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Low RCS Microstrip Patch Array with Hybrid High Impedance Surface Based Ground Plane

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Abstract—For a radiating structure such as dipole/patch array mounted on an aerospace platform, the radiation mode radar cross section (RCS) plays a significant role compared to the structural mode RCS. Thus the estimation and control of array RCS without degrading its radiating characteristics poses a challenge for an antenna engineer. In this paper, a novel design of a low profile 4-element patch array with hybrid HIS-based ground plane is presented to demonstrate both in-band and out-of-band structural RCS reductions. A significant broadband reduction in structural RCS has been achieved from 1 GHz to 80 GHz. The radiation mode RCS of the patch array is computed and controlled through optimized design parameters without degrading the radiation characteristics. The computed array RCS shows that even radiation mode RCS can be reduced except in operating frequency range.

1. INTRODUCTION

Stealth or low observable target requires the reduction in electromagnetic signatures of combat aerospace platforms, warships, and terrain vehicles in hostile environment. The reduction of radar cross section (RCS) essentially diminishes the detectability of the target. RCS is mainly contributed by the diffracted fields from the edges and corners of a structure, the surface waves travelling along the surface of the structure, waves traversing inside a cavity or partially closed structure and reflections from surfaces. In aerospace vehicles, the major contributors to the RCS are the radiating antennas mounted over such platforms. Moreover, the scattered energy becomes maximum when the antenna is in radiating mode [1]. There are instances where the RCS due to radiating antennas dominates over the RCS of platform. Thus it is important to focus on reducing the radar signatures from these antennas/array without any disturbance in their radiation characteristics.

One of the techniques to reduce the scattered energy from the antenna structure is by modifying its ground plane. High impedance surface (HIS)-based ground plane can suppress these surface waves and thus reduces the scattered energy [2]. Periodic structures comprising frequency selective surface (FSS) incorporated in the ground plane of antenna can facilitate the RCS reduction [3–5]. Specifically, inclusion of band-pass FSS in the ground plane results in a narrow out-of-band RCS reduction [6] whereas band-reject FSS elements (e.g., octagonal loop resistive FSS), incorporated in the ground plane provides wideband RCS reduction [7, 8].

Paquay et al. have demonstrated that a chessboard configuration of artificial magnetic conductor (AMC) and perfect electric conductor (PEC) cells in antenna provide narrow-band RCS reduction, based on the principle of phase cancellation [9]. Further to overcome the narrowband performance due to a single AMC element, Iriarte et al. [10] proposed a chessboard configuration consisting of two AMC elements, hereby broadening RCS reduction, but only in case of structural mode RCS.

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One should keep in mind that for a radiating antenna array, the radiation mode RCS is many folds higher than its structural mode RCS [11]. In this paper, the proposed design shows reduction in not only structural mode RCS but also in radiation mode RCS, compared with the patch array with conventional PEC ground plane. The radiation mode RCS of the designed patch array has been computed using derived analytical closed-form expressions, taking into account all the reflections and transmissions within the patch array and its feed network.

This paper comprises five sections. Section 1 gives a brief introduction about the importance of total array RCS of an antenna system in stealth applications. Section 2 presents the design and performance of the HIS unit cell used as a chessboard configuration in the ground plane. The radiation and scattering performance of the patch array with conventional metallic ground plane and HIS-based hybrid ground plane are discussed in Section 3. Further, the simulated and measured results of the fabricated reference antenna and the proposed HIS-based patch array are presented in Section 4. Section 5 concludes the work done.

2. HYBRID HIS BASED REDUCED GROUND PLANE

If a patch array is completely backed by the metallic ground plane, the incident energy may get significantly reflected back to the radar, thereby contributing to the antenna RCS. The fringing fields from the patch get coupled to the ground plane. If a full metallic ground plane (conventional patch array) is used, then the coupled fields propagate along the surface and get scattered in free space once they reach the edge of the antenna structure and hence contributing to RCS. On the other hand, the proposed hybrid ground plane does not provide a continuous path for the propagation of the surface waves and hence helps in the mitigation of the RCS contribution. Here, a reduced ground plane (RGP) technique has been implemented to overcome this issue. Further, in order to suppress the surface waves, HIS layer is incorporated along with the RGP as depicted in Fig. 1.

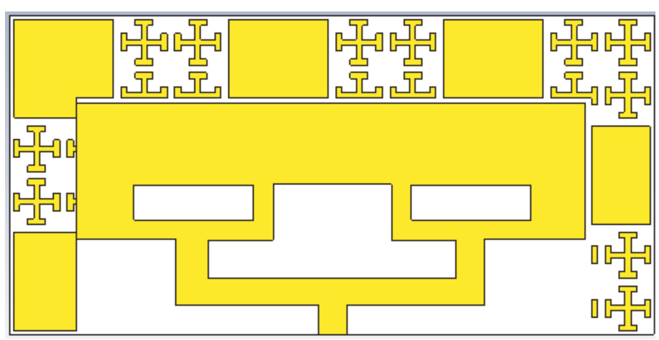


Figure 1. Hybrid ground plane of the proposed antenna.

The HIS consists of a combination of Jerusalem cross (JC) based AMC cells and metallic square patch elements arranged in a chessboard configuration. Fig. 2(a) shows the schematic of the proposed HIS unit cell. A single JC element on a dielectric substrate is shown in Fig. 2(b). The lengths of the inductive and capacitive parts are 4.8 mm and 2.5 mm, respectively. The widths of both the inductive and capacitive parts are 0.8 mm. The length of each square patch is 13.9 mm.

The lossy FR-4 substrate used has a thickness of 1.588 mm with a relative permittivity and loss tangent of 4.4 and 0.009, respectively. Copper is taken as the material for all metallic parts. The JC element used in the design has maximum reflection with zero crossing reflection phase near resonating frequency in the X-band (in-band) and maximum transmission outside the X-band exhibiting band-reject characteristics. In order to reduce the reflection in the in-band frequency range, a square patch is kept in adjacent to the JC element which would reflect the incident energy with 180° phase shift. Hence, destructive interference is observed in the whole configuration and hence RCS reduction. In order to demonstrate the efficiency of such a HIS-based RGP, Fig. 3 shows the comparison of magnitude and phase of reflection coefficient of the proposed and conventional patch arrays. The simulation was

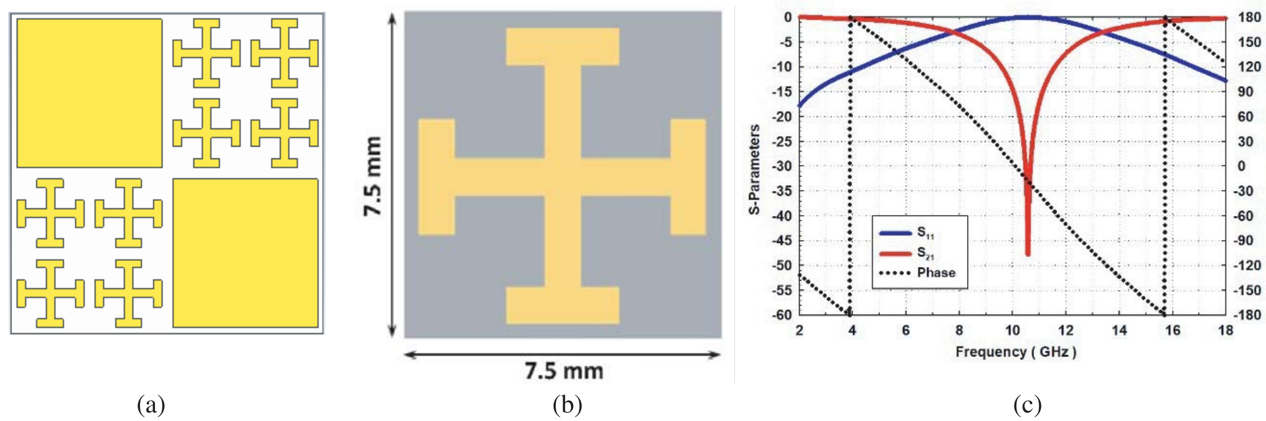


Figure 2. (a) HIS unit cell. (b) Schematic of Jerusalem Cross (JC) element. (c) S parameters and reflection phase of JC element.

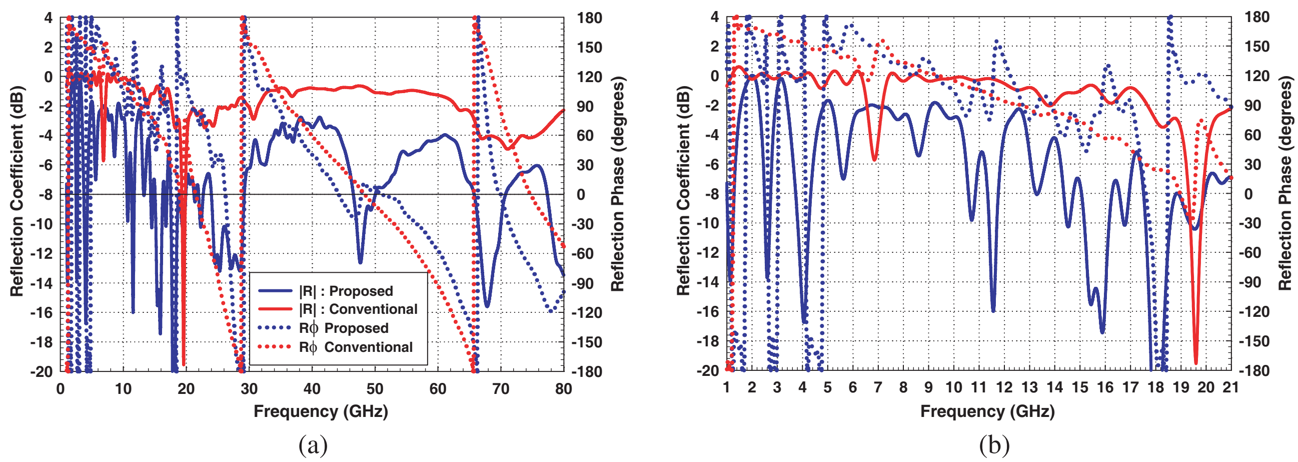


Figure 3. (a) Comparison of reflection phase and magnitude of conventional and proposed patch array. (b) Zoomed plot for 1 GHz to 21 GHz.

performed in time domain in CST. The performance of the ground plane was investigated by exciting the top and bottom of the structure using waveguide port, and the reflection parameters were computed. The boundary conditions have been applied on the patch array, placed between two waveguide ports. It can be observed from Fig. 3(a) that the reflected power in the case of patch array with full metallic ground plane is well above −10 dB in the entire frequency range. However, the extent of power reflected from the patch array with hybrid HIS based RGP is comparatively less. Fig. 3(b) shows the zoomed version of the plot for frequency range of 1 GHz to 21 GHz.

3. LOW RCS MICROSTRIP PATCH ARRAY

In the proposed design of a corporate-fed 4-element linear patch array, conventional metallic ground plane is replaced by a hybrid HIS-based reduced ground plane. The radiation and scattering performance of the proposed patch array are compared with that of a conventional patch array. Fig. 4 shows the fabricated 4-element patch array with a hybrid HIS-based RGP. The substrate dimensions of the antenna are 45 mm × 90 mm. The patch dimensions are 6.5 mm × 9.2 mm. The inter-element spacing between the patch elements is greater than half-wavelength (0.643λ), in order to avoid mutual coupling. The metallic ground plane is designed as the outline of the area occupied by the patch array on the top

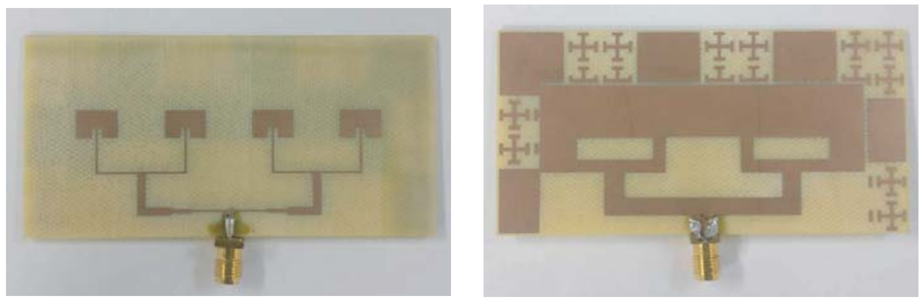
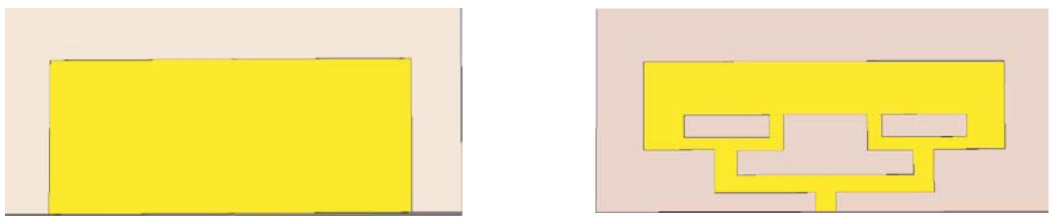


Figure 4. Top and bottom view of the fabricated 4-element linear patch array with hybrid HIS-based reduced ground plane.



(a) (b)

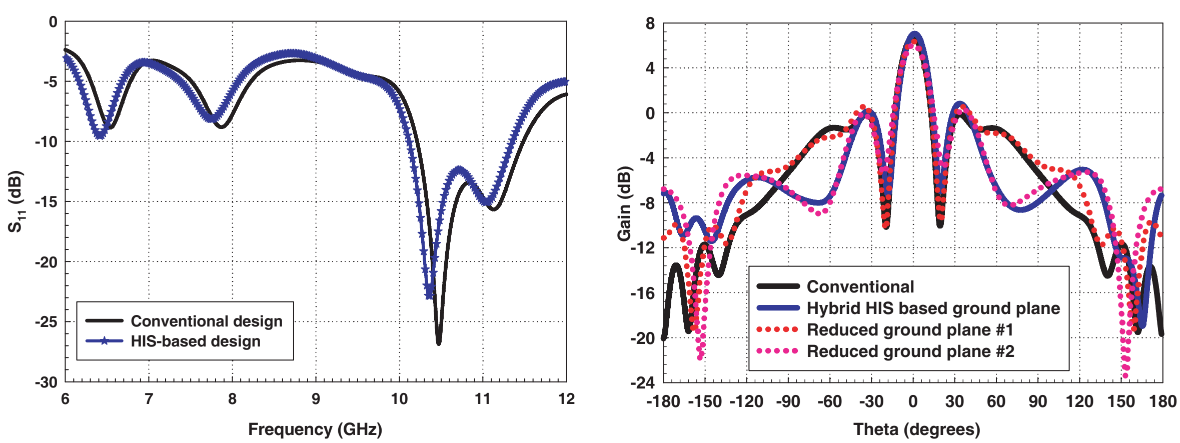
Figure 5. (a) Reduced ground plane #1. (b) Reduced ground plane #2.

surface. The rest of the area consists of chessboard arrangement of JC-elements and square metallic patches.

Apart from the proposed antenna array, the same 4-element linear patch array is also investigated with two different RGP (without HIS) configurations, as depicted in Fig. 5. In patch arrays with RGP the extent of backscattering will be less than the conventional and proposed antennas. However, it can be noted that the radiation performance of the patch array with RGP has been degraded.

The reflection coefficient of a 4-element linear patch array with conventional ground plane achieved is -27.14 dB at 10.46 GHz with % bandwidth of 12.3 while for hybrid HIS-based ground plane, it has shifted marginally towards the lower frequency to 10.36 GHz and its value has increased to -22.97 dB with reduced % bandwidth of 12.13 (Fig. 6(a)).

Figure 6(b) shows that the gains of the patch arrays (conventional and proposed patch arrays) are

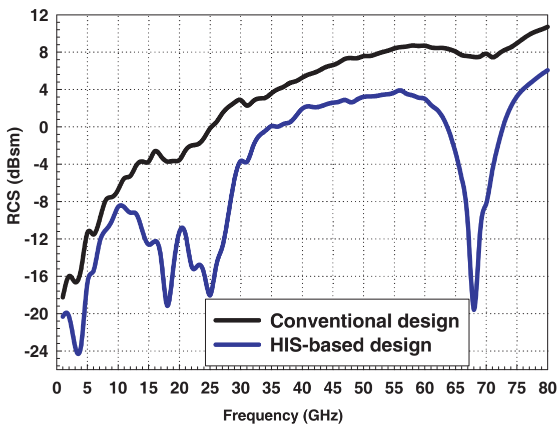


(a) (b)

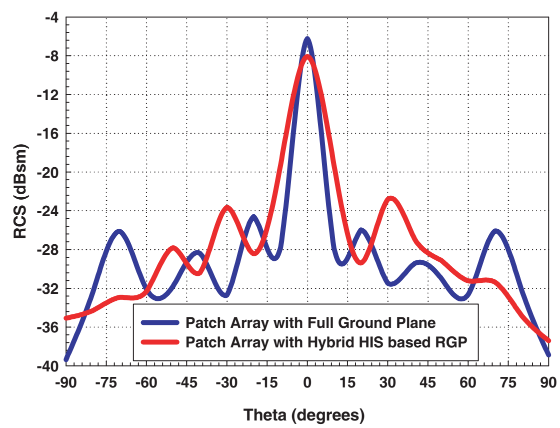
Figure 6. Radiation characteristics of a 4-element linear patch array with hybrid HIS-based ground plane. (a) Reflection coefficient. (b) Gain.

same, i.e., 7.3 dB at 10.36 GHz. However, for the patch arrays with RGP #1 and RGP #2, the gains are 6.35 dB and 6.02 dB at their resonant frequencies of 10.51 GHz and 10.36 GHz, respectively. This establishes the fact that the proposed patch array design with HIS-based RGP does not degrade the radiation performance. Only RGP (Fig. 5) in array design might be useful for RCS reduction, but it results in degradation in the antenna gain.

Figure 7(a) presents the comparison of specular structural RCS of the conventional and proposed antenna w.r.t. frequency. It is apparent that RCS reduction has been achieved for the entire frequency range of 1 GHz to 80 GHz, with minimum and maximum reductions of 1.82 dBsm and 27.07 dBsm at 10 GHz and 68 GHz, respectively. Moreover, it is already shown in Fig. 3 that the reflection magnitude in the case of the proposed antenna is less than the conventional antenna over the entire frequency range. Further, it can be observed from Fig. 7(a) that RCS reduction of at least 15 dBsm has been obtained at several frequency points. Two such local minima points in RCS plot are at 18 GHz and 25 GHz with RCS reduction of 15.43 dBsm and 17.9 dBsm, respectively. This can be explained from Fig. 3 showing the magnitude and phase of reflection coefficient of the proposed array. It can be observed that apart from the reduction in the reflection magnitude at these frequency points, considerable difference in the reflection phase exists between the proposed and conventional patch arrays. The trend of the specular structural RCS of the patch array with hybrid HIS based RGP follows the conventional patch array in the region where the reflection phases of the two arrays is about the same. This trend can be observed in the frequency range 30 GHz to 65 GHz and 69 GHz to 80 GHz. Although minima occur in the reflection magnitude at 47 GHz (Fig. 3), no minima in the specular structural RCS are obtained (Fig. 7(a)). This is due to comparable values of the reflection phase of the two patch arrays.



(a)



(b)

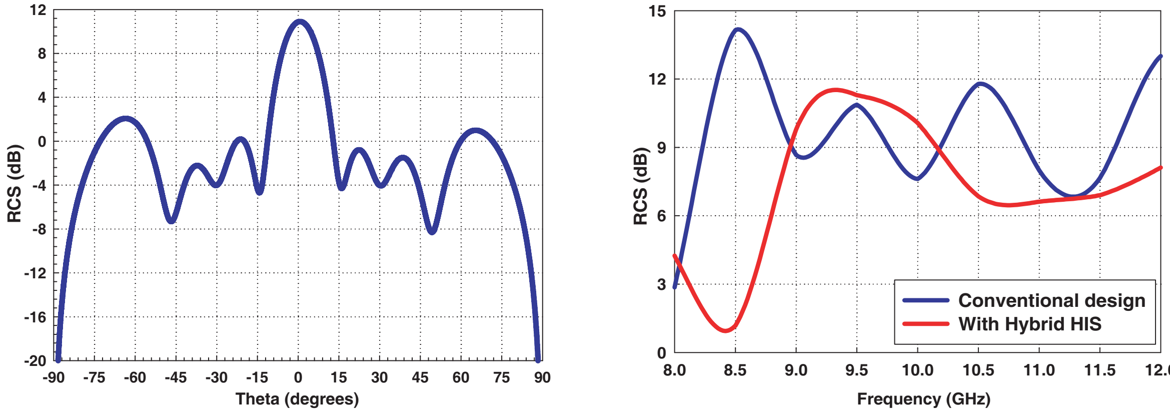
Figure 7. Comparison of structural RCS of patch array with different ground planes. (a) Specular structural RCS w.r.t. frequency. (b) RCS pattern at 10.36 GHz.

The RCS of conventional patch array is maximum (−6.22 dB) along the specular direction. It can be observed that peak RCS value of proposed array with HIS-based ground plane is reduced by 1.85 dBsm compared with the conventional array (Fig. 7(b)), even at the resonant frequency of 10.36 GHz.

The radiation mode RCS of any antenna system depends on the extent of impedance mismatches that an impinging EM wave encounters while traveling through the system. The radiation mode RCS can be controlled by optimizing array design parameters along with the dimensions/type of antenna element, geometric configuration, and many more. Here analytical closed form expressions have been derived for array RCS, taking into account the reflections and transmissions at each impedance mismatch within the patch array and the corporate feed network [12]. In general, the total array RCS is given by [11]

$$\sigma(\theta,\phi) = \frac{4\pi}{\lambda^2}\left(|\sigma_r(\theta,\phi)|^2 + |\sigma_p(\theta,\phi)|^2 + |\sigma_c(\theta,\phi)|^2 + |\sigma_s(\theta,\phi)|^2 + |\sigma_d(\theta,\phi)|^2\right) \quad (1)$$

where σ_r, σ_p, σ_c, σ_s, and σ_d correspond to RCS due to reflections from patch antennas, phase shifters,



(a) (b)

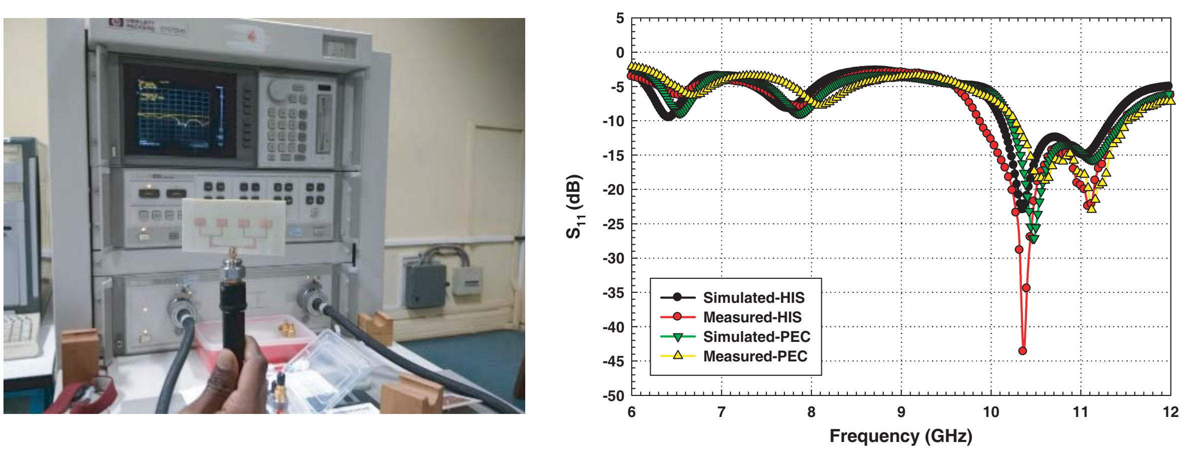
Figure 8. Radiation mode RCS of patch array with modified ground plane. (a) RCS pattern at 10.36 GHz. (b) RCS w.r.t. frequency.

coupler inputs, sum, and difference ports of couplers, and (θ, ϕ) represents the direction of incident wave. One has to trace the path of the impinging wave as it travels through the array structure, in order to determine reflection/transmission coefficients at each interface to arrive at total array RCS [13]. Fig. 8(a) shows the radiation mode RCS pattern of the patch array with modified HIS-based ground plane. The radiation mode RCS in specular direction is 10.88 dB, which is many folds higher than the structural RCS of the patch array (−8.3 dB, Fig. 7(b)). The specular radiation mode RCSs w.r.t. frequency (X-band) of both the patch arrays with different ground planes are shown in Fig. 8(b). It can be observed that out-of-band radiation mode RCS reduction has been achieved with the proposed array design.

4. MEASUREMENTS: FABRICATED PATCH ARRAYS

In order to validate the simulated radiation and scattering performance of the proposed patch array with hybrid HIS-based ground plane, the measurements were carried out on the fabricated reference and proposed patch arrays. The patch arrays with conventional PEC ground plane (reference antenna) and hybrid HIS-based ground plane (proposed antenna) are fabricated using a prototyping machine.

The experimental setup for reflection coefficient and VSWR measurements is shown in Fig. 9(a).



(a) (b)

Figure 9. (a) Experimental setup. (b) Comparison of measured and simulated reflection coefficient of patch array with conventional PEC ground plane and hybrid HIS-based ground plane.

Fig. 9(b) presents the comparison of measured and simulated reflection coefficients of the patch array with conventional and hybrid HIS-based ground planes. It can be observed that the reflection coefficient of the patch array at 10.60 GHz is −18.72 dB and VSWR of 1.27 for conventional ground plane. On the other hand, for the patch array with hybrid HIS-based ground plane, the reflection coefficient is −43.63 dB at 10.36 GHz with VSWR of 1.02.

The radiation pattern has been measured at 10.36 GHz. Fig. 10 presents the comparison of measured and simulated normalized radiation patterns of 4-element patch arrays with conventional metallic ground plane and hybrid HIS-based ground plane. It is apparent that the simulated and measured results are in good agreement.

Figure 11(a) shows the simulated and measured specular structural RCS reductions of patch arrays with conventional ground plane and hybrid HIS-based ground plane. It can be observed that by replacing conventional ground plane with hybrid HIS-based ground plane, a wideband reduction in structural array RCS has been achieved from 2 GHz to 18 GHz (Fig. 11(a)). It can be noted that the trend of measured specular RCS reduction is similar to the simulated specular RCS reduction. Further, a significant reduction in measured specular RCS is observed in in-band frequency range with a maximum reduction of 9.02 dB at 10 GHz, as compared to 2 dB reduction (simulated). Similarly, the reduction

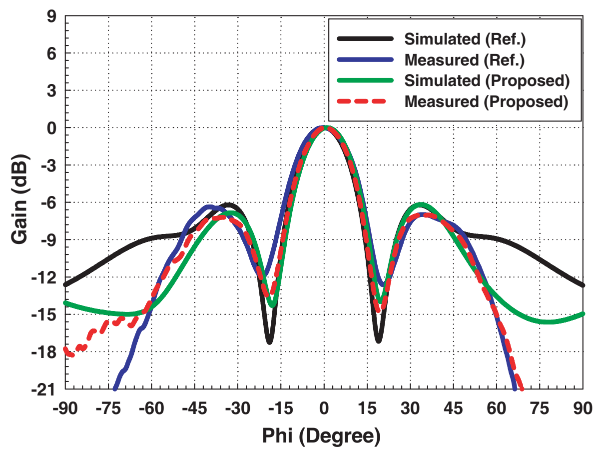


Figure 10. Comparison of measured and simulated normalized radiation pattern of patch array with conventional metallic ground plane and hybrid HIS-based ground plane.

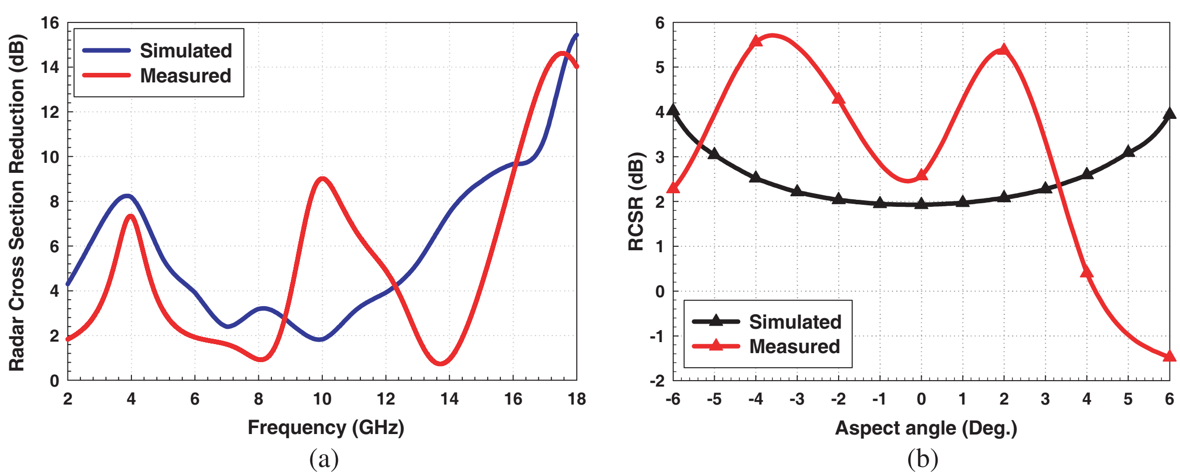


Figure 11. Comparison of measured and simulated radar cross section reduction of patch array with modified ground plane. (a) Specular RCSR w.r.t. frequency. (b) RCSR w.r.t. aspect angle at 10.36 GHz.

in monostatic RCS at the resonant frequency (10.36 GHz) for aspect angle ranging from -6° to $+6^\circ$ is obtained (Fig. 11(b)). It can be observed that the RCS reduction in the case of measured results is slightly higher than the simulated one. This mismatch between measured and simulated results may be due to miniaturized dimensions of the patch arrays and inaccuracies in the measurement setup. The patch array dimension is quite small (4.5 cm $\times$ 9 cm) compared to the measurement facility. Firstly, for such a small structure, the edges will scatter more than the antenna surface for slight variation in the azimuth plane. The non-specular scattering from the edges of the antenna will be absorbed in the anechoic chamber and thus more RCSR while the specular scattering due to edges will result in lower RCSR. Secondly, in simulation analysis, it is the plane wave that moves along the azimuth plane, and the test antenna is stationary. Instead, in measurement setup the test antenna is swept, hence edge effects will come into consideration. However, for a large phased array like 32×32, where the designed patch array will act as a sub-array, the edge effects will be less significant than the antenna structure.

Table 1 presents the comparison of the proposed design with other reported ones. It can be noted that unlike [14–17], the proposed design shows both in-band and out-of-band RCS reductions without any degradation in the antenna gain. As per the author's best knowledge, no work has shown such a broadband simulated RCS reduction for 1 GHz–80 GHz and beyond. However, due to the constraint of availability of the measurement facility, the proposed design has been measured from 2 GHz to 18 GHz (Fig. 11).

Table 1. Performance comparison of the proposed design with other reported.

Reference	**Array Size**	**Feeding Technique**	**RCS Reduction Technique**	**RCS Performance**
[14]	2×2	Coaxial	EBG	In-band: 8.2 dBsm with 2 dB gain reduction Out-of-band: 14.4 dBsm
[15]	2×2	Coaxial	Hexagonal FSS	In-band: Nil. Out-of-band 16 dB
[16]	3×3	Coaxial	Microstrip Resonators	In-band: 17 dB Out-of-band: Nil.
[17]	Single	Coaxial	Perfect Absorber Metamaterial	In-band: 15 dB Out-of-band: Nil.
Proposed	1×4	Corporate	Hybrid Ground Plane	In-band: 9.02 dB Out-of-band: $\sim$15 dB *without any gain reduction

5. CONCLUSION

Patch arrays with full ground plane support the surface waves, which emit into free space as spurious radiations. Further, these finite metallic ground planes can backscatter the incident energy to the radar source. In this regard, a high impedance surface along with reduced ground plane has been incorporated together to overcome the limitations of surface waves and backscattering. Patch array with reduced ground plane may have reduced RCS but at the cost of degraded radiation performance. On the other hand, with a hybrid ground plane comprising a chessboard configuration of AMC-square patch, wide band RCS reduction can be achieved without any degradation in reflection coefficient, VSWR, and antenna gain. A novel design of patch array with hybrid HIS-based ground plane is presented. The HIS layer consisting of JC-elements and metallic square patches is integrated along with the reduced ground plane. Both in-band and out-of-band reductions in structural RCS have been achieved maintaining the radiation characteristics. For a radiating antenna placed on any platform, the radiation mode

RCS dominates the structural mode RCS. There is always a trade-off between antenna gain and array RCS. However, specular RCS reduction in the out-of-band frequency range with an optimum RCS in the in-band frequency range can be obtained by the proper selection of design parameters such as characteristic/load impedances and antenna element dimensions. These facts have been corroborated by the computed results of radiation mode RCS of the patch array with HIS-based ground plane.

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