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Low Observable Conformal Patch Array with Hybrid HIS-Based Ground Plane

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Abstract—Conformal low profile antenna array has been widely used towards reduced radar cross section and good radiation characteristics. Being conformal, it has a number of advantages over planar antenna structure. This paper presents the radiation and scattering characteristics of a planar and conformal patch array with conventional and hybrid HIS-based ground plane on a low loss dielectric substrate. The use of a hybrid HIS layer instead of conventional metallic ground plane contributes to achieving wideband RCS reduction over 8 GHz–50 GHz, without degrading the radiation performance in terms of antenna gain, return loss, and VSWR. The measurement results of the fabricated antennas are found in good agreement with the simulated ones. The radiation mode RCS of the conformal patch array has been analytically estimated and shown to be controlled in the operating frequency range. Such a low profile low RCS antenna array can be used as a subarray of phased arrays in fire control radars.

1. INTRODUCTION

In low observable technology, the low radar cross section (RCS) of a structure is possible only when the antenna/sensors mounted over it do not scatter extensively. This can be achieved by an efficient design of antenna and its feed. Moreover, the antenna conformal to the platform facilitates controlling the overall RCS. The microstrip patch array being a low profile antenna array can be conformed to any surface. The curved platform however modifies the radiation and scattering behaviour of the mounted antenna array [1]. Further, a planar patch array mounted over a flat surface, if not perfectly matched, gives rise to large reradiated reflected (back-scattered) field at normal incidence. The reason is that each section of the array radiates back in phase and contributes to array RCS. The same is not true in the case of a non-planar patch array, where the surface normal of each antenna element points in different directions based on the radius of curvature of the platform. Thus, non-planar antennas placed on curved surfaces reradiate incident energy not only in the specular direction but also in other directions. This, however, complicates the RCS estimation of the antenna array.

The conformal patch array has several advantages compared to a planar patch array. When the antenna is mounted/integrated on a curved surface, it reduces the edge effect [2]. A patch array placed on a cylindrical or spherical surface will have an omnidirectional radiation pattern. Moreover, the error caused by the installation of radomes covered planar array can be reduced using conformal patch array [3]. Several techniques have been attempted to reduce the RCS of a conformal patch array. In order to reduce the overall RCS of a patch array, the reflections from the patch surface as well as the feed network have to be taken into consideration [4]. A combination of impedance loaded and slotted ground plane techniques has been employed towards achieving both in-band and out-of-band RCS reductions [5]. Further, it is shown that aperture coupling contributes to reducing the scattering

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from feed network. The frequency selective surface (FSS) along with an RF absorber layer can be used as the ground plane of a patch antenna [6]. This configuration acts as an absorbing screen at higher frequencies, while it reflects maximum at desired frequencies, hence facilitates wideband RCS reduction in array RCS.

The property of high impedance surfaces (HIS) to control the scattering of EM wave has been widely used in attaining reduction in radar cross section (RCS) of microstrip patch arrays. It is well known that incorporating a hybrid HIS-based ground plane in a 4-element planar microstrip patch array reduces the structural RCS over wide frequency range [7–11]. Further, low profile patch array over the curved surface contributes in reducing the antenna scattering [5]. It is well known that conformal patch arrays are preferred choice owing to their conformal geometry reducing the protruding structures from the platform. Furthermore, as compared to a planar patch array, a conformal patch array scatters the incident EM wave in the directions other than specular one, thereby reducing the array RCS. In addition, the inclusion of HIS-based hybrid ground plane further reduces the array RCS.

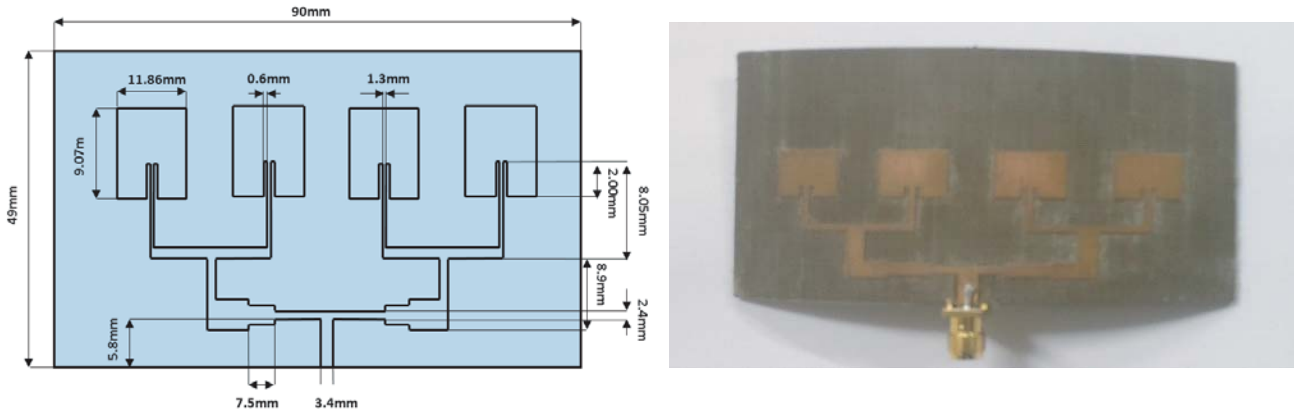
The EM design and analysis of a linear patch array with hybrid HIS-based ground plane [12, 13] demonstrate that both the structural and antenna/radiation mode radar cross sections (RCSs) can be controlled. It is shown that the RCS of a patch array is significantly reduced when the conventional ground plane is replaced with HIS-based hybrid ground plane for both in-band and out-of-band frequencies. Apart from the structural RCS, the radiation mode RCS is also a significant parameter to be considered in the scattering analysis of an antenna array. An analytical technique to estimate the radiation mode RCS of a microstrip patch array with nonuniform ground plane configuration is presented in [14]. In the case of a conformal antenna array, the radiation mode RCS of conformal patch arrays requires Euler transformation of coordinates from local to global coordinate system [4].

For an antenna mounted over any platform, it is expected that its radiation performance should not be degraded while having reduced RCS. As far as a microstrip patch array is concerned, its radiation characteristics depend on the substrate material as well. Low loss dielectric materials can be used as the substrate of patch arrays, since they are capable of providing larger gain efficiency. Further, thick substrates with low dielectric constant can provide larger bandwidth [5].

This paper pertains to the EM design and analysis of a microstrip patch array with hybrid HIS-based ground plane on a low loss RT Duroid substrate. The analysis is performed for both planar and conformal patch arrays. The simulated results are compared with the measurements performed on fabricated antennas. The RCS reduction feature of HIS and conformal platform are combined to design a low observable patch array. A combination of Jerusalem Cross (JC) and square patch elements arranged in a chessboard configuration has been used to modify the ground plane. The array performance in terms of their radiation and scattering characteristics has been presented with no substantial degradation in radiation characteristics. The motivation behind the work being carried out is to achieve a low RCS antenna array with desirable radiation performance. The radiation mode RCS of the patch array is computed using the analytical approach [14] accounting for the reflections and transmissions and an impinging EM wave encounters at each impedance mismatch within the antenna array.

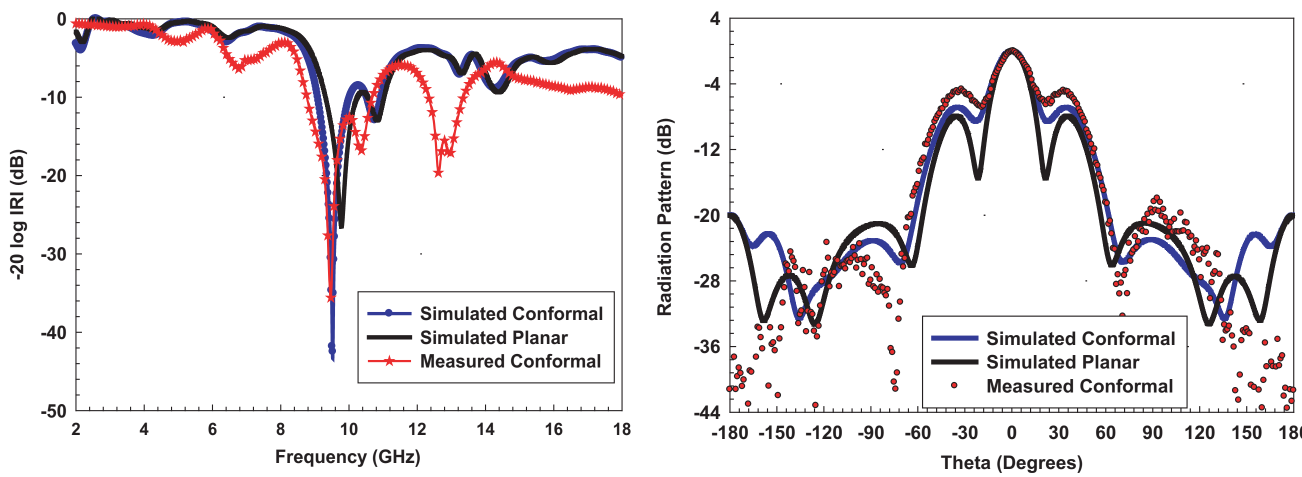
2. MICROSTRIP PATCH ARRAY WITH CONVENTIONAL GROUND PLANE

This section deals with the EM design and analysis of a microstrip patch array with conventional metallic ground plane. The 4-element linear patch array is designed to operate in the X-band. A low-loss dielectric, Rogers RT Duroid (5880), is used as the substrate material. The substrate has a thickness of 1.58 mm with relative permittivity $\varepsilon_r = 2.2$ and loss tangent $\tan\delta = 0.0009$. The metallic portion is made of copper material. The patch element has a dimension of $9.07 \times 11.86\,\text{mm}^2$ with a thickness of 18 microns. An inter-element spacing of 0.643λ is considered between patch elements to avoid mutual coupling effect. The patch array has a dimension of $49 \times 90\,\text{mm}^2$. The ground plane is a metallic copper layer of thickness of 18 microns. The radiation and scattering characteristics of the patch array have been analyzed using a full-wave simulation software (CST Microwave Studio). Fig. 1 shows the schematic of a 4-element planar and conformal patch array along with a corporate feed structure. The planar patch array shown in Fig. 1(a) has been conformed on a cylindrical surface with a radius of curvature of 90 mm. As aforementioned, the conformal patch array has many advantages over planar patch array. Fig. 2(a) shows that the planar patch array has a return loss of 26.53 dB



(a) (b)

Figure 1. Corporate-fed 4-element linear patch array with conventional PEC ground plane. (a) Planar. (b) Conformal.

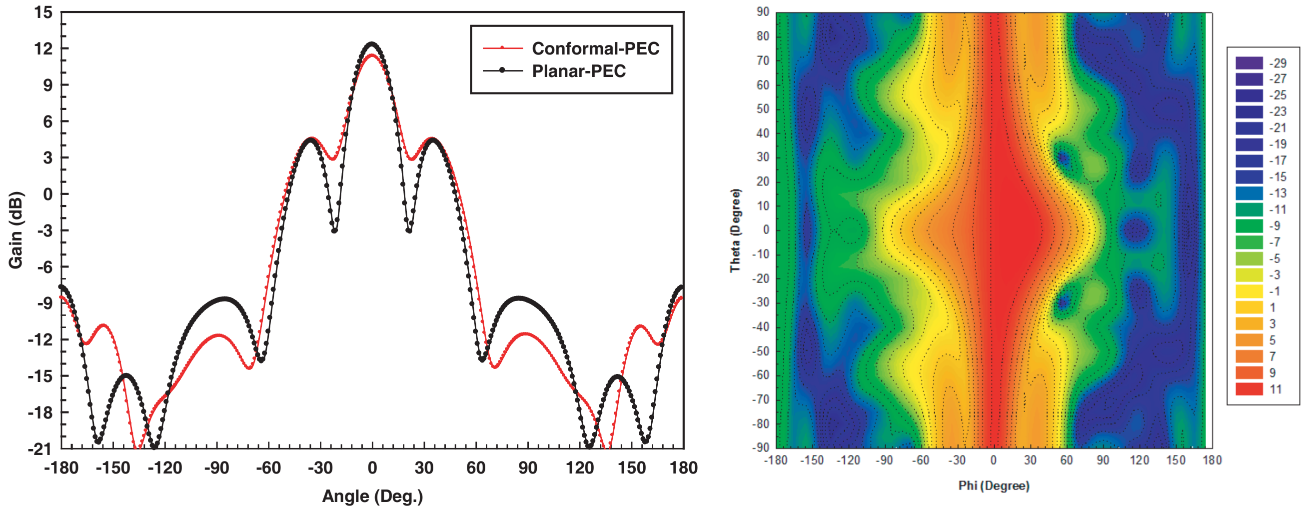


(a) (b)

Figure 2. Radiation characteristics of a 4-element planar and conformal patch array with PEC ground plane. (a) Return loss. (b) Normalized radiation pattern.

at 9.78 GHz, VSWR of 1.09, and percentage bandwidth of 9.58. It can be noted from Fig. 2(a) that the conformal patch array with conventional ground plane has a simulated return loss of 42.48 dB at 9.53 GHz and VSWR of 1.015 with a percentage bandwidth of 9.88 while the measured value obtained is 36.15 dB at 9.47 GHz.

Figure 2(b) compares the simulated and measured normalized radiation patterns of the planar and conformal patch arrays at their respective center operating frequencies, and the measured results are in good agreement with the simulated ones. The conformal array due to the curvature effect shows slightly broader mainlobe with higher sidelobes. The planar patch array has a gain of 12.4 dB along the specular direction, as shown in Fig. 3(a). The gain of the conformal patch array with radius of curvature 90 mm is slightly less than that of planar patch array, i.e., 11.36 dB along the specular direction. A contour plot illustrating the gain w.r.t. elevation and azimuth plane of the conformal patch array with conventional ground plane having radius of curvature 90 mm is shown in Fig. 3(b). It can be noted that the maximum gain of 11.4 dB of the conformal patch array is obtained along $\theta = 20^\circ$ and $\phi = 0^\circ$. The gain of the conformal patch array is prominent in directions other than the specular direction as well. Table 1 summarizes the radiation performance parameters of 4-element patch array with PEC ground plane in both planar and conformal configurations.



(a) (b)

Figure 3. (a) Gain of a 4-element planar and conformal patch array with conventional ground plane. (b) Contour plot of the gain of 4-element conformal patch array with conventional ground plane.

Table 1. Comparison of performance of patch array with conventional PEC ground plane.

Array performance	**Planar**	**Conformal**
Return loss	26.53 dB at 9.78 GHz	42.48 dB at 9.53 GHz
% Bandwidth	9.58	9.88
VSWR	1.09	1.015
Gain	12.4 dB	11.36 dB
Beamwidth	20°	22.6°
Sidelobe level	−7.9 dB	−6.8 dB
Front-to-back ratio	19.3 dB	19.93 dB
Efficiency	96.6%	95.5%

3. MICROSTRIP PATCH ARRAY WITH HYBRID GROUND PLANE

This section presents the EM design and analysis of a 4-element linear patch array with hybrid HIS-based ground plane. The conventional ground plane of the patch array discussed in Section 2 is replaced with a hybrid HIS layer constituted by a combination of Jerusalem cross (JC) and square patch elements. In the proposed design, the JC elements are used as a band reject filter where it transmits the out-of-band frequency and reflects the in-band frequency. In order to reduce the reflection in the in-band frequency range, a square patch is placed next to the JC element which reflects the incident wave with 180° phase shift. This combination of JC-elements and square patches observes a destructive interference and hence RCS reduction. Fig. 4 shows the hybrid ground plane of the planar and conformal patch arrays. Apart from the HIS layer, it includes a metallic portion with the outline of the patch array designed on the top for efficient transmission.

Thus, the configuration of ground plane consists of the combination of JC elements and metallic patches with reduced ground plane structure. This entire configuration results in phase cancellation (crossing zero point) and hence larger dip in reflection coefficient (magnitude), as shown in Fig. 5.

The radiation characteristics of the planar patch array with hybrid HIS-based ground plane are shown in Fig. 6. It can be noted from Fig. 6(a) that the array shows a return loss of 39.35 dB at 9.78 GHz.

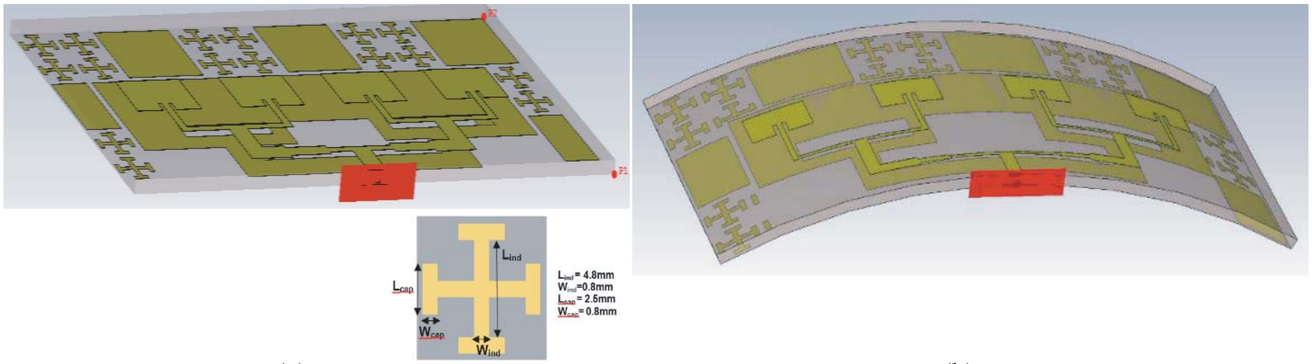


Figure 4. Corporate-fed 4-element linear patch array with hybrid HIS based ground plane. (a) Planar (b) Conformal.

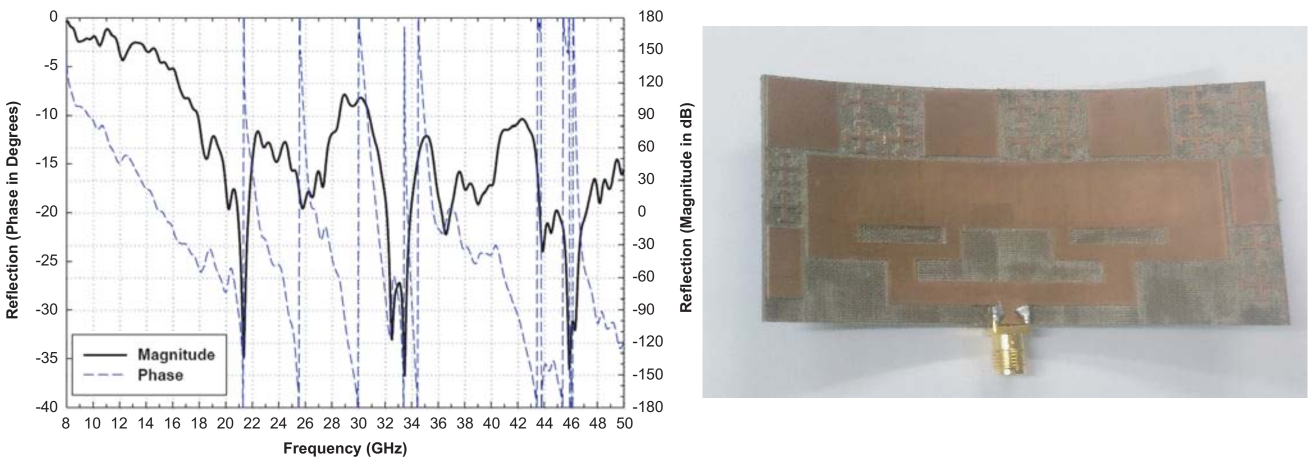


Figure 5. The reflection coefficient of the conformal patch array with hybrid HIS ground.

The VSWR of the patch array with hybrid HIS-based ground plane is 1.02. Further, the percentage bandwidth is improved from 9.58 to 17.79 compared to the planar patch array with conventional ground plane. The conformal patch array with hybrid HIS-based ground plane has a simulated return loss of 26.47 dB at 9.7 GHz and VSWR of 1.09 while the measured value obtained is 45.26 dB at 9.83 GHz and VSWR of 1.02. Fig. 6(b) compares the simulated and measured normalized radiation patterns of the planar and conformal patch arrays with hybrid HIS based ground plane at their respective center frequencies, and the measured results are in good agreement with the simulated ones. The gain of the planar patch array along the specular direction is 12.42 dB while for conformal one, it is reduced to 11.36 dB, which is expected, as the surface normal of the conformal patch array will point in different directions (Fig. 6(c)).

Table 2 provides the comparison of complete radiation performances of conformal patch array with PEC ground plane and hybrid HIS-based ground plane and also with planar patch array with hybrid HIS-based ground plane.

Another aspect which cannot be ignored is the dependence of array performance on the curvature of the platform. Thus, two cases with radii of curvatures of 60 mm and 90 mm have been considered for the same 4-element patch array. Table 3 and Table 4 show that the conformal patch array with larger radius of curvature shows better antenna performance. Fig. 7 compares the gains of the conformal 4-element patch array with HIS-based ground plane with two different radii of curvatures. In order to have a detailed picture, Fig. 8 shows the contour plots of the antenna gain of the conformal patch array with hybrid HIS-based ground plane for $-90^\circ \leq \theta \leq 90^\circ$ and $-180^\circ \leq \phi \leq 180^\circ$ with radii of curvatures

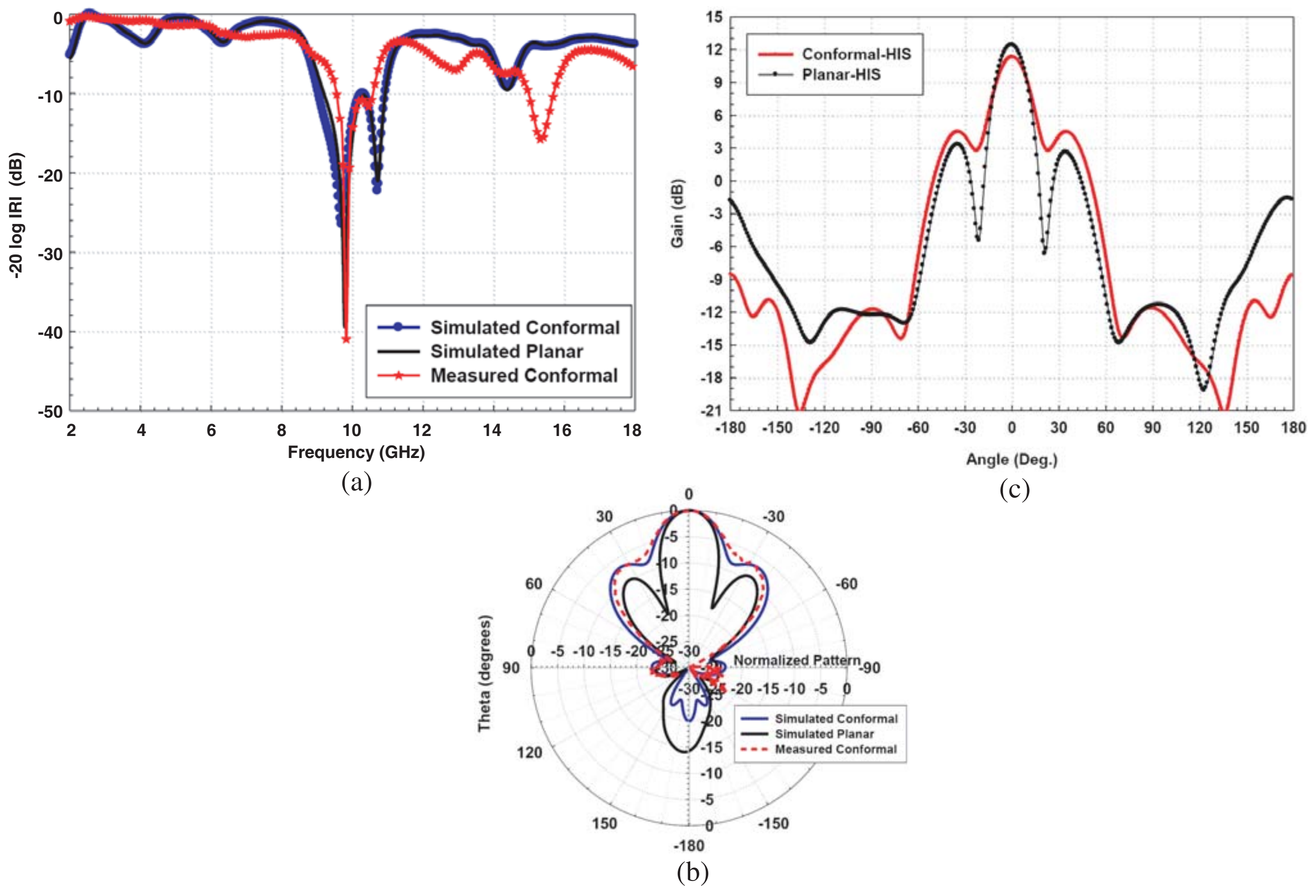


Figure 6. Radiation characteristics of 4-element planar and conformal patch array with hybrid HIS-based plane. (a) Return loss. (b) Normalized radiation pattern. (c) Gain.

Table 2. Comparison of radiation performance of conformal patch array with conventional PEC ground Plane and HIS-based ground plane.

Array performance	**Conformal patch array with PEC ground plane**	**Conformal patch array with hybrid HIS-based ground plane**	**Planar patch array with hybrid HIS-based ground plane**
Return loss	42.48 dB at 9.53 GHz	26.47 dB at 9.7 GHz	39.35 dB at 9.78 GHz
% Bandwidth	9.88	19.48	17.79
VSWR	1.015	1.09	1.02
Gain	11.36 dB	10.83 dB	12.42 dB
Beamwidth	22.6°	21.3°	19°
Sidelobe level	−6.8 dB	−6.3 dB	−9.1 dB
Front-to-back ratio	19.93 dB	14.4 dB	14.46 dB
Efficiency	95.5%	94%	95%

of 60 mm and 90 mm.

In the case of the conformal antenna array, the mainlobe of the radiation pattern happens to get tilted due to the difference in the amplitude and phase of wave received or transmitted at/from each antenna element [15, 16]. This difference in amplitude/phase of wave increases as the radius of curvature of the conformal antenna is reduced. This, in turn, degrades the radiation performance of the conformal

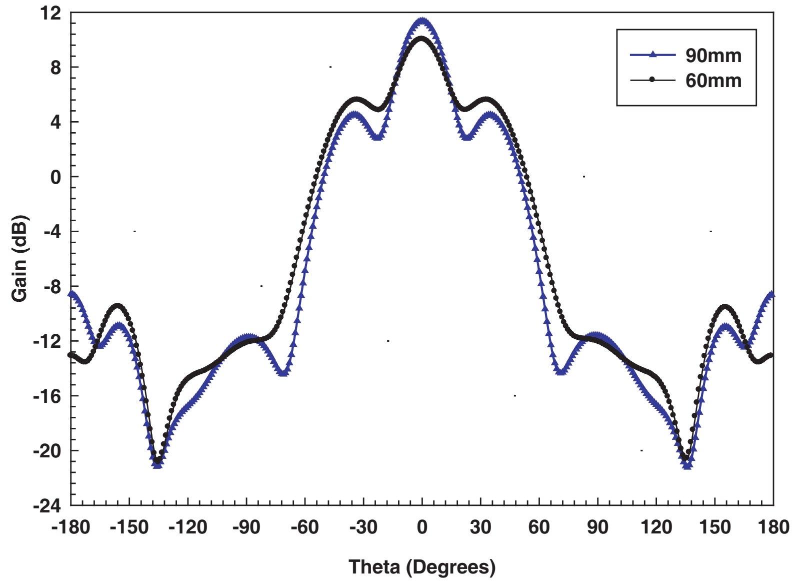


Figure 7. Comparison of gain of conformal patch array with HIS-based ground plane having different radius of curvature.

Table 3. Comparison of performance of conformal patch array with conventional PEC ground plane.

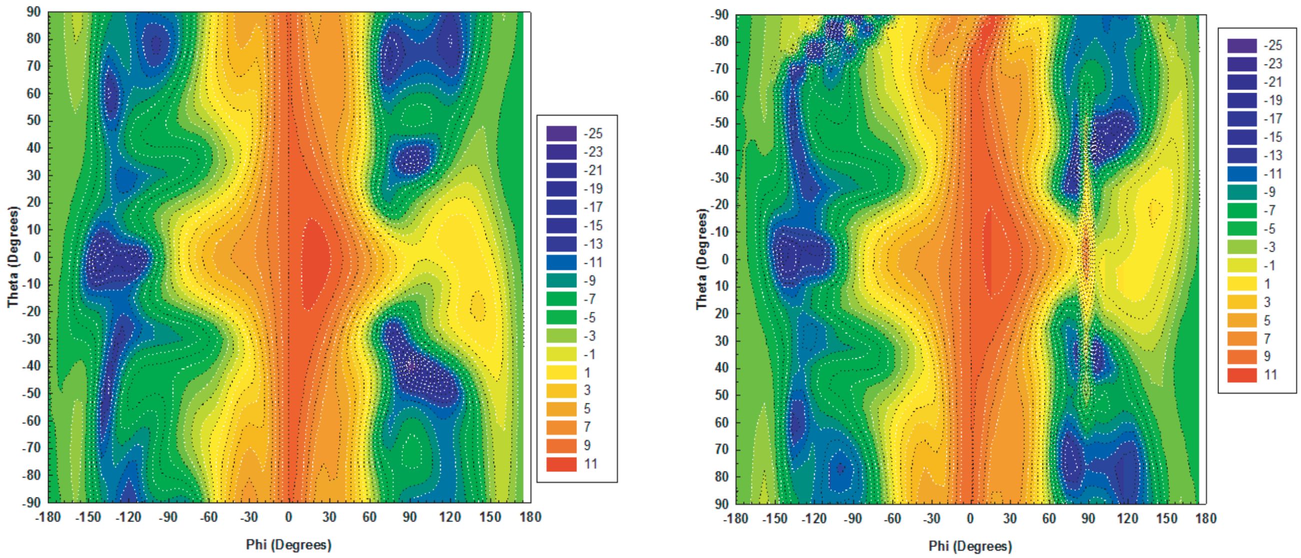
Performance	**R = 90 mm**	**R = 60 mm**
Return loss	42.48 dB at 9.53 GHz	37.31 dB at 9.51 GHz
% Bandwidth	9.88	9.52
VSWR	1.015	1.02
Gain	11.36 dB Contour plot of gain: Maximum 12.5 dB for $\theta = 20^\circ$ and $\phi = 0^\circ$	10.01 dB Contour plot of gain: Maximum 11.4 dB for $\theta = 20^\circ$ and $\phi = 0^\circ$

Table 4. Comparison of performance of conformal patch array with hybrid HIS-based ground plane.

Performance	**R = 90 mm**	**R = 60 mm**
Return loss	26.47 dB at 9.7 GHz	24 dB at 9.7 GHz
% Bandwidth	19.48	19.69
VSWR	1.09	1.13
Gain	10.83 dB Contour plot of gain: Maximum 11.9 dB for $\theta = 15^\circ$ and $\phi = 0^\circ$	9.14 dB Contour plot of gain: Maximum 10.5 dB for $\theta = 20^\circ$ and $\phi = 0^\circ$

array either by tilting the beam or increasing the beamwidth or increasing the sidelobe level. In the present work, the beam tilt in the θ-direction is in line with the above explanation.

In the case of receiving array, the phase associated with the waves received by the individual antenna elements differs more in conformal array than the planar ones. In broadside direction, the phase of impinging waves at the antenna elements gets altered by the factor of kd, with d being the inter-element



(a) (b)

Figure 8. Contour plot of gain of conformal patch array with hybrid HIS-based ground plane. (a) $R = 60\,\text{mm}$. (b) $R = 90\,\text{mm}$.

spacing. This phase shift becomes larger for smaller radius of curvature in conformal array configuration because of larger bending of antenna elements along the surface. This effect can be observed in Fig. 7. It is apparent that compared to $R = 90\,\text{mm}$, for $R = 60\,\text{mm}$, the antenna gain decreases with slightly broader beamwidth and rises in first sidelobe level. The same reason is valid for Fig. 3(a) and Fig. 6(c), where the gain of conformal array is reduced by a small amount. However, such performance degradation in conformal arrays can be handled by using phase compensation technique [15].

4. SCATTERING ANALYSIS OF CONFORMAL PATCH ARRAY

The scattering characteristics of patch arrays have been evaluated in terms of structural RCS and radiation mode RCS. The structural RCS patterns of the planar and conformal patch arrays with conventional ground plane are shown in Fig. 9(a) while those with hybrid ground plane are shown in Fig. 9(b) at their respective center frequencies. It can be noted that due to the conformal shape, the structural RCS pattern of the patch array ($f_o = 9.53\,\text{GHz}$) has a dip in the specular lobe compared to the planar patch array ($f_o = 9.77\,\text{GHz}$) with conventional full metallic ground plane.

The curvature of the antenna array results in the null at 0° of RCS pattern, unlike the case of planar array. The scattered waves from the patch elements destructively interfere at the angles close to the broadside but at the same time result in increase in the structural RCS at other angles, in accordance with the principle of conservation of energy. It is apparent that the sidelobes in the case of conformal array are relatively higher than that of planar array. Further for HIS-based ground plane (Fig. 9(b)), the destructive interference takes place for relatively broad range ($0^\circ \pm 15^\circ$) due to the multiple scatterings from the HIS-based ground plane in addition to patch elements. In Fig. 9(b), the structural RCS of the planar ($f_o = 9.78\,\text{GHz}$) patch array with hybrid HIS-based ground plane has a specular lobe of $-9.27\,\text{dBsm}$, whereas for the conformal ($f_o = 9.7\,\text{GHz}$), the maximum lobe obtained is $-13.45\,\text{dBsm}$ along $\theta = \pm 8^\circ$.

Figure 10 shows the comparison of the specular structural RCSs of the planar and conformal patch arrays with conventional and hybrid HIS-based ground plane from 8 GHz to 50 GHz. It can be noted that the specular structural RCS of the planar patch array increases almost linearly with the frequency. The specular structural RCS of planar patch array with hybrid HIS-based ground plane is less than that with conventional ground plane. In the case of conformal patch array with conventional full metallic ground plane, a minimum RCS reduction of 8 dB and a maximum RCS reduction of 20 dB in

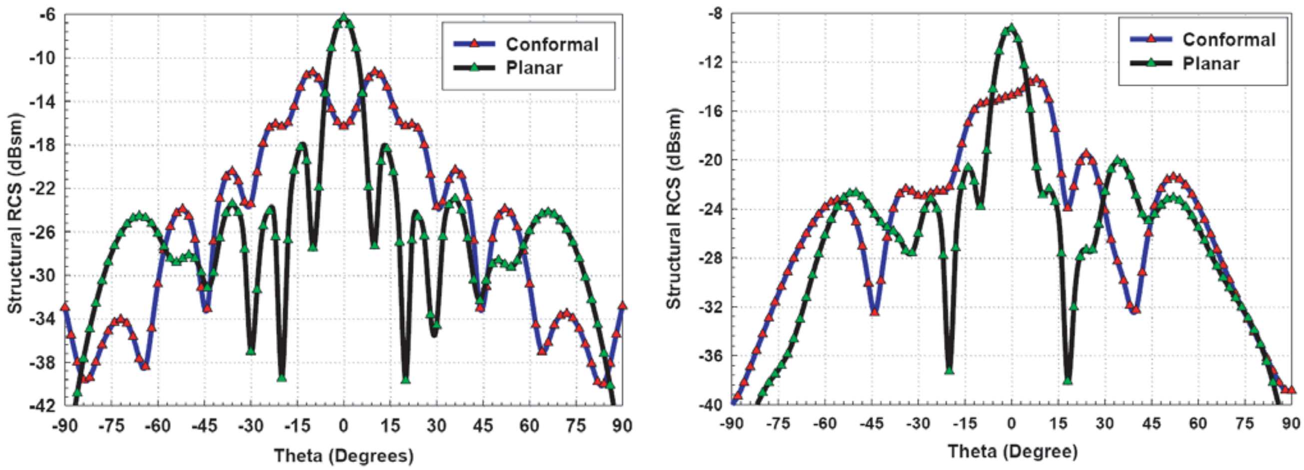


Figure 9. Structural RCS of 4-element planar and conformal patch array. (a) Conventional metallic ground plane. (b) Hybrid HIS-based ground plane.

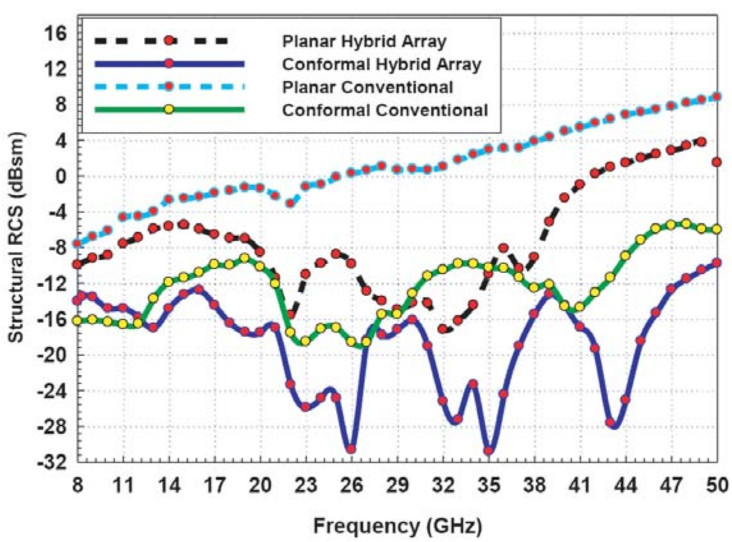
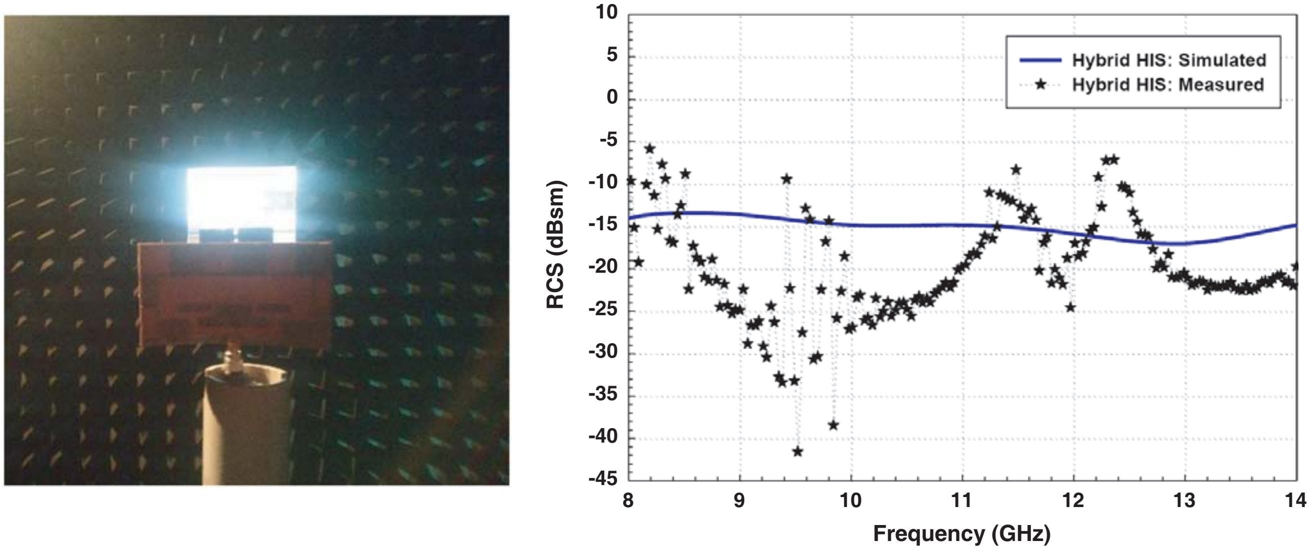


Figure 10. Specular structural RCS of 4-element planar and conformal patch array with different configurations of ground plane.

specular structural RCS are achieved as compared to planar configuration. However, for the conformal patch array with hybrid HIS-based ground plane the structural RCS has even further reduced. The obtained results can be attributed to the curved platform on which the patch array has been mounted. Furthermore, in the case of HIS-based ground plane, there are JC-elements and metallic patches along with reduced metallic ground plane. These variations in the geometry would lead to various reflections and transmissions of the travelling EM wave. This effect is more prominent at higher frequencies, due to the multiple scattering at these interfaces (comparable or smaller than the wavelength). These variations may become more rigorous at much higher frequencies. Thus intuitively one can infer that these multiple scatterings at the edges and corners of hybrid HIS-based ground plane can be the reason of variations in the RCS plots. This is not the case in the conventional PEC ground plane where no such interfaces (metallic and non-metallic) exist. This is apparent from the narrower variation span in Fig. 10.



(a) (b)

Figure 11. Specular structural RCS of 4-element conformal patch array with HIS ground plane. (a) Experimental set-up for RCS measurements. (b) Comparison of measured and simulated structural RCS.

Figure 11 shows the measured specular structural RCS of conformal patch array with hybrid HIS ground plane. The experimental setup for RCS measurements of patch array is shown in Fig. 11(a). The measurements were carried out using two collocated pyramidal horn antennas and Agilent Technologies N5222A PNA Network Analyzer in frequency range of 7 GHz to 14 GHz using two port Open-Short-Load (OSL) calibration technique with 85054D Type N calibration kit. All reflections from the target area or support structure are removed using time gating. It is apparent that the measured results present lower structural RCS of HIS-based conformal patch array than the simulated ones. The difference between the simulated RCS and measured RCS can be attributed mostly to the measurement setup. Moreover, the size of the patch array is very small (49 mm × 90 mm).

Further, when the patch array is radiating, the radiation mode RCS should be either high or comparable to the array gain. This high array RCS necessitates its accurate estimation and hence its control, without degrading the radiation performance. In contrast to planar patch arrays, the curvature of conformal patch arrays demands modification in the coordinate system. This is because on the curved surface, the surface normal of each patch points in different directions. Thus, the associated local coordinates are transformed into global coordinates using Euler transformation [4]. The expressions for azimuth and elevation angles are henceforth obtained and used to modify the factor q, a constant parameter [4] used in computing array RCS.

$$q(i) = j\frac{\lambda}{16\pi}G\sin\theta'\cos\phi' \tag{1}$$

where G is the gain of the antenna.

The antenna mode RCS is computed using the approach described in [14], in which the patch array is divided into individual patch segments, resulting in separate antenna impedances for each segment. Therefore, the term q has to be computed for each patch segment. The values are finally incorporated in the formulation of antenna mode array RCS. The contribution of the radiating patch elements (σ_r) and the feed (σ_p) is coherently summed to arrive at total array RCS.

$$\sigma_r(\theta,\phi) = \sum_{i=1}^{n} q(i)r_r(i)e^{j2(i-1)\alpha} \tag{2}$$

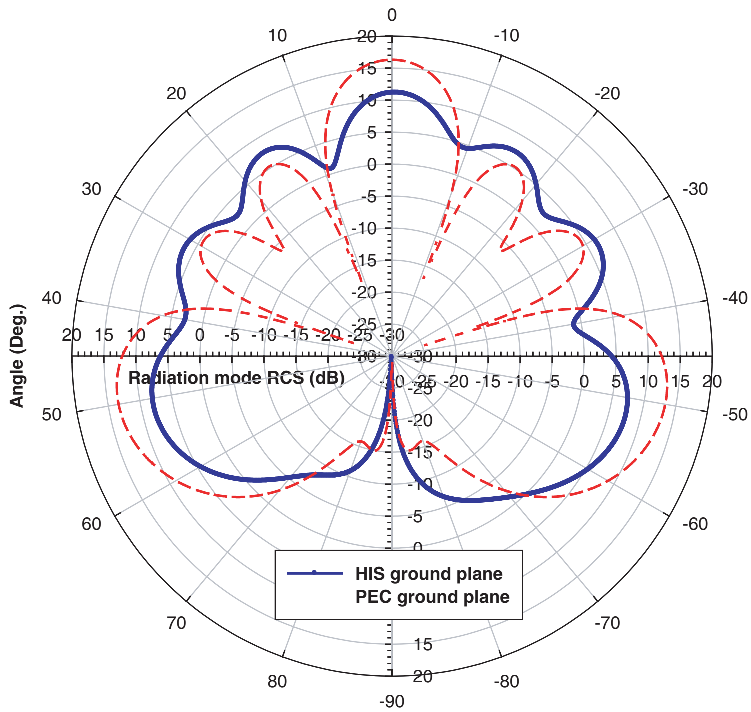


Figure 12. Radiation mode RCS of conformal patch array at 9.78 GHz.

$$\sigma_p(\theta, \phi) = \sum_{i=1}^{n} q(i) r_p(i) t_r^2(i) e^{j2(i-1)\alpha} \quad (3)$$

$$\sigma_A(\theta, \phi) = \frac{4\pi}{\lambda^2} \left(|\sigma_r(\theta, \phi)|^2 + |\sigma_p(\theta, \phi)|^2 \right) \quad (4)$$

where r_r and r_p are the reflection coefficients from each patch radiator and phase shifter. t_r is the transmission coefficient of radiator, n the number of antenna elements, and α the phase delay.

A software code has been indigenously developed in Fortran 90, based on the analytical formulation derived for an array RCS of conformal antenna array. Fig. 12 presents the comparison of computed radiation mode RCS of 4-element conformal patch array with conventional metallic ground plane and HIS-based ground plane. It may be observed that the antenna mode RCS of HIS-based patch array is less than the conventional one in the operating frequency range. A maximum RCS of 11.08 dB along the specular direction is observed for HIS-based conformal array in contrast to 16.28 dB for conventional conformal patch array at 9.78 GHz. Thus, the proposed conformal patch array shows low structural and radiation mode RCSs without any significant degradation in its radiation performance. This feature makes such low profile antenna configuration a preferred choice for low observable platforms for both ground-based and airborne applications.

5. CONCLUSION

The contribution of RCS by a planar patch array with conventional ground plane increases linearly with the increase in the frequency. The scattering performance of such a planar patch array is undesirable for stealth applications. Instead, the conformal patch arrays are known to have reduced backscattering compared to planar configurations. The curved platform attributes towards the RCS reduction. For planar patch array configuration, the surface normal of each patch element points towards the same direction (specular). For conformal patch array, the surface normal points toward different directions. Hence, the coherent sum of all the scattering contributed by the planar configuration is more than the conformal patch array configuration.

A wideband RCS reduction is obtained for the conformal configuration for the entire frequency band, i.e., 8 GHz to 50 GHz without any significant degradation in the radiation performance (antenna gain, return loss). In X-band, for a 4-element conformal patch array with radius of curvature 90 mm, the maximum reduction of 12.02 dBsm is observed at 12 GHz. The HIS layer used in the ground plane of patch array consists of JC elements and square patches arranged in a chessboard configuration. The ground plane is also reduced in accordance to the patch and the feed line geometry, in order to achieve high antenna gain but low RCS. The maximum reduction of 33.98 dBsm is attained at 43 GHz for the conformal patch array. The measurement results of the fabricated patch array are shown in good agreement with the simulated ones for both radiation and scattering performance. The computed results for radiation mode RCS of conformal patch array establish the fact that the radiation mode RCS is almost equivalent to the gain of the patch array in the specular direction. However, the proposed design is able to control both the structural RCS and radiation mode RCS of conformal patch array without degrading the array gain, return loss, and hence VSWR. The low profile structure of the proposed low RCS patch array can be used as subarrays in fire control radars of stealth platforms.

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