Prediction and Reduction of Antenna RCS

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Abstract

Antenna is a special scattering object which should be used to transmit and receive the electromagnetic fields firstly. In recent years, antenna radar cross section (RCS) reduction has received high priority in the design of many platforms since it contributes to the total RCS of low-observable platforms significantly. Antenna RCS is distinctly different for frequencies in the operating band as compared to those out of the operating band. Thus, effective control of antenna RCS must address the in-band and out-of-band frequencies separately. However, methods those are effective out of the operating band impact the antenna performance in its operating band. Traditional methods for scattering objects are difficult to use for antennas. This talk will review the theory and the reduction methods for antennas. Some case studies including Broadband Polarization Rotation Reflective Surface, Low RCS and High-gain Antennas, etc, will be discussed. A conclusion will be given in the end.

Index Terms: Antenna, RCS, Polarization Rotation Reflective Surface, Phase Gradient Metasurface
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Her research interests include antenna theory and technology, prediction and control of antenna RCS. She has authored or coauthored over 100 refereed journal papers. She has also authored *Prediction and Reduction of Antenna Radar Cross Section* (Xi’an: Xidian Univ. Press, 2010), and *Antennas for Mobile Communication Systems* (Beijing: Electronics Industry Press, 2011). Dr. Liu is IET Fellow, a Senior Member of Chinese Institute of Electronics (CIE) and a senior member of IEEE. She was the recipient of “New Century Excellent Talents in University” of the Ministry of Education for China in 2011. She is the Vice-Chair of IEEE AP Xi’an Chapter (CH10767) and is in charge of organizing the activities of Xi’an Chapter. She also is an Associate Editor of IEEE Access and reviewers of many magazines such as IEEE Transactions on Antennas and Propagation etc. As an active researcher, she serves as TPC members or session chairs for several IEEE flagship conferences and has been invited to give invited lectures in several international academic conferences and seminars.
Contents

1. Antenna Scattering Theory
2. Methods for Antenna RCSR
3. Conclusion
Antenna Scattering Theory

- Theoretical formula of antenna RCS
- Calculation model of antenna RCS
The fundamental equations of antenna scattering are developed for the case of an antenna fed from a single transmission line that supports only one propagating mode. $(a_0, b_0)$ is the signal on the transmission line. The field in the outer space of the antenna can be expressed by applying spherical wave function:

$$\vec{E} = \sum_i (a_i \vec{e}_i^{in} + b_i \vec{e}_i^{out})$$

Theoretical Formula

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ \vdots \\ \vdots \end{bmatrix} = \begin{bmatrix} S_{00} & S_{01} & S_{02} & \cdots & \cdots \\ S_{10} & S_{11} & S_{12} & \cdots & \cdots \\ S_{20} & S_{21} & S_{22} & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \cdots \\ \vdots & \vdots & \vdots & \cdots & \ddots \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ \vdots \end{bmatrix}$$

$$b_0 = \sum_{j=0}^{\infty} S_{0j} a_j = S_{00} a_0 + \sum_{j=1}^{\infty} S_{0j} a_j \quad \text{(reflection/receiving amplitude)}$$

$$b_i = \sum_{j=0}^{\infty} S_{ij} a_j = S_{i0} a_0 + \sum_{j=1}^{\infty} S_{ij} a_j \quad \text{(radiation/scattering amplitude)}$$
For the case of radiating: \( a_i = 0 \quad (i \neq 0) \)

\[
b_0 = S_{00}a_0 \quad \text{(reflection amplitude)} \quad b_i = S_{i0}a_0 \quad \text{(radiation amplitude)}
\]

\[
S_{00} = \Gamma_a = \frac{Z_{in} - Z_c}{Z_{in} + Z_c} \quad \text{(reflection coefficient of the antenna)}
\]

For the case of receiving and scattering: \( a_0 = \Gamma_l b_0 \quad \Gamma_l = \frac{Z_l - Z_c}{Z_l + Z_c} \)

\[
b_0 \bigg|_{a_0=0} = \sum_{j=1}^{\infty} S_{0j}a_j = b_0^m \quad \text{(defined as matched receiving amplitude)}
\]

\[
b_0 = \frac{1}{1 - \Gamma_a \Gamma_l} \sum_{j=1}^{\infty} S_{0j}a_j = \frac{1}{1 - \Gamma_a \Gamma_l}
\]

\[
b_i = b_i^m + \frac{\Gamma_l}{1 - \Gamma_l \Gamma_a} b_0^m S_{i0}
\]

The scattering matrix representation can be converted directly to field components:

\[
E^s(Z_l) = E^s(Z_c) + \frac{\Gamma_l}{1 - \Gamma_l \Gamma_a} b_0^m E_1^t
\]
Total scattering fields: \[ E^s(Z_l) = E^s(Z_c) + \frac{\Gamma_l}{1 - \Gamma_l \Gamma_a} b_0^m E_1^t \]

\[ = E^s(Z_c) + E^a(Z_l) \]

It is corresponding to the scattered electric fields when the antenna is terminated with a matched load.

When the termination is a matched circuit, \( Z_l = Z_c, \Gamma_l = 0 \), the portion of scattering due to antenna reradiation is zero.

\( b_0^m \) is the receiving amplitude when the antenna is terminated with a matched load. \( E_1^t \) represents the radiated field for a 1 amp antenna current excitation.

When the antenna is terminated with an arbitrary load, there will be received signals transmitting to the antenna port and a portion of these signals will be reflected back to the load at the antenna port.
R.B. Green, 1963, conjugate matched

\[ \tilde{E}^s(Z_l) = \tilde{E}^s(Z_{in}) + \Gamma_A I_m \tilde{E}_3^t \]

R.E. Collin, 1969

matched

\[ \tilde{E}^s(Z_l) = \tilde{E}^s(0) - \frac{Z_l}{Z_{in} + Z_l} I(0) \tilde{E}_3^t \]

R.C. Hansen, 1989

short circuit

\[ \tilde{E}^s(Z_l) = \tilde{E}^s(Z_{in}) + \Gamma_A I_m \tilde{E}_3^t \]

In 2000, Xidian University

\[ E^s(Z_l) = E^s(Z_c) + \frac{\Gamma_l}{1 - \Gamma_l \Gamma_a} b_0^m E_1^t \]

- Fundamental theory of antenna scattering
- Unify the theory of antenna scattering
Calculation Model of Antenna RCS

Phase difference?

Structural mode ↔ Antenna mode

Condition 1: \( Z_l = 0 \) \quad \Gamma_l = -1 \quad \tilde{E}^s(0) = \tilde{E}^s(Z_c) - \frac{1}{1 + \Gamma_a} b_0^m \tilde{E}_1^t

Condition 2: \( Z_l = \infty \) \quad \Gamma_l = 1 \quad \tilde{E}^s(\infty) = \tilde{E}^s(Z_c) + \frac{1}{1 - \Gamma_a} b_0^m \tilde{E}_1^t

\[
\tilde{E}^s(Z_l) = \frac{(1 - \Gamma_a) \tilde{E}^s(\infty) + (1 + \Gamma_a) \tilde{E}^s(0)}{2} + \frac{\Gamma_l}{1 - \Gamma_a} \frac{1 - \Gamma_a^2}{2} [\tilde{E}^s(\infty) - \tilde{E}^s(0)]
\]


The structural mode scattering and antenna mode scattering can be obtained respectively. As a result, the bottleneck problem of antenna RCS calculating is solved.
Calculation Model of Antenna RCS

Antenna geometry

A NOVEL MODEL FOR ANALYZING THE RADAR CROSS SECTION OF MICROSTRIP ANTENNA

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Abstract: A novel model is proposed to analyze the scattering of antenna by which the scattering of antenna with arbitrary load is obtained conveniently and the antenna mode RCS together with the structural mode RCS are illustrated separately. The model is realized by the ANSOFT HFSS and some useful results are illustrated. The structural mode RCS and antenna mode RCS are compared with the results by other methods, which proves the model correct and efficient. The results are meaningful for the antenna RCS prediction and reduction.
Methods for Antenna RCSR
Artificial Magnetic Conductor (AMC)

Reduction principle:
Artificial magnetic conductor (AMC) is a two-dimensional periodic structure. The AMC has a 0° reflection phase while the perfect electric conductor (PEC) has a reflection phase of 180° for the same incident wave. Thus the RCS reduction can be achieved by using their 180° reflection phase difference.

Low RCS, high gain and wideband Mushroom antenna:

- The mushroom structure acts as the radiation structure of the antenna, which not only broadens the antenna’s operation band and improves the antenna gain, but also reduces the in-band RCS.
- By replacing the metal ground with FSS, the out-band RCS reduction is realized.
The proposed high-gain and low RCS antenna:

- The relative bandwidth of the proposed antenna is 26.4% while the reference antenna is 5.4%.
- The average gain of the proposed antenna is 9dBi which is 5dB higher than the reference antenna.
- The RCS of the proposed antenna is reduced from 2GHz to 16GHz.
low RCS and high-gain circular polarized antenna:

- Polarization rotation reflective surface is used as the radiation structure to achieve the high-gain and circular polarized characteristics.
- The proposed antenna surrounded by three different AMCs has a significant RCS reduction taking advantage of the reflection phase differences among the four structures.

The -10dB impedance bandwidth of the antenna is 21%, the -3dB axial ratio bandwidth is 14.9% and the maximum gain is up to 9.4dBi.

The in-band and out-band RCS of the proposed antenna is reduced at least 5dB compared with the reference antenna.
The reduction principle:

- **The holographic surface can record the specific pattern.** By optimizing a reasonable structure, the reflection wave can be made to point to the non-threatening angular domain when the holographic surface is irradiated by the incident wave. Thus the RCS in the threatening angular domain is reduced.
Load the holographic surface:

- have little effect on antenna reflection coefficient
- the degradation of the antenna gain is about 1dB.
- the antenna RCS has been reduced from 8GHz to 20GHz

**Polarization Rotation Reflective Surface (PRRS)**

### Reduction principle:
- The polarization of the incident wave can be rotated by 90° when reflected by the PRRS. With the chessboard configuration, the reflection phase difference between the PRRS arranged in orthogonal directions is 180° so that the antenna RCS is reduced.

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**References**

Structure of the PRRS

Comparison of the reflection coefficient for different modes

Configuration 1

Configuration 2

High-efficiency and Wideband Polarization Rotation Reflective Surface with Dual-patch Metasurfaces


RCS Reduction (dB) = 10log10 \[ |r_{xy}|^2 \]
= 10log10 \[ 1 - |r_{xy}|^2 \]
= 10log10 [1 - PCR]
Ultra-wideband and High-efficiency Polarization Rotation Reflective Surface

Structure of the PRRS

Diagram of the principle of rotating the y-polarized incident wave to x-polarized reflective wave

Amplitude and phase difference of the reflection coefficient for incident electric field along u-axis and v-axis

Co-polarized and cross-polarized reflection curve for normal incident wave

Co-polarized reflection amplitude for normal incident wave

Loading the PRS structure around the antenna:

- The reflection coefficient of the antenna has not been affected and the gain is reduced by 0.5dB.
- The antenna RCS is reduced from 2GHz to 12GHz under normal incident wave.

The working frequency of the antenna is slightly shifted to the low frequency, and the gain is decreased by 0.2dB.

The RCS is significantly reduced from 6GHz to 18GHz.

After loading the PCM:

- The -10dB impedance bandwidth remains unchanged.
- The gain is increased by 4.8dB at maximum.
- The RCS is obviously reduced from 6GHz to 14GHz under normal incident wave.
In generalized refraction law, when $\theta_i = \theta_r$, $n_i = n_t$, the generalized reflection law can be obtained.

If $\frac{d\Phi}{dx} \neq 0$, then $\theta_r \neq \theta_i$, the incident wave can be reflected to space abnormally.

The incident wave can be coupled into surface wave with properly selected $\frac{d\Phi}{dx}$ and $\theta_i$.

RCS reduction principle
The reflected main beam is deflected to the direction of \( \varphi_r = 7\pi/4, \ \theta_r \approx \pi/6 \) at 12GHz, which is in accordance with the theoretical value.

- Diffuse reflection occurs at 16GHz.
- RCS is reduced by 10dB in 7-16.3GHz.
The RCS is significantly reduced from 7GHz to 20GHz for normally incident waves. Maximum value of RCS reduction is about 30dB.

(a) x-polarized incident wave
(b) y-polarized incident wave

RCS comparison for normally incident waves
Conclusion
A novel broadband polarization rotation (PR) reflective surface (PRRS) with a high polarization conversion ratio (PCR) is proposed, which can reflect the linearly polarized incident wave with 90 degrees PR. The proposed PRRS consists of a periodic array of square patches printed on a substrate, which is backed by a metallic ground. By connecting the square patch with the ground using two nonsymmetric vias, a 49% PR bandwidth is achieved with a high PCR of 96%, which is a significant improvement from the state-of-the-art 23% PR bandwidth. Moreover, the frequency responses within the operation frequency band are consistent under oblique incident waves. Furthermore, another ultra-wideband PRRS with a periodic array of quasi-L-shaped patches is proposed, which increases the PR bandwidth further to 103%. In addition, the designed PRRS is applied to wideband radar cross section (RCS) reduction. Different arrangements of the unit cells of the PRRS are proposed and their effects on RCS reduction are investigated. To validate the simulation results, prototypes of the PRRSs are fabricated and measured. The measured results are in good agreement with the simulated ones.
A new approach to reducing the monostatic radar cross section (RCS) and preserving the radiation characteristics of a slot array antenna by employing polarization conversion metasurfaces (PCMs) is presented in this communication. The PCM is arranged in a chessboard configuration consisting of fishbone-shaped element. It is placed on the surface of the slot array antenna. The characteristics and mechanism of the RCS reduction are analyzed. Simulated and experimental results show that the monostatic RCS reduction band of the antenna with PCM ranges between 6.0 and 18.0 GHz for normally impinging both x- and y-polarized waves. The radiation characteristics of the antenna are well preserved simultaneously in terms of the impedance bandwidth, radiation patterns, and realized boresight gains.
References


Thank you!