Design of QR-Coded Metasurfaces for RCS Reduction at mmWave

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ABSTRACT This article presents the design of 1-bit metasurfaces for radar cross section (RCS) reduction over wide frequency band from 60 GHz to 120 GHz. The proposed 1-bit metasurfaces can be designed without the need for any complicated optimization algorithms such as genetic algorithms (GA) or particle swarm algorithms (PSO), or time-consuming simulations to achieve the optimized phase distribution map. The phase distribution maps required for more than 10-dB RCS reduction of the proposed metasurfaces were generated using two-dimensional (2D) quick response (QR) 1-bit generator in MATLAB which are fast and efficient. After we carefully studied several metasurfaces with various 2D QR codes, it was found that the QR coded metasurfaces are very powerful in achieving more than 10-dB RCS reduction with low-level diffusive scattering patterns. Two metasurfaces with their unit cells phase distributions being exactly the same as the QR codes of the words “IEEE” and “Metasurface” were designed and their RCS reduction characteristics were investigated. For off-normal or oblique incidence, more than 10-dB RCS reduction is preserved up to incident angles of 60° over the entire frequency band. The simulation and measured results show the proposed QR coded metasurfaces reduce the backscattered energies and RCS by more than 10-dB for different polarizations over the frequency range from 60 GHz to 120 GHz yielding a fractional bandwidth of 66.7%. The proposed approach is powerful and fast and makes the realization of coding metasurface much easier.

INDEX TERMS Metasurface, radar cross section, reflection, reflectarray, diffuse reflection, scattering.

I. INTRODUCTION Diffusion of backscattered electromagnetic (EM) waves and radar cross section (RCS) reduction of objects using metasurface have received a lot of attention among researchers in recent years [1]–[8]. Metasurfaces are the 2D version or counterparts of the 3D metamaterials which are usually composed of an array of sub-wavelength dimensions metallic or dielectric resonators [13]–[14]. Checkerboard and chessboard metasurfaces were proposed as RCS reducer surfaces and excellent RCS reduction bandwidth was achieved [15]–[17]. However, those surfaces suffer from degraded diffusion performances under oblique incidence of incoming plane waves with strong scattering in certain angles. To overcome these issues and achieve a diffuse scattering, 1-bit and 2-bit coding metasurfaces were proposed [18], [19]. However, coding metasurfaces requires that unit cells must be arranged according to an optimized coding phase distribution to achieve the 10-dB RCS reduction which is not an easy task [20]–[23]. Coding metasurfaces uses time-consuming optimization algorithms such as particle swarm algorithms (PSO) [24], neural networks [25], or genetic algorithms (GA) [4] to reach the optimized phase distribution that ensures 10-dB RCS reduction. Finding the optimum coding phase distribution costs lots of time and computing resources and can be difficult to reproduce by different students and researchers. Recently, few attempts have been proposed to avoid the using of complex optimization algorithms to design coding metasurfaces [20]–[22].

Two-dimensional Quick Response (QR) codes, invented in 1994 by one of the Toyota group companies named Denso Wave [26], is 2D array of 1-bit symbols that was initially proposed for production of automotive control uses, and nowadays has become very popular in many other fields and can be seen and used in our daily life.

In this article, QR coded 1-bit metasurfaces for RCS reduction for 60 GHz to 120 GHz band are proposed. The proposed 1-bit metasurfaces can be designed without
according to Pancharatnam–Berry (PB) phase theory [27] such that the unit cell reflection phase is function of the cut-wire resonator rotation angle (β). The optimized geometrical parameters of the PB unit cell are (all in mm): \( P = 1.7 \), \( L = 1.2 \), and \( W = 0.2 \). The reflection characteristics of the PB unit cell in Fig. 1 were studied via conducting a series of EM numerical simulations using frequency solver of CST Microwave Studio [28]. First the cross-polarized (cross-pol) and co-polarized (co-pol) reflection components of the PB unit cell when illuminated by a CP plane wave were computed using CST Microwave Studio and presented in Fig. 1(b). As can be seen when illuminated by a CP plane wave, a strong co-pol reflection is dominant over the whole frequency band from 60 GHz to 120 GHz with low cross-pol reflection. The PB unit cell has three resonance frequencies at 66.2 GHz, 89.5 GHz, and 113.5 GHz as shown in Fig. 1. According to Faraday’s law [4], the three resonance frequencies are generated as result of the surface currents flowing on the metallic resonators on located on the upper surface of the dielectric substrate and the solid ground plane on the bottom side. Based on the current flow direction on both metallic structures, magnetic and electric resonances will be generated [4]. It was also noticed that the simulated cross-pol reflection magnitude at these three resonance frequencies were below \(-65\) dB. The reflection phase profile of the reflected co-pol component was computed using CST microwave studio and shown in Fig. 1(c). As can be seen, the reflection phase (\( \varphi_R \)) is a function of the rotation angle (\( \beta \)) of the cut-wire resonator. The reflection phase is related to angle \( \beta \) as \( \varphi_R = \pm 2\beta \), where the polarization sign “−” and “+” corresponds to LHCP and RHCP incident waves. To achieve the 1-bit coding bits with 180° phase difference between their reflection phases, the metallic resonator is rotated by \( \beta = 45^\circ \) and \( \beta = -45^\circ \) to achieve the “0” and “1” bits of the QR coding sequence, see Figs. 2(c) and (d).

### III. QR CODED METASURFACES DESIGN

An important design step of coding metasurface is the optimization of the coding sequence (phase distribution across the metasurface aperture) to ensure more than 10-dB RCS reduction is a time-consuming process, requires extensive computing resources and is difficult to reproduce by different students and researchers. The proposed 1-bit QR coded metasurfaces in this work can be designed to achieve more than 10-dB reduction of RCS without the need to use any time-consuming optimization algorithms such as PSO or GA. In this work, QR algorithms were implemented in MATLAB based on the formulas of binary QR code generation to generate a QR code of any word (or sentence). In the MATLAB code, the metasurface was assumed to be composed of \( M \times N \) unit cells along \( x \)- and \( y \)-axes, respectively. Each unit cell of the metasurface is represented by one pixel of the two-dimensional QR code. The QR codes generated by the MATLAB script consists of 21 × 21 two colored pixels and each color (pixel) can be replaced by a one coding state of the 1-bit coding sequence, i.e., either “0” bit or “1” bit. Then the binary phase
distribution maps (QR coding sequence) required for more than 10-dB RCS reduction of the proposed metasurfaces were produced by the MATLAB code. After carefully studying several metasurfaces with various QR codes using different words (the results are not presented for brevity), it was found that the proposed method is very powerful and fast in achieving the coding sequences required for more than 10-dB RCS reduction. As a proof of concept, two metasurfaces with their unit cells phase distributions that are exactly the same as QR codes of the words “IEEE” and “Metasurface” were designed and named as QR1 and QR2, respectively.

The MATLAB generated QR codes of the words “IEEE” and “Metasurface” are displayed in Fig. 2(a) and (b). Using a mobile phone, it is easy to scan the two QR codes, the information inside the codes which are “IEEE” and “Metasurface” can be easily retrieved. The two colors of the QR codes are replaced by the 1-bit coding elements with $\beta = 45^\circ$ and $\beta = -45^\circ$ to represent the “0” and “1” bits, respectively. Two information carrying metasurfaces QR1 and QR2 are designed as shown in Fig. 2(c) and (d) and the PB unit cells were distributed according to the QR codes. Each metasurface consisted of $21 \times 21$ PB unit cells and occupied an area of $35.7 \times 35.7$ mm$^2$. One of the issues related to QR coded metasurfaces design is that they consist of only $21 \times 21$ PB unit cells and the challenge is whether it is possible extend this approach to design larger coding metasurfaces.
FIGURE 6. Simulated 2D bistatic scattering diagrams in front of all three metasurfaces under CP plane wave illumination. All Metasurfaces were placed in the xy-plane.

using QR codes. The proposed solution to quickly design larger QR coded metasurfaces is to arrange both QR1 and QR2 metasurfaces in a chessboard-like configuration as shown in Fig. 3(a). For such QR coded chessboard-like configuration, the “0” and “1” bits distribution map was achieved using a MATLAB script and is shown in Fig. 3(b). The scattering characteristics of the QR1, QR2, and chessboard metasurfaces were computed and investigated using the time-domain solver of CST Microwave Studio [28]. The simulated RCS reduction characteristics of the three metasurfaces are shown in Fig. 4. The RCS reduction can be calculated (or measured) by comparing the RCS of the metasurface under test to the RCS of metal plate of same dimensions. The RCS reduction can also be defined as the reduction (in dB) using the metasurface compared to that of a bare PEC plate [20]–[23]. As can be seen in Fig. 4, QR1 and QR2 metasurfaces can efficiently reduce the RCS by more than 10-dB from 60 GHz to 120 GHz. When the QR1 and QR2 metasurfaces are arranged in a chessboard-like configuration the RCS reduction improved as shown in Fig. 4 and the maximum RCS reduction was 22 dB. The computed 3D scattering patterns of all three metasurfaces are presented in Figs. 5(a), (b), and (c) with scattering patterns of a bare copper plate at 90 GHz for comparison. As can be seen in Fig. 5, the backscattered patterns of a bare copper plate are a directive pencil beam with specular reflection dominates according to Snell’s law of reflection [2]. However, for the QR coded QR1, QR2, and chessboard metasurfaces the diffuse scattering dominates and all three metasurfaces can strongly diffuse the backscattered fields across all directions and reduces the RCS by more than 10-dB. To further investigate the scattering performances of the proposed three surfaces, the backscattered energy distribution in the area in front of the metasurfaces is presented in Fig. 6. As can be seen, for a bare PEC plate strong specular reflection dominates and can be seen as a high intensity red spot at the boresight direction. On the other hand, QR1, QR2, and chessboard metasurfaces strongly diffuse the backscattered energy into countless angles with more than 10-dB RCS reduction. Furthermore, to investigate the RCS reduction sensitivity to incident angle, the QR coded chessboard metasurface has been simulated under CP wave excitation with different oblique incidences. Four cases were considered here when the incidence angle ($\theta_{inc}$) was increased to 15°, 30°, 45°, and 60° and the RCS patterns are shown in Fig. 7. As can be seen, the diffuse scattering pattern still dominates with low magnitude levels of the backscattered energies even when the incident angle increases to 60°. The RCS reduction versus frequency curves of the chessboard metasurface were computed and displayed in Fig. 7. It can be seen that for the whole frequency band from 60 GHz to 120 GHz, the magnitude of the RCS reduction was more than 10-dB under CP plane wave excitation. These results shows that the proposed QR coded metasurface can
FIGURE 8. Photographs of the fabricated (35.7 × 35.7 mm²) QR coded metasurfaces (a) QR1 and (b) QR2. (c) Measurement setup inside anechoic chamber. (d) Measured RCS of QR1, QR2, and copper plate.

significantly reduce the RCS with good angular stability. The proposed QR coded metasurfaces can diffusively scatter the incident CP waves to nearly all angles, not just suppressing the specular scatterings.

IV. FABRICATION AND MEASUREMENTS

To further verify the RCS reduction performance of the proposed QR coded metasurfaces, samples of the QR1 and QR2 metasurfaces were fabricated using the standard printed circuit board (PCB) technology as shown in Fig. 8(a) and (b). The dimensions of the fabricated samples were identical with those used in the simulations in Section III. In addition, a bare metal sheet of the equivalent dimensions was measured as a reference. The measurement setup is shown in Fig. 8(c) in which two horn antennas (connected to ports of a network analyzer) were employed one as transmitter (to generate the incident waves) and the other one as receiver to collect the backscattered energies. During the measurements, the fabricated QR metasurfaces were placed at the same height as the two horn antennas. The distance between QR metasurface and horn antennas was chosen carefully according to the far-field formula [29] to avoid near field effects. It is important here to point out that the available measurement facilities only cover the frequency range from 75 GHz to 110 GHz and RCS outside this frequency band could not be measured. The measured RCS of the QR1 and QR2 metasurfaces along with that of a metal plate are shown in Fig. 8(d). A clear RCS reduction can be seen for QR1 and QR2 metasurfaces from 75 GHz to 110 GHz. The measured RCS reduction is more than 10-dB over the whole frequency band. Both simulated and measured results show how effective the proposed technique in designing coding metasurface for RCS reduction without the need to any complicated optimization algorithms.

An important advantage of the proposed design is that it is scaled to be designed and operate at any frequency band. In other words, those QR codes can be generated at any frequency band in addition to mmWave. For instance, the QR coded metasurfaces can be redesigned for X-band, Ka-band, K-band... etc by changing the unit cell dimensions and periodicity to make the unit cell have similar reflection characteristics as those in Figure 1 but at other frequency bands. It is important here to mention that the generated 1-bit QR codes and the “1” and “0” bits distribution across the metasurface is not frequency dependent and such QR codes can work at any frequency band.

V. CONCLUSION

In summary, it is shown that metasurfaces can be realized without the need for any optimization algorithms such as GA or PSO, or time-consuming simulations to achieve the optimized phase distribution map required for diffuse scattering and 10-dB RCS reduction. The proposed QR coded metasurfaces with their unit cells phase distribution being exactly the same as the QR codes of the words “IEEE” and “Metasurface” were designed, and their RCS reduction characteristics were deeply investigated. It is shown that QR metasurfaces reduces the RCS by more than 10-dB over a frequency range from 60 GHz to 120 GHz under arbitrary polarization incidences which yielded a fractional bandwidth of 66.7%. For off-normal or oblique incidence, more than 10-dB RCS reduction is preserved up to incident angles of 60° over the entire frequency band. In addition, a metasurface that contains both QR1 and QR2 as building blocks and distributed in a chessboard like fashion can extend the possibility of designing QR coded metasurfaces with any physical dimensions. Its also found that the chessboard metasurface composed of QR metasurfaces of different coding words can efficiently reduce the RCS under both normal and oblique incidence of CP plane wave up to incidence angle up to 60°. Both QR1 and QR2 can be distributed in chessboard or random distributions to achieve better RCS reduction characteristics compared to using QR1 or QR2 alone.

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