A Novel Electromagnetic Surface for Super-wideband RCS Reduction

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***Abstract*—In this research, a checkerboard metasurface based on a novel physical mechanism, optimized multielement phase cancellation (OMEPC), is proposed for super-wideband radar cross-section (RCS) reduction. Multiple local waves produced by the basic meta-particles at multiple frequencies sampled in a super-wide frequency band are manipulated and optimized simultaneously to achieve super-wideband phase cancellation. The proposed metasurface can achieve 10 dB RCS reduction in a super-wide frequency band from 5.08 to 27.74 GHz with a ratio bandwidth (f_H/f_L) of 5.5:1.**

Keywords—metasurface; super-wideband RCS reduction; optimized multielement phase cancellation

I. INTRODUCTION

Metamaterial and metasurfaces are artificial structures designed for controlling electromagnetic and acoustic waves or fields. They exhibit exceptional, unexpected physical properties from their chemical constituents [1]. One of the potential applications of metasurfaces is to reduce the scattering field of a metal object.

The basic idea is to exploit the cancellation effects arising from the well-known 180° phase difference between the corresponding reflection coefficients. In 2007, based on a combination of artificial magnetic conductors (AMC) and perfect electric conductors (PEC) in a chessboard like configuration, Paquay et al proposed a planar structure for RCS reduction [2]. In [3], a planar monolayer chessboard structure is presented for broadband RCS reduction using AMC technology. Fractional bandwidth (FBW) of more than 40% is obtained with a monostatic RCS reduction larger than 10 dB. In 2015, Balanis et al proposed a hexagonal checkerboard surface of periodic phase arrangement [4], with a 10 dB monostatic RCS reduction bandwidth of about 61%. A chessboard AMC surface composed of saltire arrow and four-E-shaped unit cells has a bandwidth of 85% for 10 dB RCS reduction [5]. Then, the dual wideband checkerboard surfaces are presented in [6]; and the bandwidths of 10 dB RCS reduction in the frequency bands of 3.94–7.40 GHz and 8.41–10.72 GHz is about 61% and 24% by utilizing two dual-band electromagnetic bandgap (EBG) structures. In 2017, Haji-Ahmadi et al proposed a pixelated checkerboard metasurface for ultra-wideband RCS reduction [7].

Previous research focused mainly on the design of unit cells with a fixed phase difference of approximately 180° for opposite phase cancellation or coding metamaterials. However, bandwidth expansion for RCS reduction is extremely difficult. Our research is focused primarily on the development of novel phase cancellation methods. A metasurface based on the new physical mechanism of optimized multielement phase cancellation (OMEPC) is proposed for super-wideband RCS reduction.

II. MULTIELEMENT PHASE CANCELLATION

For a multi-element checkerboard surface with $P\ (= M \cdot N)$ tiles, the RCS reduction can be derived based on Eq. (5) in [4], which can be approximated by

$$\sigma_R = 10\log\left|\frac{\mathrm{AF}(0,\varphi)}{P}\right|^2 = 10\log\left|\frac{\sum_{i=1}^{P} A_i e^{j\phi_i}}{P}\right|^2 \tag{1}$$

The reflection amplitudes are unity $(A_1 \approx A_2 \approx \cdots A_P \approx 1)$ due to a lossless ground surface. To achieve a 10 dB RCS reduction, the reflection phases of basic meta-particles need to satisfy the follow relationship

$$\left|\sum_{i=1}^{P} e^{j\phi_i}\right| \le P\sqrt{0.1} \tag{2}$$

which is a multivariate exponential inequality. It is noted that Eq. (2) have many solutions. More basic meta-particles and variable phase differences between them greatly increase the ability for super-wideband manipulation of EM waves and realizing super-wideband phase cancellation.

III. METASURFACE DESIGN

A. Unit cell and its reflection characteristics

The square ring patch was chosen as the basic meta-particle of the metasurface for its reflection phase change characteristics. The range of reflection phase change with the change of side length is large enough in a super-wide frequency band. The unit cells were printed on the surface of PTFT Woven Glass substrate with a dielectric constant

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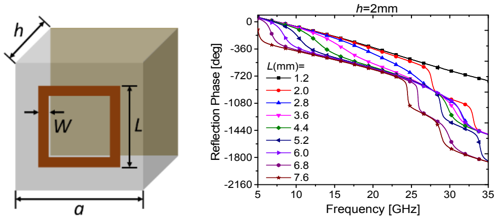
$\varepsilon_r = 2.65$ and loss tangent $\tan\delta = 0.001$. The back of the substrate is a PEC ground plane. The geometry structure of the basic meta-particle is illustrated in Fig. 1 (a). In this simulation, side length L of the meta-particles varied from 1.2 to 7.6 mm with a step size of 0.02 mm, while there were three choices of layer thickness for the dielectric substrate: 2 mm, 4 mm, and 6 mm. The periodicity a of the unit cell and the width w of square ring were fixed. A part of the reflection phase curves are plotted in Fig. 1 (b).



(a) (b)

Fig. 1. Geometry of the basic meta-particle and its reflection phase properties. (a) Geometry structure of the square ring element. Dimensions are: a=8, w=0.4, h=2,4,6 in mm. (b) The reflection phase of basic meta-particles with the change of side length L of square rings.

B. *Optimization design of basic meta-particles*

The schematic diagram for super-wideband control of RCS reduction by adjusting the side length of square ring and the thickness of dielectric layer is depicted in Fig. 2, where M is the number of optimization frequencies. The main objective of this work was to control 16 local waves produced by 16 basic meta-particles to achieve phase cancellation for a 10 dB RCS reduction in the super-wide frequency band. Particle swarm optimization (PSO) together with Eq. (1) was used to optimize the side length L and layer thickness h of 16 basic meta-particles. In optimization, RCS reduction (σ_R) values at M optimization frequencies sampled in a super-wide frequency band needed to be evaluated.

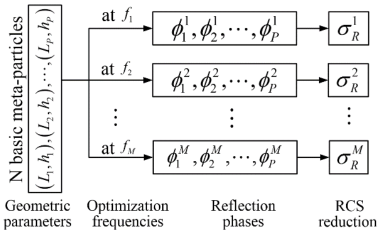


Fig. 2. Schematic diagram for super-wideband manipulation of RCS reduction by geometric parameter adjustment. The side length L and dielectric layer thickness h are two adjustable geometric parameters.

The initial side length of the basic meta-particle is a random value chosen from a uniform distribution between 1.2 mm and 7.6 mm. Layer thickness h is a discrete value chosen from 2 mm, 4 mm, and 6 mm. When 1000 iterations were finished, we got the optimal geometric parameters of 16 basic meta-particles for the metasurface with the lowest backward RCS in a desired super-wide frequency band.

The optimized results of side length L and layer thickness h are listed in Table I. The predicted RCS reduction is shown in Fig. 3. In a super-wide frequency band from 5.08 to 27.74 GHz, the RCS reductions are larger than 10 dB. The advantage of this approach is that more basic meta-particles and variable phase differences between them greatly increase the ability for super-wideband manipulation of EM waves and realizing super-wideband phase cancellation.

Table I

The optimized results of 16 basic meta-particles

Meta-particle :	1	2	3	4	5	6	7	8
L (mm)	7.1	1.2	4.0	6.8	6.0	4.2	7.3	7.6
h (mm)	4	6	4	4	2	2	4	2
Meta-particle:	9	10	11	12	13	14	15	16
L (mm)	4.3	6.7	4.3	6.8	2.5	7.6	6.7	6.1
h (mm)	2	6	6	4	6	2	2	6

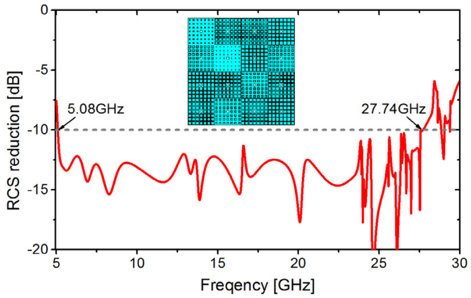


Fig. 3. The monostatic RCS reduction.

IV. CONCLUSION

A novel checkerboard metasurface based on optimized multielement phase cancellation (OMEPC) was designed, fabricated, and tested for super-wideband RCS reduction. The metasurface can achieve more than 10 dB RCS reduction in a super-wide frequency band ranging from 5.5 to 32.3 GHz with a ratio bandwidth of 5.87:1 under normal incidence.

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