Progress In Electromagnetics Research Letters, Vol. 66, 135–141, 2017

RCS Reduction Using a Miniaturized Uni-Planar Electromagnetic Band Gap Structure for Circularly Polarized Microstrip Antenna Array

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Abstract—In this paper, a new method for radar cross section (RCS) reduction of circularly polarized (CP) microstrip antenna array with small element spacing is proposed. By employing the element rotation technique and loading EBG structures, the in-band and out-of-band RCSs are reduced simultaneously despite the extreme small space between array elements. The simulated results show that the proposed antenna has an average RCS reduction over 10 dB in the X-band for x-polarized and y-polarized incident waves impinging from normal direction compared to the original CP microstrip antenna array, indicating a fractional bandwidth of 40%. The maximum RCS reduction is over 25 dB. Meanwhile, the radiation performance of the proposed antenna array is kept.

1. INTRODUCTION

In recent years, radar cross section (RCS) reduction has attracted more and more attention in designing the low observable platform [1]. Antenna, as an electromagnetic wave radiating component, is a great contributor to the overall RCS. Therefore, it is a challenging and meaningful research to achieve RCS reduction for the antenna without degrading its radiation performance [2, 3].

A microstrip antenna has the advantages of low profile, low cost and light weight, which make it a good candidate for communication systems. In the open literature, a number of methods of RCS reduction for microstrip antennas have been reported. The shaping of the antenna surfaces and loaded radar absorbing materials (RAMs) are the two methods used commonly among them. By cutting slots in the proper place where the current amplitude is small, the former approach can deflect the scattered energy away from the incident wave direction while keeping the good radiation performance of antennas, whereas the latter usually converts the incoming energy into heat instead of backscatter [4–7]. Metamaterials provide another promising way to enhance the radiation and scattering performances of antennas [8, 9]. For example, frequency selective surfaces (FSS) can be used as a radome to uniformly scatter the impinging wave everywhere outside the antenna operating band [10–12]. Compared to the FSS, the artificial magnetic conductors (AMC) [13, 14] and electromagnetic band gap (EBG) structures [15, 16] contribute not only to the out-of-band RCS reduction, but also to the in-band RCS reduction, which are based on the principle of the scattered wave cancelation.

In this paper, a new method of out-of-band and in-band RCS reduction of a CP microstrip array is proposed under the condition of small element spacing. To achieve the goal, EBG structures and element rotation technique are employed simultaneously. Compared with methods of RCS reduction by loading EBG structures published before, this paper has the following characteristics. Firstly, different from other literature in which the element spacing is arbitrarily distant to load enough number of EBG

Received 15 January 2017, Accepted 25 March 2017, Scheduled 31 March 2017
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structures, this paper focuses on the RCS reduction with small element spacing to satisfy the engineering application requirement for beam steering without grating lobe. As an example, the element spacing here is strictly limited to half of a wavelength (corresponding to the operating frequency) in the free space, which is commonly used in engineering. So the method of this paper can be easily extended to the RCS reduction of phased array antennas. Secondly, because of its larger size than that of mushroom-like EBG, the uni-planar compact electromagnetic band gap (UC-EBG) structure is seldom employed in the RCS reduction of microstrip antennas, especially under the condition of small element spacing. In this paper, considering its easier fabrication than that of mushroom-like EBG, the UC-EBG structure is miniaturized to satisfy the constraint of element spacing. Finally, the in-phase reflection bandwidth of the UC-EBG structure is narrow, which will result in a narrow RCS reduction bandwidth. The methods of wide RCS reduction published before usually have to reserve sufficient space to load EBG structures, so they are not suitable for applications with small element spacing. As a result, in this paper, the function of the dielectric slab in the RCS reduction is considered, which is ignored by other literature. By adjusting the phase difference and optimizing the occupied area among the radiation patches, the UC-EBG structure and grounded substrate, the complex design of the wide EBG structure is negligible, and a wide RCS reduction band is achieved.

The paper is organized as follows. In Section 2, the design of a miniaturized UC-EBG and its equivalent circuit are discussed. Section 3 introduces the simulated and measured results of the reference CP microstrip antenna and the low-RCS CP microstrip antenna. Section 4 concludes the whole paper.

2. DESIGN OF THE MINIATURIZED UC-EBG STRUCTURE

A conventional UC-EBG is composed of an FSS and a dielectric slab backed by a conducting plane, the structure of which is shown in Fig. 1, and its electromagnetic properties can be interpreted by an equivalent transmission line model which is exhibited in Fig. 2, according to [17, 18]. The whole structure can be viewed as an LC parallel circuit. The resonant frequency of the structure depends on the equivalent capacitances which result from the gaps between the conductor edges of two adjacent cells and the equivalent inductances which are rooted in the narrow strips.

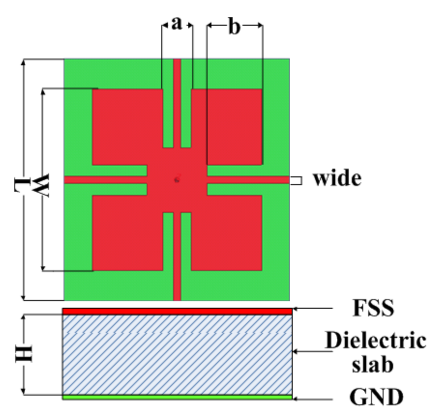


Figure 1. Unit cell of the UC-EBG structure.

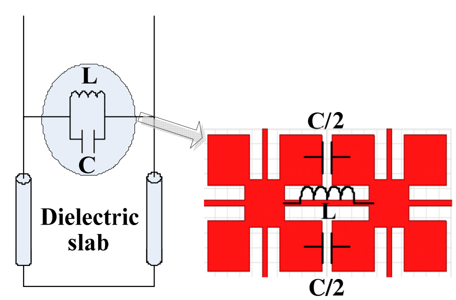


Figure 2. The equivalent transmission line model.

Based on the theory of LC parallel circuit, the miniaturization of the conventional UC-EBG can be achieved by introducing the interdigital structure to increase the capacitances and employing the meandered strips to increase the inductances. The proposed miniaturized UC-EBG structure is illustrated in Fig. 3.

To verify the validity of this method, a conventional UC-EBG and the proposed UC-EBG are simulated with the high frequency structure simulator (HFSS) under the condition that both have the same dimensions and that the same dielectric slab is selected. The relevant parameters of two structures are listed in Table 1, and the reflection phase of them is plotted in Fig. 4 in the case of normal incidence.

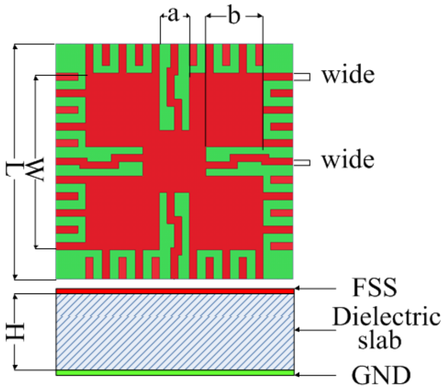


Figure 3. Unit cell of the proposed UC-EBG structure.

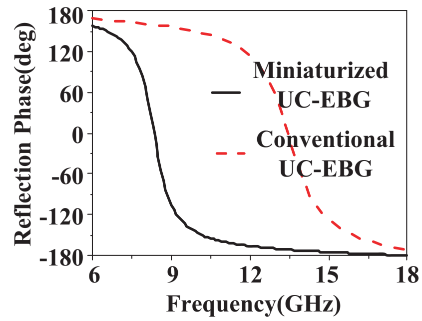


Figure 4. Reflection phase of conventional UC-EBG and proposed UC-EBG.

Table 1. The relevant parameters of two structures (units: millimeter).

L	W	a	b	wide	H	ε_r
3.2	2.4	0.4	0.775	0.1	3.18	6.15

Table 2. The operating frequency and relative bandwidth of two structures.

	resonant frequency (GHz)	relative bandwidth
Conventional UC-EBG	13.44	12.98%
Miniaturized UC-EBG	8.35	12.02%

Meanwhile, the resonant frequency and relative bandwidth of in-phase reflection are also summarized in Table 2.

As listed in Table 2, it can be concluded that the miniaturization factor of the proposed UC-EBG structure with respect to the conventional UC-EBG structure is 1.61 : 1, which means that the proposed UC-EBG structure will be more compact than the conventional UC-EBG structure under the condition that both resonate at the same frequency.

3. DESIGN OF THE LOW-RCS CP MICROSTRIP ANTENNA

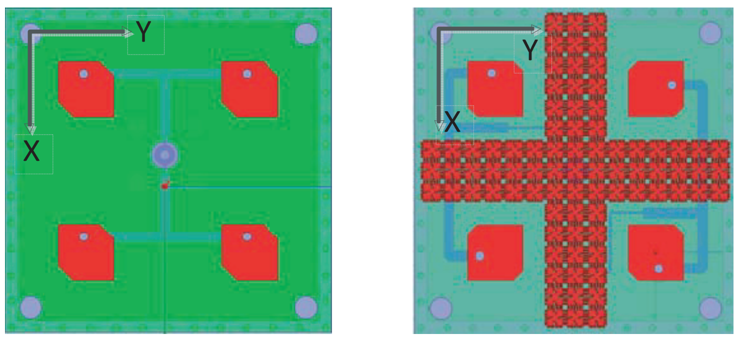
In this section, two 2×2 CP microstrip antenna arrays are designed to verify the effectiveness of the proposed method. The truncated microstrip antenna is employed here as an element of the arrays, and the antenna works at 6 GHz, so the element spacing is strictly limited to 25 millimeters, corresponding to the half of an operating wavelength. The in-band RCS reduction principle is based on the element rotation technique, and the bandwidth of in-band RCS reduction is corresponding to the axial ratio (AR) bandwidth (AR $<$ 3 dB) of the employed truncated microstrip antenna element, as described in detail in [19].

The out-of-band RCS reduction principle is based on the scattered wave cancelation by employing the aforementioned miniaturized UC-EBG structure investigated in Section 2. If only the cancelation between the UC-EBG structure and the patches is considered, in theory the RCS reduction bandwidth only depends on the in-phase reflection bandwidth of the UC-EBG structure, because patches have a constant 180° reflection phase. To broaden the RCS reduction bandwidth, the reflection phase of the grounded substrate is considered, shown in formula (2), in which η_0 represents the wave impedance in free space, ω the angular frequency of incident plane wave and h the thickness of the substrate. By adjusting the phase difference and optimizing the occupied area among the radiation patches, UC-EBG structure and grounded substrate, the scattered wave can be canceled in a wide frequency range to achieve a wide RCS reduction. The frequency range of out-of-band RCS reduction is focused on the X band (covering from 8 GHz to 12 GHz), where the fire control radar and target-tracking radar operate.

$$Z_d = \frac{j\eta_0}{\sqrt{\varepsilon_r}} \tan(\omega\sqrt{\varepsilon_0\varepsilon_r\mu_0}h) \tag{1}$$

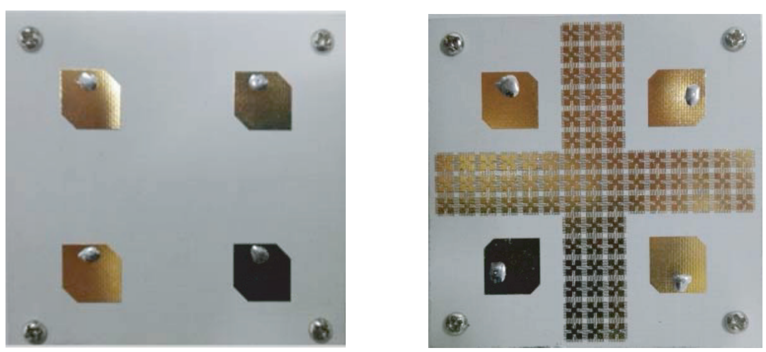
$$\Phi = \mathrm{Im}\left[\ln\left(\frac{Z_d - \eta_0}{Z_d + \eta_0}\right)\right] \tag{2}$$

After optimizing the performances of two microstrip antenna arrays with the HFSS, the permittivity of substrate is finally selected as 6.15, and the thickness is 3.18 millimeters. The antenna arrays are fed by the strip line power division network below. Their geometries are exhibited in Fig. 5(a) and Fig. 5(b), respectively. To validate the method, two prototypes are fabricated, which are shown in Fig. 6.



(a) (b)

Figure 5. Geometry of the circularly polarized microstrip antenna array. (a) The reference antenna and (b) the low-RCS antenna.



(a) (b)

Figure 6. The photograph of two antennas. (a) The reference antenna and (b) the low-RCS antenna.

The two antenna arrays are measured in an anechoic chamber. Before investigating the RCS reduction of the arrays, their radiation performances are firstly considered, including the reflection coefficient (S_{11}), AR and radiation patterns. Fig. 7 shows the reflection coefficient curves of the two antenna arrays, in which both of the antenna arrays have a good impedance matching around 6 GHz. The AR results are plotted in Fig. 8. Compared to the reference antenna, the low RCS antenna has a lower AR values in a wider band, which results from the element rotation technique. The radiation patterns at 6 GHz are exhibited in Figs. 9(a) and (b), respectively. It can be seen that the circularly polarized gain of the low RCS antenna is only 0.26 dB less than that of the reference antenna which is

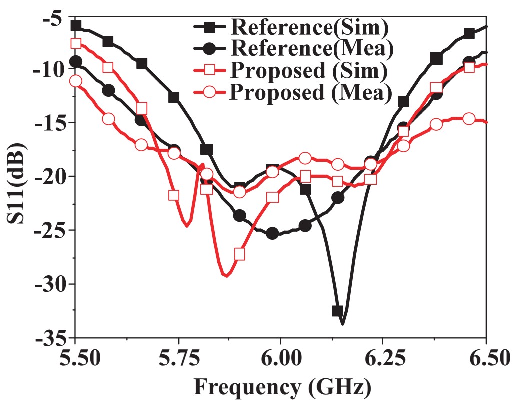


Figure 7. S_{11} of the two antennas.

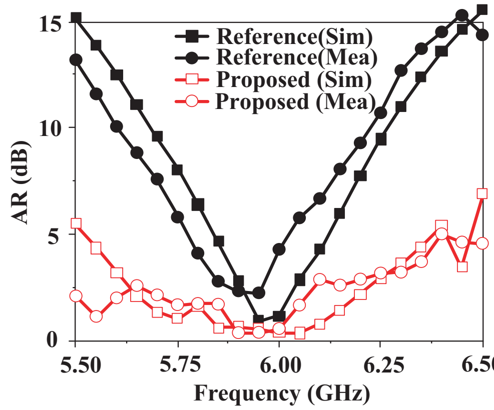
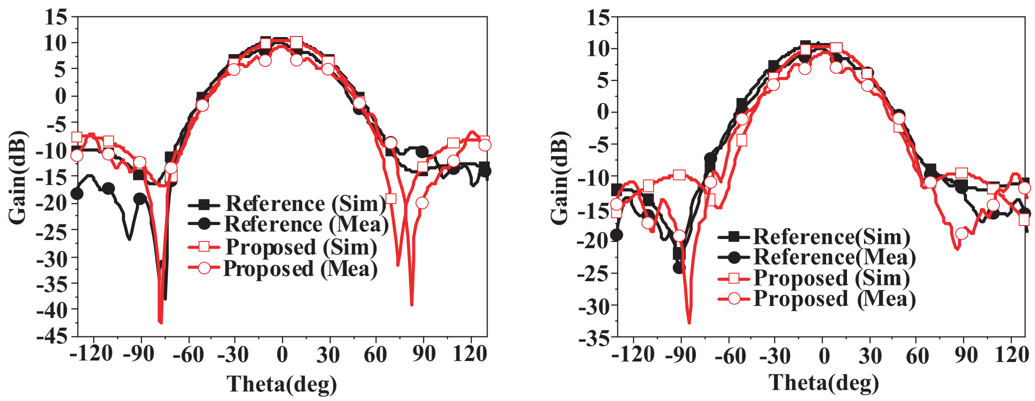


Figure 8. AR of the two antennas.



(a) (b)

Figure 9. Circularly polarized radiation patterns of the two antennas at 6 GHz. (a) Phi = 0 deg plane and (b) Phi = 90 deg plane.

derived from the difference of the feed network between the two antennas. The simulated (Sim) results have a good agreement with the measured (Mea) ones. As illustrated above, it can be concluded that the low RCS antenna can keep the radiation performances very well compared to the reference antenna.

Figure 10 shows the monostatic RCS of the two antenna arrays impinging from normal direction, in which it can be found that the RCS of the proposed antenna is significantly reduced in and out of the working frequency band for the x-polarized and y-polarized incident waves simultaneously. There are two main reduction areas: one is around the working frequency, and the other is the X-band. In the band away from the operating band, the maximum RCS reduction is 25.21 dB for x-polarization and 25.41 dB for y-polarization, which are obtained at the frequency of 11 GHz. The proposed antenna has average RCS reductions of 10.03 dB and 10.09 dB for x-polarization and y-polarization in the X band, respectively. The RCS reduction bandwidth of the proposed antenna is 40%. At the working frequency, the RCS reduction is 8.02 dB for x-polarization and 10.02 dB for y-polarization individually. Discrepancies can be observed between the simulated and measured results, which may come from the misalignment in the measurement setup, imperfection of the environment in the chamber, deviation of permittivity of the substrate and fabrication tolerance.

From the experimental results, it can be concluded that the proposed method is valid and has the potential in achieving a wide RCS reduction for other frequency range requirements or a larger array. In the process of co-design of the UC-EBG structure and the antenna, the UC-EBG's influence on the radiation performances of arrays and the fabricating precision should be considered carefully.

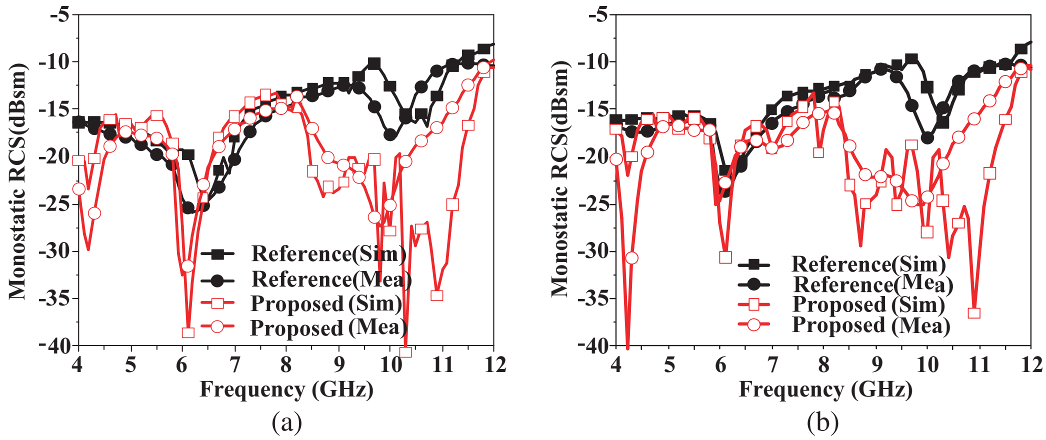


Figure 10. Monostatic RCS of the two antennas versus frequency for normal incidence. (a) x-polarization and (b) y-polarization.

4. CONCLUSION

In this paper, a method of achieving the in-band and out-of-band RCS reduction of a CP microstrip antenna array is proposed with severe restriction in the space between elements. The element rotation technique and miniaturized UC-EBG structure are employed in this design to achieve final goals based on the principle of the scattered wave cancelation. To verify the effectiveness of the proposed strategy, two CP antenna arrays are simulated, fabricated and measured. The experiment results show that the proposed antenna has a lower RCS value in-band and out-of-band (X band) than that of reference antenna, indicating a 40% RCS reduction bandwidth. Moreover, the radiation performances of the proposed antenna have not been degraded significantly.

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