetic (EM) energies into wide and countless angles. The proposed surface can achieve an excellent monostatic/bistatic RCS reduction performance of more than 10 dB over a wide frequency range from 60 – 120 GHz under wide-angles of incidence up to 75°. This is achieved by designing a wide-band anisotropic polarization rotator unit cell with a relative polarization conversion bandwidth of 66.7% and polarization conversion efficiency of more than 99%. The unit cell and its mirrored version are used to represent the “0” and “1” coding states of an optimized 1-bit coding sequence. The distribution of the “0” and “1” coding states and the dimensions of the anisotropic unit cell are optimized carefully such that the unit cell will have 180±30° reflection phase difference between their absolute reflection phases [17]. The simplest method of designing 1-bit coding metasurfaces for RCS reduction is to generate a phase distribution matrix with “0” and “1” elements randomly distributed across the metasurface aperture [18]-[22]. Several designs have been proposed in the literature to realize broadband RCS reduction using the polarization conversion principle [23]-[25]. It has been noticed that most of the polarization conversion based metasurfaces in the literature were proposed at microwave frequencies and very few or rare works have been reported operating at millimeter wave bands such as V, E, or W-bands. In addition, some designs such as phase gradient metasurfaces redirect the backscattered energies into off-normal directions and cannot reduce the bi-static RCS [26], [27]. Some other designs such as checkerboard and chessboard are not beneficial to bi-static RCS reduction as it can significantly reduce only the mono-static RCS but the backscattered patterns have a strong reflections toward the diagonal angles [28]-[29]. In addition, the scattering performances are degraded severely under oblique incidence of incoming EM-waves, and RCS reduction cannot be achieved under wide-angle incidence. Therefore, realizing a wideband and wide-angle with nearly uniform backscattering under wide angle incidence (>60°) is still very challenging and such designs are still of great needs.

In this article, a 1-bit coding random phase distribution millimeter wave engineered reflector for monostatic/bistatic RCS reduction at 60–120 GHz is designed based on wideband polarization rotation using anisotropic unit cells. The 1-bit coding states are obtained by rotating the resonator (unit cell) according to Pancharatnam-Berry (PB) phase theory [30], and the proposed engineered reflector therefore consists of unit cells with “0” and “1” digital states owing to their 0° and 180° reflection phase responses. The proposed 1-bit random coding engineered reflector reduces the RCS by greater than 10 dB over a wideband frequency range from 60–120 GHz under normal incidence. More importantly, the proposed engineered reflector maintains low amplitude backscattering energy and more than 10 dB of RCS reduction for off-normal wide-angle incidences up to 75°. Simulation and measurements have proved its feasibility and have shown good agreement.

II. UNIT CELL DESIGN

The key step to realize the proposed 1-bit coding millimeter wave engineered reflector is the design of the wideband high-efficiency cross-polarization rotator anisotropic unit cell (coding element) operating at 60 – 120 GHz, and then using it to construct the engineered reflector. The physical dimensions (\(P, W, L, \) and \(R\)) of the unit cell shown in Fig. 1(a) were optimized proposed in [16] for RCS reduction and can easily be designed using only two unit cells “0” and “1” with 180°±30° phase difference between their absolute reflection phases [17]. The simplest method of designing 1-bit coding metasurfaces for RCS reduction is to generate a phase distribution matrix with “0” and “1” elements randomly distributed across the metasurface aperture [18]-[22]. Several designs have been proposed in the literature to realize broadband RCS reduction using the polarization conversion principle [23]-[25]. It has been noticed that most of the polarization conversion based metasurfaces in the literature were proposed at microwave frequencies and very few or rare works have been reported operating at millimeter wave bands such as V, E, or W-bands. In addition, some designs such as phase gradient metasurfaces redirect the backscattered energies into off-normal directions and cannot reduce the bi-static RCS [26], [27]. Some other designs such as checkerboard and chessboard are not beneficial to bi-static RCS reduction as it can significantly reduce only the mono-static RCS but the backscattered patterns have a strong reflections toward the diagonal angles [28]-[29]. In addition, the scattering performances are degraded severely under oblique incidence of incoming EM-waves, and RCS reduction cannot be achieved under wide-angle incidence. Therefore, realizing a wideband and wide-angle with nearly uniform backscattering under wide angle incidence (>60°) is still very challenging and such designs are still of great needs.

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and cross-pol reflection coefficients versus frequency of the unit cell
the frequency range of 60–120 GHz. The magnitudes of co-pol
and the unit-cell was surrounded by unit-cell boundary
of the commercial software CST Microwave Studio (CSTMS). During the simulation
series of full-wave simulations via the frequency-domain solver
anisotropy of the unit cell geometry, it can convert the incident linearly polarized wave to its orthogonal one, for instance,
rotating x- or y-polarized incident waves into cross-pol waves in the frequency range of 60–120 GHz. The magnitudes of co-pol
and cross-pol reflection coefficients versus frequency of the unit
cell are shown in Fig. 1(b). The co-pol reflection magnitude is
significantly reduced to less than –20 dB and a strong cross-pol reflection reaches 0 dB, which indicates that a cross polarization conversion has been realized successfully under incident of linearly polarized wave. Polarization conversion ratio (PCR) of the unit cell was calculated as shown in Fig. 1(c). The PCR is
higher than 99% which indicates that a 66.7% cross-pol conversion bandwidth is obtained. Owing to the anisotropic characteristics of the unit cell, a phase difference $\Delta \phi = \text{Phase (u)} - \text{Phase (v)}$ is valid between the reflection components of the unit cell ($\beta = -45^\circ$) and its mirrored version ($\beta = +45^\circ$) and will be used as the “0” and “1” coding states of the 1-bit coding sequence. According to PB phase theory [30], the unit cell can be considered as a PB unit cell for which the reflection phase of the unit cell would be a function to $\beta$ under illumination of a CP plane wave. This is very important property to cancel-out the polarization sensitivity of the proposed engineered reflector to the polarization of the incident plane wave. For the rest of the article, the scattering characteristics of the engineered reflector will be investigated under CP plane-wave illumination. As can be seen in Fig. 1 (b), the unit cell has three plasmon resonances, the surface current distributions are monitored at those three frequencies as shown in Fig. 2. According to Faraday’s law, magnetic and electric resonances are generated by anti-symmetric (anti-parallel) and symmetric (parallel) couplings of the surface currents on the cut wire resonator on top and ground plate. Thus, the 66.2 GHz and 89.5 GHz plasmon resonances both frequencies are magnetic resonances. At 113.5 GHz, the currents flow in the same direction (symmetric coupling) which means that it is an electric resonance.

### III. 1-BIT ENGINEERED REFLECTOR DESIGN

The 1-bit coding engineered reflector presented in this article is composed by the unit cell and its rotated version to represent the binary digital “0” and “1” elements with $180^\circ\pm30^\circ$ phase difference to realize the required phase-cancellation across the surface aperture, and thus RCS reduction. The proposed 1-bit coding engineered reflector can diffuse the incident EM waves through a random distribution of the “0” and “1” elements across the engineered reflector aperture. It is important here to point out...
that the unit cell polarization conversion characteristics and the random distribution sequence of “0” and “1” elements across the engineered reflector aperture both control the RCS reduction characteristics of the proposed engineered reflector. The coding sequence of a conventional polarization converter engineered reflector (S#1) in which all unit cells have the same reflection phase and orientation is shown in Fig. 3(a). The optimized diffusive 1-bit phase distribution of the “0” and “1” elements across the engineered reflector (S#2) apertures was achieved based on antenna array theory [33]. The proposed S#2 surface was considered as a square antenna array which contains $M \times N$ unit cells of equal periodicity, and each unit cell represent the coding state “0” or “1” which are randomly distributed across the S#2 aperture. Then an in-house MATLAB code based on the random function and the formulas in [17] was used to generate a random 1-bit coding sequence for $M \times N$ unit cells. MATLAB was used to automatically construct the proposed surfaces in CSTMS according to the 1-bit phase distribution map. Then the simulation results are automatically exported back to MATLAB for processing and checking the RCS reduction level. This routine was repeated several times until the optimal results in terms of scattering pattern shape and RCS reduction under oblique incidence was achieved. After few attempts, the optimized 1-bit phase sequence for wideband and wide-angle EM wave diffusion and RCS reduction was obtained and shown in Fig. 3(b) which can efficiently reduce the RCS by redirecting the backscattered EM energies into multiple directions under both normal and oblique incidence of CP plane wave. The unit cell and its mirrored version were distributed according to the coding sequences in Figs. 3(a) and (b), and two engineered reflectors were designed (named S#1 and S#2) as shown in Figs. 3 (c) and (d). The proposed 1-bit S#2 surface contains 20 × 20 anisotropic unit cells and has an overall size of 34 × 34 × 0.508 mm$^3$. The RCS reduction characteristics of S#2 were computed using the time-domain solver of the CSTMS. The far-field incident plane wave option in CSTMS was used to emulate the incoming CP plane wave. Far field monitors were applied for extracting the scattered RCS patterns. For comparison purposes, the 3D scattering patterns of a metal (PEC) surface at 90 GHz of equivalent dimensions to that of S#1 and S#2 were simulated as well. As can be seen in Fig. 4, instead of the strong scattering levels of the PEC plate and S#1 which both reflect the incident energy along the boresight direction according to Snell’s law of reflection [28], the scattered energy of the S#2 engineered reflector is highly diffused and redirected into numerous directions in the half-space in front of S#2, which means the RCS is significantly reduced. The 2D Cartesian scattering patterns of S#2 presented in Fig. 5 under normal incidence of CP plane-wave shows that the engineered reflector S#2 destroyed the strong specular reflection of a PEC plate, and the backscattered energy has low magnitude and is distributed over a wide range of angles in the area in front of S#2 without strong reflection lobes. Additionally, the results in Fig. 5 indicate that the RCS reduction bandwidth is consistent with the PCR band.
and the reflection phase difference of the anisotropic unit cell as shown in Fig. 1 (a) and (c). The RCS reduction performance of S#2 has been further investigated via studying the backscattered energy distribution in front of S#2 under CP plane-wave illumination. The bare PEC plate and S#1 both have single strong reflection spots in the boresight direction, see Fig. 6. However, the backscattered energy is significantly diffused in the case of S#2, and the RCS is reduced accordingly. The diffusion scattering sensitivity of the proposed 1-bit S#2 under different oblique incidences of CP plane wave has been investigated thoroughly and the results are presented in Fig. 7 along with the scattering behavior of a metal plate for comparison purposes. The angle of incidence ($\theta_{\text{inc}}$) was increased gradually from 0° to 75° in steps of 15° as shown in Fig. 7(a). $\theta_{\text{inc}}$ is the angle between z-axis and the main-axis of the incident beam with S#2 is placed on the xy-plane. Theta ($\theta$) and Phi ($\phi$) are the elevation and azimuth angles, respectively. In the case of PEC plate, the incident energy will be totally reflected according to Snell’s law and specular reflection is dominated with angle of incidence equal to the angle of reflection which can be seen as strong reflection spots. When the same EM waves impinged on the proposed S#2 engineered reflector, the specular reflection is not dominant anymore while the low-level diffuse scattering dominates. It is important to mention that the diffusive scattering behavior of S#2 can be preserved up to 75° off-normal incidence and the RCS reduction of S#2 is still larger than 10 dB over the whole frequency band. The RCS reduction of S#2 was further investigated from 60 – 120 GHz under oblique incidence of CP plane wave in various planes, see Fig. 8. As can be seen in Fig. 8(a)-(c), when $\theta_{\text{inc}}$ varied from 15° to 75° the RCS reduction magnitude is still more than 10 dB in phi=0°, phi=45° and phi=90° planes. It also verified that the proposed 1-bit S#2 surface exhibits broadband and broad-angle monostatic/bistatic RCS reduction. Simulated RCS versus frequency curves of S#2 and the PEC plate are presented in Fig. 8 (d), from which it can be observed that the backward scattering of the proposed 1-bit engineered reflector S#2 has been significantly reduced by more than 10 dB over the entire frequency band from 60 – 120 GHz, yielding RCS reduction fractional bandwidth (FBW) of 66.7%.
Fig. 9. (a) Photograph of the fabricated S#2 engineered reflector sample. (b) Back side of S#2. (c) Schematic view of the RCS experimental setup inside an anechoic chamber. (d) Measured RCS and RCS reduction of S#2.

IV. FABRICATION AND EXPERIMENTAL RESULTS

For experimental verification, the proposed 1-bit coding S#2 has been fabricated and a photo of the fabricated prototype is presented in Fig. 9(a) with a bare PEC plate in Fig. 9(b). A schematic view of the RCS experimental setup inside an anechoic chamber is shown in Fig. 9(c). In the experiments, the 1-bit S#2 sample was placed at the same height as the transmitting and receiving horn antennas and in the far-field (R > 2D/λ, where D is the physical aperture dimensions of S#2) [33]. In the measurements, R was chosen as 0.48 m and the gap between the horn antennas was optimized to 9 mm during the measurement to reduce the mutual coupling effects. To further reduce the coupling between the horn antennas, a tiny piece of EM wave absorbing material was installed between the horn antennas. In addition, a bare copper plate of equivalent dimensions was measured as a reference. The reflection coefficients of the copper plate and of the 1-bit S#2 surface were measured and are shown in Fig. 9(d). It is important to mention here that because of the wideband characteristics of the proposed 1-bit engineered reflector and lack of measurement facilities that cover the whole frequency range from 60 – 120 GHz, it was only possible to perform the measurements from 75 to 110 GHz. As can be seen in Fig. 9(d), the RCS is clearly reduced by more than 10 dB from 75 – 110 GHz, and the maximum RCS reduction is 17.6 dB. Both simulated and measured results demonstrate that the proposed 1-bit coding engineered reflector (S#2) can effectively diffuse the backscattered energies and reduce the RCS over a wideband range of frequencies under normal-incidence and wide-range of incident angles up to 75°. The slight discrepancy between the simulated and measured results are caused by the fabrication error, horn antennas misalignments inside the chamber, and the uncertainty of the dielectric constant of the dielectric material over the frequency range. For the sake of benchmarking, the RCS reduction characteristics of S#2 have been compared with other previously published works from the literature. The comparison results are listed in Table I. The comparison indicates that S#2 can maintain more than 10 dB RCS reduction under oblique incidence of EM waves up to 75° over wide bandwidth which is wider than the maximum angles and FBW reported in the literature using various design techniques. It is important to mention here that the proposed design is scaleable and can be designed at any frequency band. In other words, the 1-bit phase distribution map in Fig. 3(b) can be regenerated at any desired frequency. For instance, the proposed engineered reflector can be redesigned for SHF band (3-30 GHz) by changing the unit cell dimensions and periodicity to make the unit cell have similar reflection characteristics as that in Fig. 1.

V. CONCLUSION

In this article, a 1-bit coding engineered reflector which exhibits wideband and wide-angle monostatic/bistatic RCS reduction is presented. Both simulation and measurement results show that the backward scattering and monostatic/bistatic RCS of the proposed 1-bit engineered reflector has been significantly reduced by more than 10 dB over the entire frequency band from 60 – 120 GHz, yielding a fractional bandwidth 66.7% and also under a wide-range of incident angles up to 75°. RCS reduction under such wide-angle of incidence has not been achieved by phase gradient metasurface or chessboard metasurface in the literature. This makes it promising for EM-wave stealth applications at millimeter wave frequencies.

| Ref. | Surface Type | h (m) | 10-dB RCS BW (GHz) | FBW | Max. Inc. Angle |
|------|-------------|------|---------------------|-----|-----------------|
| [1]  | Random      | 0.33 | 10-16 (1-bit)       | 46% | 60°             |
| [3]  | Random      | 0.055| 5.5-7.37            | 67% | 45°             |
| [8]  | Aperiodic   | 0.1  | 9.5-15.5            | 50% | 30°             |
| [13] | Chessboard  | 0.063| 14.8 - 22.7         | 42% | N/A             |
| [28] | Chessboard  | 0.08 | 4.2-7.8             | 60% | N/A             |
| [34] | AMC         | 0.09 | 5.9-12.7            | 73% | N/A             |
| [12] | Aperiodic   | 0.1  | 16 – 23.8           | 39.2%| 60°             |
| [36] | Staggered   | 0.06 | 9-16                | 56% | N/A             |
| [37] | Coding array| 0.026| 3.9 - 4.05          | 3.8% | N/A             |
| [38] | Random      | 0.046| 6.94-9.23           | 28.3%| 40°             |
| [39] | Random      | 0.07 | 9-10.8              | 18.2%| N/A             |
| [40] | Spiral coding | 0.081| 12.2-23.4          | 62.9%| 60°             |
| [41] | Chessboard  | 0.22 | 10.5-18             | 52% | 45°             |
| [42] | Zero gradient | 0.1  | 9.9-19.8            | 66.6%| 60°             |
| [43] | Chessboard  | 0.14 | 7-13                | 60% | 30°             |
| [44] | phase gradient | 0.12 | 11.95 - 18.3       | 42.3%| N/A             |
| [45] | FSS         | 0.03 | 6.25 - 12           | 63% | N/A             |
| This Work | 1-bit Random | 0.1 | 60 - 120 | 66.7% | 75° |
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