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Symmetrically Stepped Reflective Surfaces for Enhanced Multiband Stealth and Phase Cancellation

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ABSTRACT: This work proposes a compact multiband Symmetrically Stepped Phase Cancellation Reflective Surface (PCRS) that can be used to lower radar cross section (RCS), achieve high Absorption Conversion Ratio (ACR) and high Polarization Conversion Ratio (PCR). Two FR4 layers make up the Symmetrically Stepped PCRS unit cell. With three asymmetrically positioned vias along its diagonal, the Symmetrically Stepped patch is present in the first FR4 layer, which has a thickness (t_1) of 1.6 mm and high PCR and ACR. On top of layer 1, there is another layer of FR4 stacked with a thickness (t_2) of 3.2 mm to give multiple bands with improved bandwidth efficiency. The PCRS unit cell's entire dimensions, which are only 5 mm $\times$ 5 mm $\times$ 4.8 mm, are determined by its lowest operational wavelength. Multiple frequencies, 5.6 GHz, 9.8 GHz, 11.3 GHz, and 16.7 GHz, yield RCS reductions of 24 dB, 33 dB, 42 dB, and 24 dB, respectively. 99.9% maximum PCR and 99.9% maximum ACR are obtained with up to 60 degrees of angular stability. Furthermore, in order to minimize RCS and prevent unnecessary reflections from the PCRS, the proposed reflective PCRS unit cells are positioned orthogonally to offer reflection phase cancellation. The most important objective of the proposed research is to lower the RCS while maintaining high PCR and ACR in various frequency bands that are necessary for detection and stealth technologies.

1. INTRODUCTION

Due to advances in detection technology, RCS reduction has become crucial, particularly for military applications like stealth aircraft, where minimizing detectability is essential. RCS measures an object's visibility to Radio Detection and Ranging (RADAR) by analyzing the scattering of electromagnetic waves. Smaller RCS values indicate reduced visibility, making RCS reduction vital for stealth technology. Modern RADAR systems use RCS measurements to distinguish targets and assess their position, speed, and range, highlighting the importance of understanding scattering mechanisms and polarization effects.

In recent years the phase, magnitude, and polarization characteristics of electromagnetic waves are controlled arbitrarily using metasurfaces [1–7]. This arbitrary control is highly required in radar stealth technology in achieving RCS reduction by efficiently modulating the scattered waves. In [1], a broadband metasurface was proposed for high-efficiency RCS reduction by utilizing a binary design that allows for efficient transmission windows within the intraband. This metasurface was designed to operate across a wide frequency range, improving RCS reduction while maintaining high transmission efficiency. In [2], a ternary metasurface was introduced, based on a parallel resonance circuit configuration. This design enhances RCS reduction by incorporating multiple resonant elements, which allows for more precise control of the scattering characteristics of electromagnetic waves. The inclusion of ternary elements in the structure enables better performance across a broader range of frequencies. Additionally, in [3], bionic-inspired designs were explored to reduce RCS by mimicking irregularities found in nature. The study focused on the bio-inspired principles that enhance the electromagnetic wave scattering properties, leading to an improved stealth performance by effectively diffusing or redirecting the incident waves. A checkerboard surface with a combination of square loop and circular loop Electronic Band Gap (EBG) structures is designed in [4] to produce dual-band operation. The dual-band EBG with two different configurations provides 61% and 24% RCS reduction bandwidth that is greater than 10 dB over the frequency bands of 3.94 GHz to 7.40 GHz and 8.41 GHz to 10.72 GHz. The maximum RCS is decreased by 5.1 dB and 7.1 dB, at theta, $\theta = 27$ degrees, 35 degrees along phi, $\varphi = 45$ degrees and 135 degrees planes respectively compared to that of Perfect Electric Conductor (PEC). Various enhancements in low-profile antennas, holographic leaky wave antennas and RCS reduction using the principles of Artificial Magnetic Conductor (AMC) are analyzed [7]. By combining two single band AMCs in a checkerboard fashion, an RCS reduction bandwidth of 60% is achieved. The 10 dB RCS reduction bandwidth is enhanced to 83% by introducing blended checkerboard surface but with a limitation on reflection phase criteria. Further modifications are made to the blended checkerboard surface to eliminate the reflec-

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tion phase limitation and to provide 91% enhancement in 10 dB RCS reduction bandwidth. Additionally, plasma technology, including plasma antennas, offers dynamic control over wave propagation and significantly reduces RCS by absorbing or deflecting incident waves [8, 9]. These advancements highlight the variety of approaches available for improving stealth technology. Plasma technology presents notable advantages over conventional methods, as plasma-based reflective surfaces allow for dynamic control of the reflection phase, enabling real-time adjustments that further enhance RCS reduction beyond what is achievable with traditional metasurfaces [10]. Moreover, plasma technology facilitates polarization conversion and delivers superior performance in dynamic or changing environmental conditions, making it a more adaptable solution for stealth applications [11]. While the techniques discussed above provide stable RCS reduction up to an angle of 45°, plasma surfaces offer greater flexibility and the potential for enhanced performance across a wider range of conditions.

Polarization Conversion Metasurface (PCM) represents one of the methods employed to manipulate scattered electromagnetic waves. PCM operates with a 180-degree phase difference, and by arranging its mirror structures orthogonally, it effectively achieves phase cancellation. In [12], for the purpose of reducing wideband radar cross section (RCS) by 10 dB and more than 10 dB over the whole bandwidth, a monolayer metasurface is suggested. Positive scattering suppression effects have been reported from a number of comparable initiatives [13–17]. However, every polarization converter on the preceding list is a linear-linear polarization translator. Then, a polarization translator using PIN diodes as components is projected, which allows switching between linear-linear and linear-circular polarization conversions by altering the on-off state of the diodes [18, 19].

The review of related works indicates that plenty of chessboard structures mainly use the concepts of AMCs, EBGs, and high permittivity materials. Only a few articles focus on implementation of surfaces that reduce RCS not only at the incident angle but also at various oblique angles with high ACR and PCR. A multi-folded transmitting array antenna which uses multi-folded quasi-optic trace principle is proposed by Fan et al. [12]. The multi-folded transmitting array antenna has a pair of U-shaped slots to introduce sole polarization selectivity and uniplanar compact Photonic Band Gap (PBG) element to increase the bandwidth. The reflection of incident and polarized Electromagnetic (EM) wave occurs back and forth between the transmitting array antenna and Polarization Rotation Reflective Surface (PRRS) repeatedly. Therefore, the transmitting array antenna's thickness is reduced to only about 1/3 of its focal length. A cross polarization of −30 dB with −1 dB gain bandwidth of 5% is achieved with an aperture efficiency of 46%. 80% PCR is achieved with an RCS reduction bandwidth of 79%, and 68% PCR is achieved with an RCS reduction bandwidth of 32% with an angular stability up to 60 degrees. But the PCR and ACR so achieved are not up to the expected level. Various other surveys provide either single band RCS reduction with high PCR and ACR or multiband/wideband RCS reduction with low PCR and ACR [19–24]. The polarization rotators of the reflection type that have been proposed thus far exhibit either low PCR in narrower polarization frequency bands or high PCR in larger polarization frequency bands. Additionally, incidence angles less than 45 degrees are the limit on angular stability.

In this paper, a compact multiband Symmetrically Stepped PCRS is proposed for achieving high PCR, high ACR, and reduced RCS. RCS reductions of 24 dB, 33 dB, 42 dB, and 24 dB are obtained at multiple frequencies namely 5.6 GHz, 9.8 GHz, 11.3 GHz, and 16.7 GHz, respectively. A maximum PCR of 99.9% and a maximum ACR of 99.9% are achieved with an angular stability up to 60 degrees. In addition, the proposed Symmetrically Stepped PCRS is arranged in orthogonal manner to form a checkerboard structure to provide reflection phase cancellation in order to avoid unnecessary reflections from the PCRS and to minimize RCS.

2. DESIGN OF COMPACT MULTIBAND SYMMETRICALLY STEPPED PCRS

The proposed Symmetrically Stepped PCRS unit cell consists of two FR4 layers as shown in Figure 1. The proposed PCRS is designed using an FR4 substrate with a relative permittivity of $\varepsilon_r = 4.4$ and a loss tangent of 0.02. The first FR4 layer has a thickness (t_1) of 1.6 mm, and second layer FR4 has a thickness (t_2) of 3.2 mm with a period, $p_l = 5$ mm. In order to achieve high ACR and PCR, the unit cell contains Symmetrically Stepped patch of width, $w_l = 4.6$ mm, with three asymmetrically placed vias along its diagonal whose distances from its position are shown as belonging to the unit cell's center as d_{l1}, d_{l2}, and d_{l3}. The outer patch's width and length are represented by L_{l1} and L_{l2}. Steps are introduced in the outer patch, and its values are obtained by using the relation given in Equation (1).

$$L_{l1} = \frac{h_2}{h_1} = \frac{h_3}{h_2} = \frac{v_2}{v_1} \tag{1}$$

By introducing steps using the above relation successive resonances are overlapped, and multiple broadbands can be produced. The outer patch is symmetrically mirrored. The inner PCRS patch is formed by scaling the outer patch's dimension by a value of 0.3125 and symmetrically placing it in the opposite direction. The scaled inner patch's width and length are represented by L_{l3} and L_{l4}. Table 1 contains a tabulation of the necessary design parameters.

TABLE 1. Dimensions (mm) of proposed Symmetrically Stepped PCRS.

w_l	g_l	L_{l1}	L_{l2}	L_{l3}	L_{l4}
4.6	0.8	1.289	3.5	0.402	1.094
h_1	h_2	h_3	v_1	v_2	p_l
0.307	0.416	0.565	0.416	0.565	5
d_{l1}	d_{l2}	d_{l3}	t_1	t_2	D
2	1.25	2	1.6	3.2	0.5

The design uses logarithmic steps in the L-shaped patch to achieve broadband operation by ensuring overlapping resonances from different segments. This technique suppresses

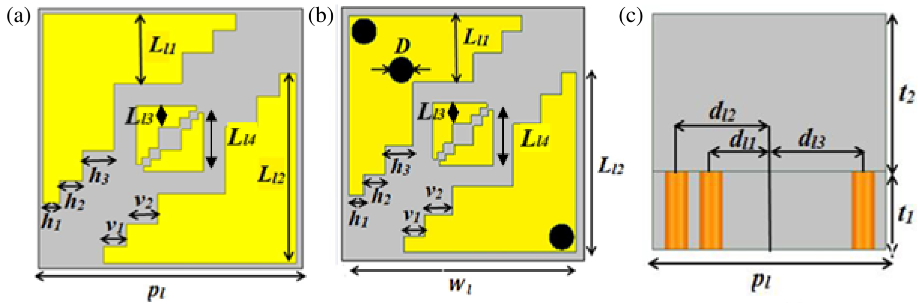

FIGURE 1. Step by step design of the proposed Symmetrically Stepped PCRS. (a) Without vias (Step 1). (b) With vias (Step 2). (c) Side view of entire PCRS unit cell (Step 3).

sharp peaks and creates a continuous resonance band, enhancing metasurface performance across a wide frequency range. Consequently, the metasurface effectively reduces RCS without performance drops. The proposed Symmetrically Stepped PCRS provides absorption as well as polarization conversion mechanisms. Thus, in the reflected wave, both the co- and cross-polarization coefficients must be taken into account at that instant. The ACR and PCR can be expressed as given in Equation (2) and Equation (3) [19].

$$ACR = 1 - |r_{yy}|^2 \tag{2}$$

$$PCR = \frac{|r_{xy}^2|}{(|r_{xy}^2| + |r_{yy}^2|)} \tag{3}$$

Here, r_{yy} and r_{xy} represent the reflection coefficients for the y-polarized incident wave and cross-polarized reflection, respectively. The reflection coefficient r_{xx} corresponds to the reflection for the x-polarized incident wave. Since the design is symmetrical along both the x- and y-directions, it is reasonable to assume that $r_{xx} = r_{yy}$.

The numerical analysis of the proposed Symmetrically Stepped PCRS was conducted using ANSYS HFSS, employing a frequency-domain simulation setup. The simulations utilized Master and Slave boundary conditions along the x- and y-axes to model the periodic structure of the metasurface, effectively simulating an infinite array of unit cells. A Floquet port was used for excitation, allowing for the analysis of both normal and oblique incidence angles. The Floquet port analysis enabled the extraction of reflection coefficients for various polarizations.

In the initial stages of the proposed Symmetrically Stepped PCRS, transmission and reflection analyses were conducted. Without grounded vias and when only Symmetrically Stepped patches are present (Step 1), two narrowband frequencies at 8 GHz and 12.25 GHz were obtained, as depicted in Figure 1(a). Subsequently, in Step 2 (Figure 1(b)), with the introduction of non-symmetric grounded vias in the Symmetrically Stepped unit cell, two narrowband frequencies at 8.25 GHz and 17 GHz were obtained. In Step 3 (Figure 1(c)), the addition of an FR4 superstrate with a thickness of 3.2 mm resulted in four resonances at 5.6 GHz, 9.8 GHz, 11.3 GHz, and 16.7 GHz. This configuration provided multiple polarization bandwidths and significantly improved PCR (Polarization Conversion Ratio) and ACR (Axial Ratio Conversion) metrics. The proposed Symmetrically Stepped PCRS interface was designed to combine the several reflections from the air interface, and transmission and reflection analyses were performed for each step. The results are plotted in Figure 2(a) and Figure 2(b). The analysis clearly indicates that the proposed PCRS with symmetrical steps and a superstrate achieves a PCR and ACR greater than 99% at multiple frequencies, namely 5.6 GHz, 9.8 GHz, 11.3 GHz, and 16.7 GHz.

3. RESULTS AND DISCUSSIONS

3.1. Reflectance Analysis of Proposed Symmetrically Stepped PCRS

Figure 3(a) and Figure 3(b) display the simulated reflection and transmission coefficients of Symmetrically Stepped PCRS. The design almost converts all TE polarization modes into TM polarization modes at multiple resonances. From Figure 3(a), it is clear that the frequency response of the proposed Symmetrically Stepped PCRS is almost stable by increasing the angle of incidence from 0 to 45 degrees. As the incident angle exceeds 45 degrees, the metasurface's ability to manipulate the polarization and match the surface impedance diminishes. Since the design is optimized for normal incidence, larger angles cause performance degradation. When the angle of incidence increases to 60 degrees, the reflectance is not stable, but the bandwidth is maintained in the required frequency range above 3 dB.

As seen in Figure 3(a), the multiple resonance is further reduced from 4 to 3 by increasing the EM wave's angle of incidence. Since the Symmetrically Stepped PCRS is designed to reflect waves, the transmission coefficient should be very low or nearly zero. However, at certain resonant frequencies, a small amount of transmission might occur due to minor imperfections or coupling effects, but it remains minimal, confirming that the metasurface primarily reflects the incident waves.

3.2. Current Distribution Analysis of the Proposed Symmetrically Stepped PCRS

When the electric field is incident in the y direction, the electrons on the surface of the patch are excited and move in the y direction. In general, asymmetric vias affect the surface impedance in the x-direction and are uneven. This imbalance in the surface impedance creates a potential difference along

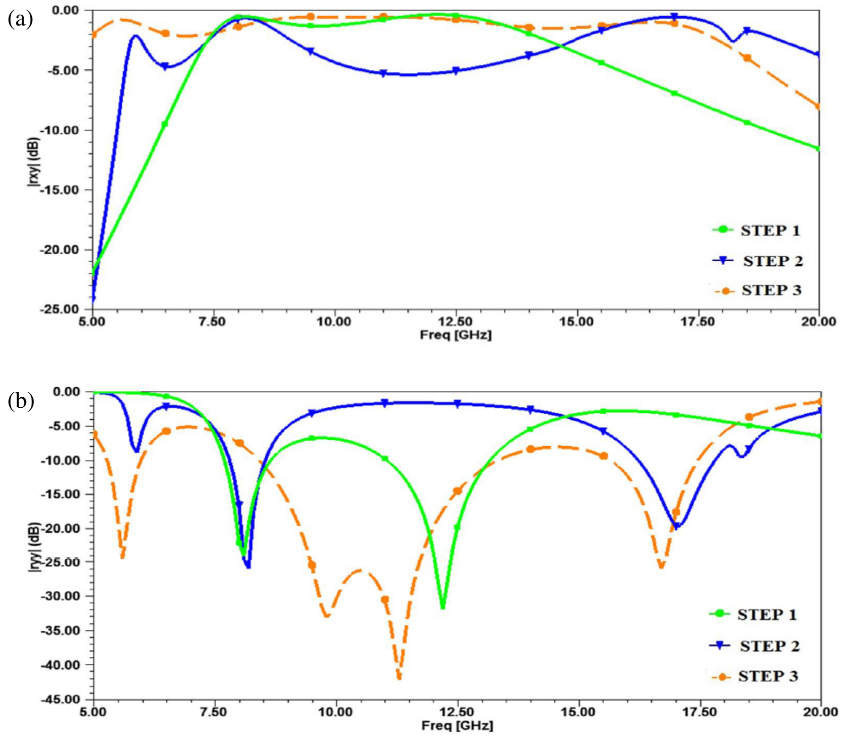

FIGURE 2. Simulated transmission and reflection coefficients of proposed Symmetrically Stepped PCRS for every step: (a) $|r_{xy}|$ and (b) $|r_{yy}|$.

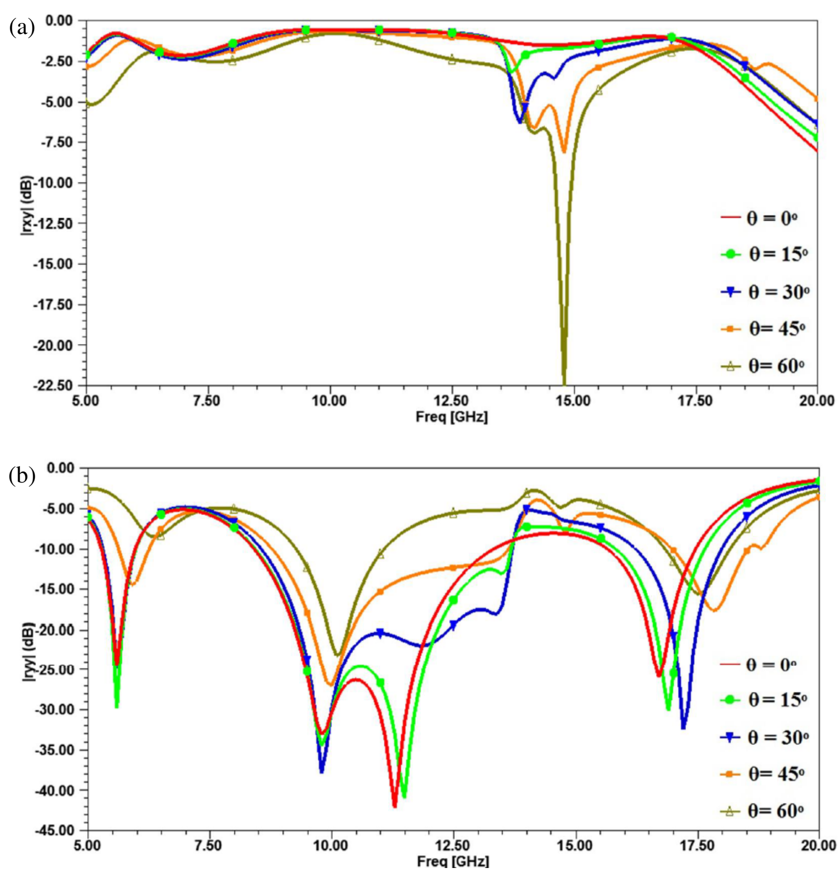

FIGURE 3. Simulated transmission and reflection coefficients at the y-direction of the electromagnetic wave incidence for the proposed Symmetrically Stepped PCRS: (a) $|r_{xy}|$ and (b) $|r_{yy}|$.

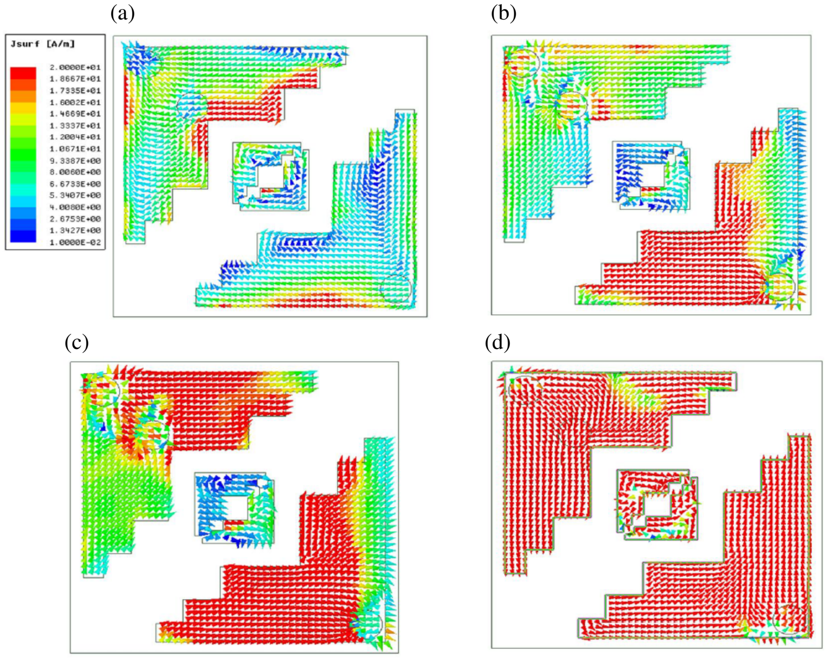

FIGURE 4. Simulated surface current distributions for the proposed unit cell at four different resonant frequencies, (a) 5.6 GHz, (b) 9.8 GHz, (c) 11.3 GHz, (d) 16.7 GHz.

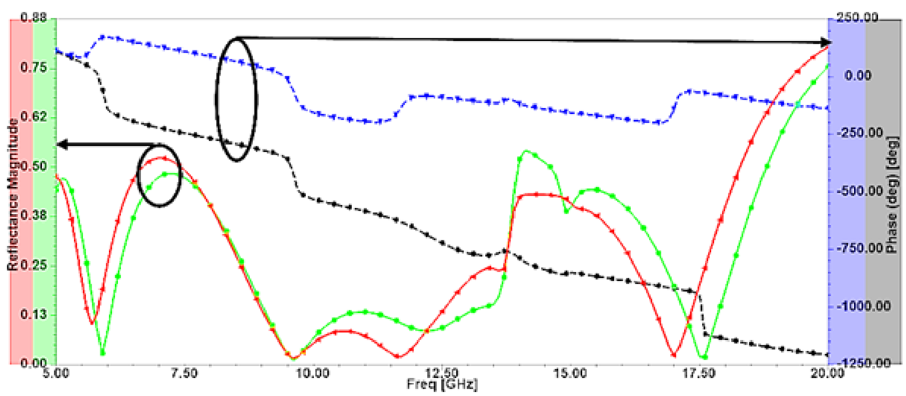

FIGURE 5. Reflection phase (deg) and magnitude of the reflectance for the incident y polarized electromagnetic wave.

the x-direction. However, the proposed Symmetrically Stepped PCRS has asymmetric arrangement of metal vias that disrupts the uniform current flow along the diagonal, leading to a surface impedance imbalance that enhances polarization conversion in a broadband. The incident electric field, as seen in Figure 4, undergoes polarization conversion near the vias, modifying the polarization state along the y-direction within the necessary frequency range [25]. In Figure 5, the symmetrical design of the metasurface ensures that the co-polarization and cross-polarization components of the reflected wave have equal magnitudes, resulting in balanced reflection for both polarizations. A 180-degree phase shift is introduced by strategically positioning the vias and patches to manipulate the surface impedance. This phase difference enables effective polarization conversion and RCS reduction by inducing destructive interference in the co-polarization direction. As a result, the metasurface enhances stealth capabilities while facilitating polarization transformation. Additionally, the PCR plot, as shown in Figure 6, visually demonstrates the change in the polarization state, maintaining a value of approximately 0.99 within the resonance bands.

The proposed Symmetrically Stepped PCRS is analyzed through its equivalent circuit. Capacitances (C_{lk}) are attributed to the gap between adjoining metal patches; strip inductances (L_{lk}) are associated with the metal patches; inductances (L_{lU}) are related to the conducting paths between nearby grounded vias [25]. In Figure 7, the finished equivalent circuit is shown. Equation (4) can be used to determine the impedance of the L-shaped stepped PRRS in the y-direction as,

$$Z = \sum_{k=1}^{k=4} Z_{lk} = \sum_{k=1}^{k=4} \frac{j\omega C_{lk}}{1 - \omega^2 C_{lk}(L_{lk} + L_{lU})} \tag{4}$$

where $k = 1, 2, 3, 4$. Based on the parameters listed in Table 1, the equivalent circuit's capacitances and inductances are calculated. Using formulas in Equations (5), (6), and (7), the

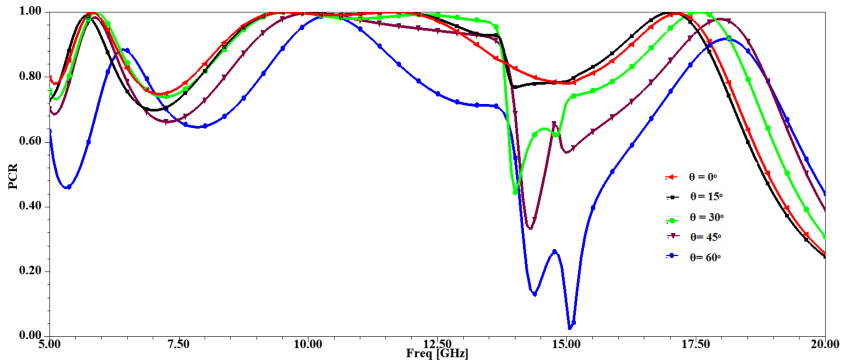

FIGURE 6. PCR plot for the incident y polarized electromagnetic wave.

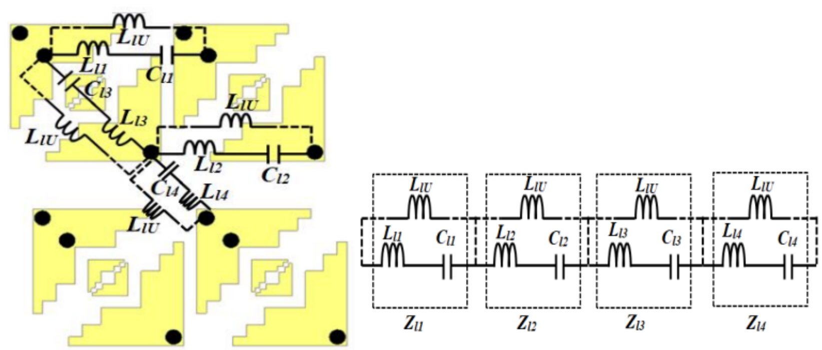

FIGURE 7. Equivalent circuit of proposed Symmetrically Stepped PCRS.

capacitance and inductance values are determined

$$L_{lk} = 2 \times 10^{-7} t_1 \left[\ln\left(\frac{4t_1}{D}\right) + 0.5\left(\frac{D}{t_1}\right) - 0.75 \right] \quad (5)$$

$$L_{lU} = \frac{\mu t_2}{2} \quad (6)$$

$$C_{lk} = \frac{W_l \varepsilon_0 (1+\varepsilon_r)}{\pi} \left(\frac{W_l + g_l}{g_l}\right) \quad (7)$$

where the values of t and g_l vary depending on the conductivity of the metal patch and the distance between metal patches. The lumped circuit parameters are then derived as follows: $L_{lU} = 0.6258\,\text{nH}$, $L_{l1} = 2.964\,\text{nH}$, $C_{l1} = 0.225\,\text{pF}$, $L_{l2} = 0.5464\,\text{nH}$, $C_{l2} = 0.225\,\text{pF}$, $L_{l3} = 0.2558\,\text{nH}$, $C_{l3} = 0.225\,\text{pF}$, $L_{l4} = 0.222\,\text{nH}$, $C_{l4} = 0.225\,\text{pF}$. By substituting these lumped parameter values into the relevant equations, four resonant frequencies are obtained. This circuit model helps us understand the behavior of the metasurface by modeling the interactions among the patches, vias, and the surrounding environment. The resonant frequencies of the structure are determined by the inductances and capacitances in the circuit, which are inclined by the geometry of the patches and the spacing between them. The wideband feature is achieved by overlapping successive resonances through the use of an L-shaped patch, which broadens the resonance response. The resonant frequencies can be calculated using Equation (8).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

where L is the inductance, and C is the capacitance. These parameters are derived based on the geometry of the patch and the placement of the vias, and their values vary for each resonant frequency in the metasurface.

According to Figure 8, the impedance Z exhibits very high values for these four resonant frequencies.

3.3. Multiband RCS Reduction Using Proposed Symmetrically Stepped PCRS

The proposed Symmetrically Stepped PCRS unit cells are utilized to create checkerboard structures aimed at reducing RCS in flat metal structures. The proposed PCRS unit cells are divided into four parts and arranged in an orthogonal pattern to generate the checkerboard structure. Each section consists of a 3×3 arrangement of unit cells, resulting in a total dimension of 30 mm $\times$ 30 mm. Through this orthogonal arrangement, the incident wave's polarization is effectively altered as the reflected electric fields from different parts of the metasurface interact and suppress the original polarization. The varied orientations of the unit cells ensure that the reflected waves from each section of the metasurface are out of phase with each other, which leads to the reduction or conversion of the incident wave's polarization. This spatially distributed phase shift helps in minimizing the reflected polarization, thus achieving the desired effects such as polarization conversion or enhanced RCS reduction. The fabricated prototype of the proposed Symmetrically Stepped PCRS checkerboard structure is presented in Figure 9. The RCS measurements were conducted inside an ane-

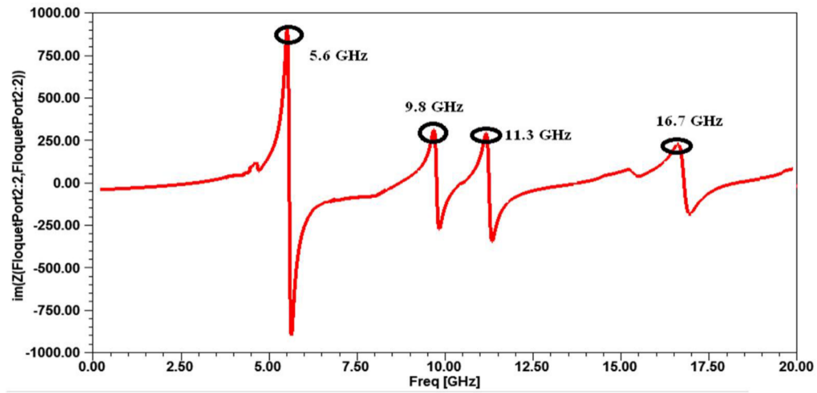

FIGURE 8. Impedance Vs frequency of the proposed Symmetrically Stepped PCRS based on AMC.

(a) (b)

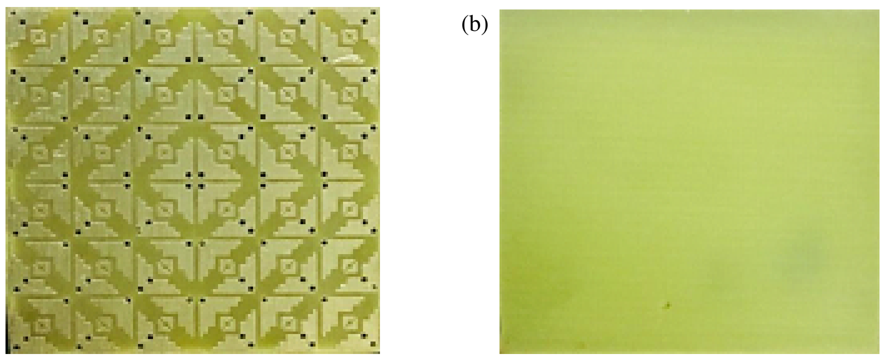

FIGURE 9. (a) Layer 1, (b) Layer 2 — Prototype fabrication of 6 × 6 proposed Symmetrically Stepped PCRS.

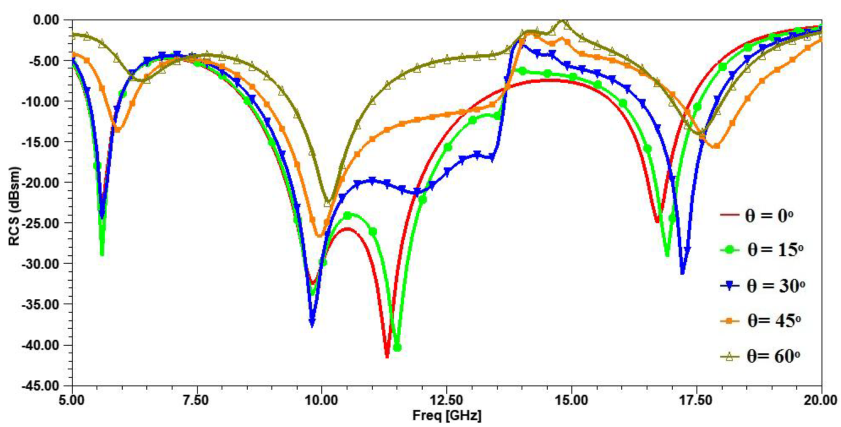

FIGURE 10. RCS simulation results of different incident EM waves.

choic chamber with a frequency range of 700 MHz to 18 GHz and a total chamber dimension of 5.7 m × 3.5 m × 3 m. In the measurement setup, both the transmitting and receiving horns were aligned with the same polarization, pointing towards the planar surface of the radiator [26]. Reflections from the PCRS were captured by the receiving horn to obtain the r_{yy} value. Subsequently, the receiver antenna was rotated to measure the r_{xy} value. These reflection coefficients were recorded using a Vector Network Analyzer (VNA), where both the transmitting and receiving antennas were connected for the measurements.

The PCR value is used to assess the RCS reduction achieved by the proposed Symmetrically Stepped PCRS, which can be determined using Equation (9).

$$RCS\ reduction\,(\text{dB}) = 10\left[\frac{4\pi R^2\left(\frac{|E_{ry}|}{|E_{iy}|}\right)^2}{4\pi R^2\,(1)^2}\right]$$

$$= r_{yy}(\text{dB}) = 10\,[1 - PCR] \tag{9}$$

TABLE 2. Simulated results of the proposed Symmetrically Stepped PCRS.

	Frequency of operation (GHz)	Bandwidth inference	RCS reduction (dB)	PCR (%)	ACR (%)	Angular stability (degree)
Symmetrically Stepped PCRS	5.6 9.8 11.3 16.7	Wideband from 8.41 GHz −13.35 GHz and 15.63 GHz −17.46 GHz	24 33 42 24	99.6 99.9 99.9 99.6	99.9 99.8 99.9 99.8	Up to 60°

TABLE 3. Comparison of the Symmetrically Stepped PCRS with the existing reflection surface.

References	Frequency of operation (GHz)	RCS reduction (dB)	PCR (%)	ACR (%)	Angular stability (degree)
[27]	7.2 GHz–17.2 GHz (Peak at 7.6 GHz and 15 GHz)	Maximum of 30 dB at 7.6 GHz and 15 GHz	99.9	-	Up to 60 degrees
[28]	7.5 GHz–22.5 GHz (Peak at 7.8 GHz)	Maximum of 17 dB at 7.8 GHz	98	-	Up to 30 degrees
[29]	9.5 GHz–13.9 GHz and 15.2 GHz–20.4 GHz	maximum of 29 dB at 18 GHz	99.8	-	Up to 45 degrees
[30]	9 GHz to 16.8 GHz	>10 dB	>90	-	-
This work	8.41 GHz–13.35 GHz and 15.63 GHz–17.46 GHz	maximum of 42 dB at 11.3 GHz	99.9	99.9	Up to 60 degrees

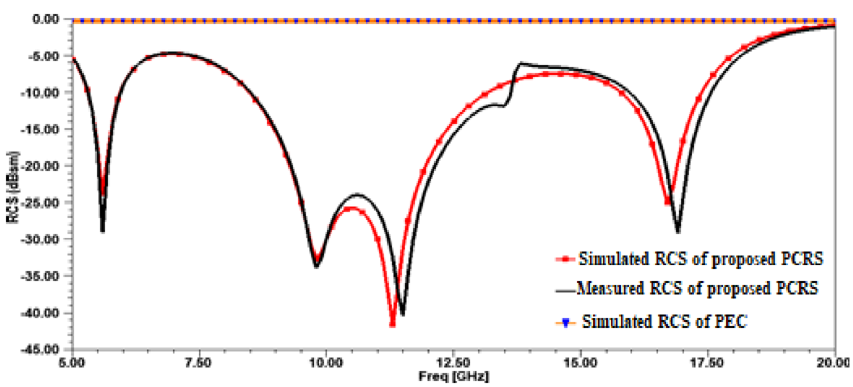

FIGURE 11. Simulated and measured RCSs of 0° incident EM wave.

Table 2 demonstrates that at all four resonance frequencies, RCS reduction exceeding 24 dB is accomplished, with PCR and ACR both exceeding 99%. The findings indicate that the RCS reduction remains consistently effective up to a 60° angle, as depicted in Figure 10. Figure 11 illustrates the comparison between simulated and measured RCSs of the Symmetrically Stepped PCRS structure under a y-polarized incident electromagnetic wave. Table 3 shows the comparison of the Symmetrically Stepped PCRS with the existing reflection surfaces. The outputs reveal that the existing works provide better RCS reduction either in narrow bandwidth or only up to 45 degree angular stability, whereas the proposed work provides better RCS reduction at a wider bandwidth without deteriorating the angular stability up to 60 degrees.

4. CONCLUSION

A compact multiband Symmetrically Stepped PCRS for achieving high PCR, high ACR, and reduced RCS is proposed. The whole dimensions of PCRS unit cell are related to its minimum operating wavelength and are only 5 mm × 5 mm × 4.8 mm. RCS reductions of 24 dB, 33 dB, 42 dB, and 24 dB are obtained at multiple frequencies namely 5.6 GHz, 9.8 GHz, 11.3 GHz, and 16.7 GHz, respectively. A maximum PCR of 99.9% and a maximum ACR of 99.9% are achieved with an angular stability up to 60 degrees in the respective multiple frequency bands. In addition, the proposed reflective PCRS unit cells arranged in an orthogonal manner reduces RCS by providing reflection phase cancellation. The fabricated prototype of the proposed PCRS checkerboard structure confirms that the construction can achieve RCS reduction with high PCR and ACR at multiple frequency bands required for stealth and detection technologies.