A Low RCS Microstrip Patch Antenna Array Using Hybrid Ground Plane

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***Abstract* – A (2×2) microstrip patch antenna array (MSPAA) is designed at 10 GHz., for low radar cross section (RCS) outside the operating band of the antenna in the frequency band from 16 GHz. to 26 GHz. The conventional ground plane of the MSPAA is modified by using a hybrid ground plane comprising Jerusalem cross slot (JCS) frequency selective surface (FSS) elements in a square grid. The optimized gain of the antenna array is 13.38 dB with bandwidth of 6%. Superstrate effects are studied and the design is re-optimized for preserving the radiation properties of the antenna. Antenna radiation pattern measurements are carried out in microwave anechoic chamber to verify the design.**

Keywords — RCS, EBG, RCSR,FSS.

I. INTRODUCTION

Airborne antennas onboard stealth air vehicles need to be designed for low radar cross section (RCS) both in-band and out-of-band radiating frequency band(s) of the antenna. Frequency selective surfaces(FSS) radomes [1,2] designed for ideal band-pass spatial filtering properties at microwave frequencies with maximum RF transparency in the radiating frequency band(s) of the antenna combined with good reflection loss in the desired out-of-band frequencies enable out-of-band monostatic RCS reduction of antennas. This is augmented by *primary* shape design of the stealth air-vehicle which redirects the impinging EM energy into less important threat directions.

Conformal microstrip antennas find extensive applications in aircraft and UAVs due to inherent advantages such as low profile, conforming to curved surfaces etc.

Hansen[3] clarifies the antenna RCS definition: The field scattered by an antenna contains a component that is the short circuit scattered field normalized by the short circuit current, and a second component that is the radiation field normalized by the transmitting current and multiplied by a factor (1 -Γ). RCS is the magnitude squared of the difference between two terms, one being the square root of a complex "structural" cross section, and the other (1 - Γ) times the square root of a complex "antenna" cross section. Hence the RCS of an array antenna [1] comprises both antenna component and structural component and the total RCS of the target, σ is given by:

$$\sigma = \left| \sqrt{\sigma_s} - (1 - \Gamma_A)\sqrt{\sigma_r}\, e^{i\phi} \right|^2 \qquad (1)$$

Where, σ is the total RCS of the target, σ_s is related to the field scattered by the short-circuited antenna, σ_r represents the field scattered by the antenna that involve the value of the port impedance, Γ_A is the antenna reflection coefficient, and φ is the relative phase between the two terms.

Switchable RCS Reduction (RCSR) technique for microstrip antennas is reported in [4] and using mushroom – like electromagnetic band gap (EBG) structures on patch array antenna, microstrip antenna RCSR is realized in [5]. In a recent paper [6], using a hybrid FSS, reduced out-of-band RCS has been realized from 6 GHz to 8GHz.

In this paper, we present the design of (2×2) microstrip patch antenna array (MSPAA) which is optimized for reduced RCS in the out-of-band frequency band of the antenna. Monostatic RCSR has been realized by modifying the conventional metallic ground plane by a hybrid ground plane (HGP). The HGP comprises Jerusalem cross slot (JCS) FSS elements designed for PEC like response at the operating frequency band of the antenna with maximum RF transparency at 38 GHz. The design of JCS FSS based HGP enables out-of-band RCSR from 16GHz to 26 GHz. The full-wave analysis of the design is carried out in HFSS 2014 software. The gain of the HGP antenna array is optimized to 13.38 dB. Radiation pattern measurements are carried out in microwave anechoic chamber to verify the design.

II.DESIGN OF MSPAA AND SIMULATION

The geometry model of MSPAA in HFSS superimposed with the 3D radiation pattern is shown in Fig.1. The design of MSPAA is optimized for realizing a gain of 13.57 dBi. VSWR or return loss bandwidth of the MSPAA is 8% centered at 10 GHz. The dielectric substrate used is RT Duroid with ε_r = 2.5, $\tan\delta$ =0.0019, and thickness 1.6 mm. The simulated VSWR and 2d radiation pattern plots of the MSPAA are given in Fig. 2a and Fig. 2b respectively.

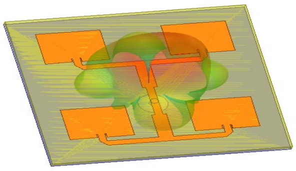


Fig. 1. A (2×2) MSPAA geometry model in HFSS.

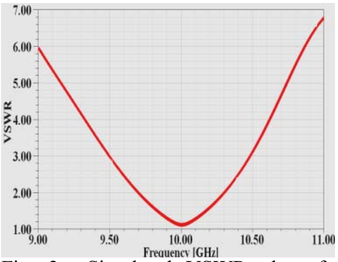


Fig. 2a. Simulated VSWR plot of (2×2) MSPAA with PEC ground plane in HFSS.

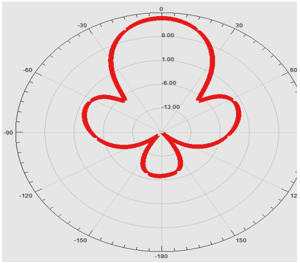


Fig. 2b. Simulated 2D radiation pattern plot of (2×2) MSPAA with PEC ground plane.

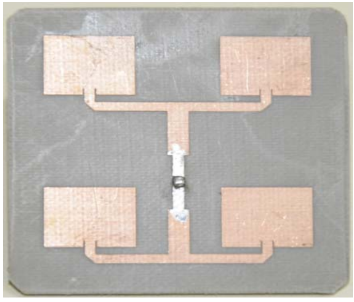


Fig. 3. Photograph of the (2×2) MSPAA with co-axial feed and PEC ground plane.

It is observed from Fig. 2a, that best VSWR of 1.09 is realized with a bandwidth of 8%, for a centre frequency of operation at 10 GHz. From Fig 2b, a gain of 13.57 dBi may be realized with this design using a conventional PEC ground plane. A photograph of the fabricated (2×2) MSPAA is shown in Fig. 3. The size of the substrate is (40 ×40) mm^2.

VSWR measurements are carried out using vector network analyzer instrumentation and a graph of VSWR vs. frequency is given in Fig. 4. From the graph, a VSWR of 1.2 is measured at the centre frequency of operation, at 10GHz.

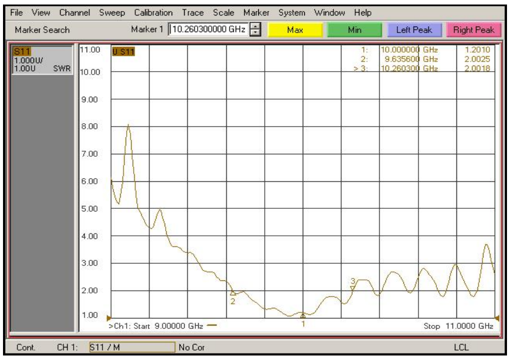


Fig. 4. Measured VSWR of (2×2) MSPAA on PEC ground plane.

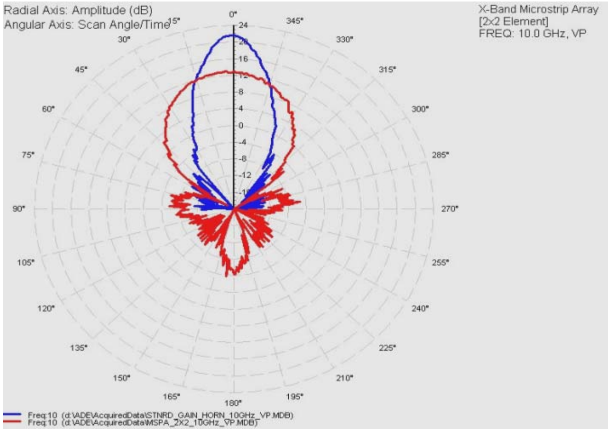


Fig. 5. Measured radiation pattern of (2×2) MSPAA with PEC ground plane. Frequency: 10 GHz. Polarization: Vertical.

The radiation pattern measurement of the MSPAA is carried out in microwave anechoic chamber. A 2D polar plot of measured radiation pattern of the antenna is shown in Fig. 5. It is observed that a gain of 12.8 dBi is realized at 10 GHz.

The plot in blue color in Fig. 5 corresponds to a calibrated, standard gain horn antenna, whose measured gain is 22 dBi. The red colored plot corresponds to the MSPAA and the gain realized is 12.8 dBi. The measured gain is lesser than the simulated gain by 0.7 dB. The deviation is due to limitations in fabrication of the prototype antenna and can be streamlined in fabrication of a flight worthy antenna.

III DESIGN OF JCS FSS GROUND PLANE BASED MSPAA

Frequency selective surfaces (FSS) are periodic structures in two dimensions developed on a dielectric substrate using conventional photolithographic technology. The inherent periodicity of FSS can be used for realizing various spatial filter characteristics. In this paper, Jerusalem cross slot (JCS) FSS element geometry is chosen for modifying the antenna ground plane. The choice of FSS element geometry should enable realizing the desired structural RCSR in the out-of-band frequencies of the antenna. The JCS FSS should be so designed that the patch antenna radiation properties such as gain, bandwidth and radiation efficiency are not degraded and desired structural RCSR is also realized.

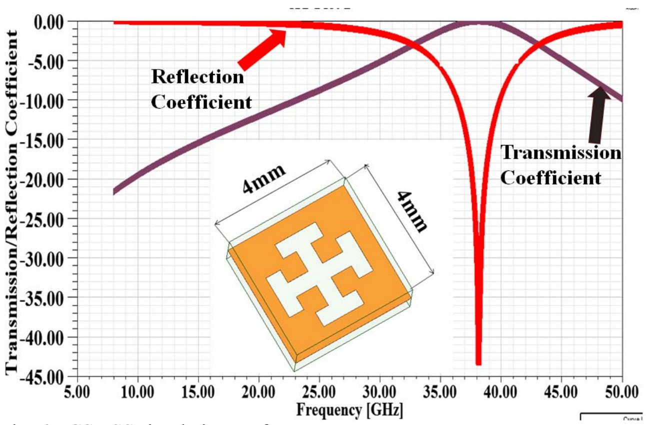


Fig. 6. JCS FSS simulation performance.

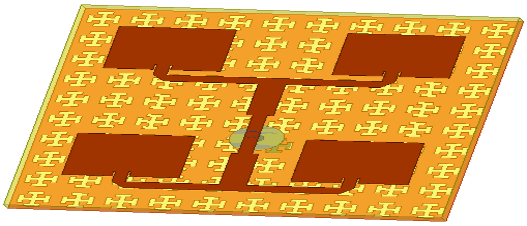


Fig.7. A (2×2) MSPAA with finite FSS JCS ground plane Geometry model in HFSS.

Fig. 6 gives the simulated ***S***-parameters of the JCS FSS. A free-standing JCS FSS is also shown in the inset for better clarity. From Fig. 6, it is observed that JCS FSS is designed for RF transparency at 38 GHz. and the total size of single FSS element is 4×4 mm^2. The transmission loss at 38 GHz. is 0.08 dB. The JCS FSS is designed to ensure undisturbed PEC like response at the operating frequency band of the patch antenna array.

Fig.7 shows a (2×2) MSPAA with finite FSS JCS ground plane geometry model in HFSS. The substrate dimensions of the MSPAA remains the same as that of the antenna designed with PEC ground plane i.e. 40 ×40 mm^2. The total size of the single FSS element designed is 4×4 mm^2. So the MSPAA with finite FSS JCS ground plane comprises 100 JCS elements.

The radiation properties of the MSPAA with the modified ground plane comprising JCS FSS get degraded both in terms of reduction in gain and shift in the resonant frequency of the MSPAA. Fig. 8 gives the S-parameter ***(S_{11})*** vs. frequency. A return loss of 27.06dB is realized but a shift in the operating frequency from 10GHz to 9.47GHz. is observed.

Fig.9 gives the 2D plot of reduced gain of MSPAA with FSS JCS ground plane. The gain obtained for (2×2) antenna array with FSS JCS ground plane is 0.77dB less than the gain obtained for 2×2 antenna array with solid ground plane that is 13.57dB. It is observed that the patch antenna with the modified FSS ground plane results in shift of the operating frequency and also a reduction in gain as compared to the MSPAA with conventional PEC ground plane. To realize desired radiation performance of the MSPAA combined with structural RCSR, a hybrid ground plane (HGP) is designed and is presented in the next section.

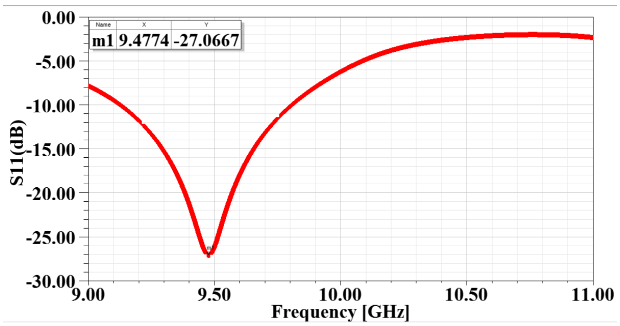


Fig.8. Plot of return loss of MSPAA with FSS JCS ground plane indicating a frequency shift due to FSS ground plane.

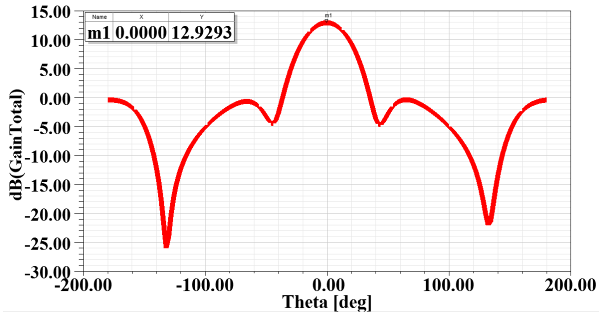


Fig.9. 2D plot of reduced gain of MSPAA with FSS JCS ground plane.

IV DESIGN AND MODELING OF LOW RCS MSPAA WITH HGP

Fig. 10 gives the geometry model of a (2×2) MSPAA with hybrid ground comprising solid copper ground just below the microstrip patch and the feed lines only. The remaining ground plane area is filled with JCS FSS elements. The construction of the HGP with copper patches aids in realizing the desired unaltered antenna radiation characteristics with structural RCSR. The size of the 2×2 patch antenna array remains same i.e.40×40 mm^2.

Fig.11 gives the simulated plot of VSWR of MSPAA with HGP. VSWR obtained is 1.19 and bandwidth is about 6%. Fig. 12 shows the 2D plot of gain of the 2×2 patch antenna array with hybrid ground plane. The gain obtained is 13.38dB.

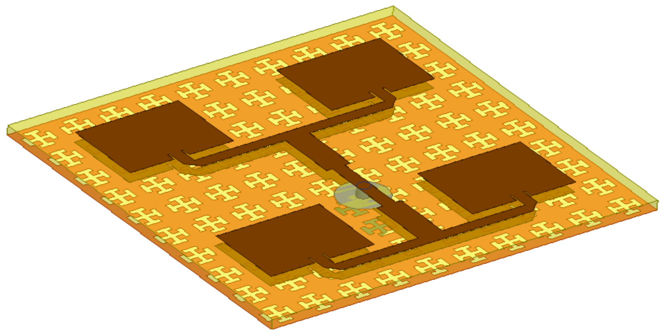


Fig.10. The geometry model (2×2) MSPAA with hybrid ground plane (HGP) in HFSS.

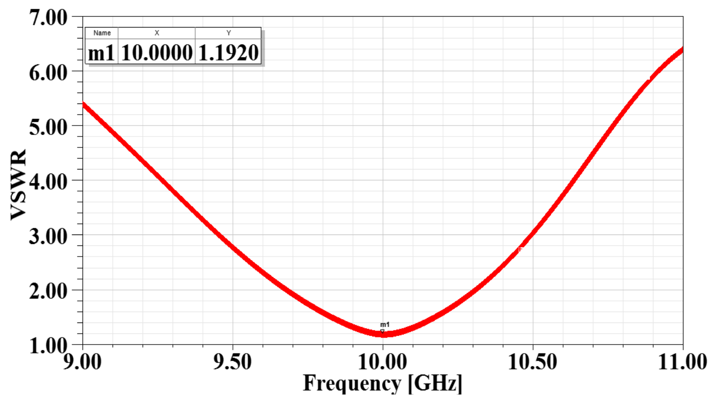


Fig.11. VSWR plot of (2×2) MSPAA with hybrid ground plane (HGP).

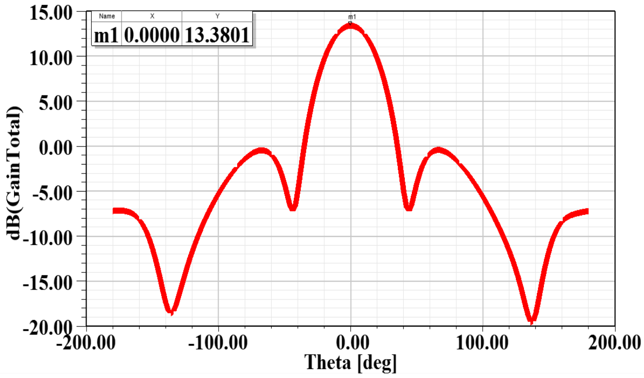


Fig.12. 2D plot of simulated gain of MSPAA with HGP

A. Comparison of Radiation Performance With Three Ground Planes

Any modification in the ground plane in the form of either modified FSS ground plane or HGP leads to reduction in MSPAA bandwidth. In order to quantify the effect of the modified ground plane on the antenna radiation characteristics, the return loss performance of the MSPAA with conventional/ solid ground plane is compared with the MSPAA using finite FSS and the hybrid ground plane. Fig. 13 gives the comparison of the three antenna designs. From the Figure, it is clear that the HGP has a very minor effect on the S_{11} of the MSPAA with solid ground plane with no shift in the operating frequency whereas the finite FSS ground plane results in a shift of the resonant frequency from 10 GHz. to 9.47 GHz.

The gain of the antenna with solid ground plane is 13.57 dB whereas the gain realized with HGP is 13.38 dB. Hence a very slight reduction in gain (0.2 dB) of the MSPAA with HGP is observed compared to the antenna with finite FSS elements resulting in reduced gain (0.7 dB) of 12.92 dB. The antenna array with HGP provides a gain very close to the one offered by the PEC ground plane. Hence proving that the hybrid ground plane has very minor effect on the radiation properties of the antenna array and provides the desired RCSR of 12 dB to 26 dB from 16 GHz. to 26 GHz., as shown in Fig.14. In conclusion, hybrid ground plane is the best design choice for realizing wide band (10 GHz.) structural RCSR.

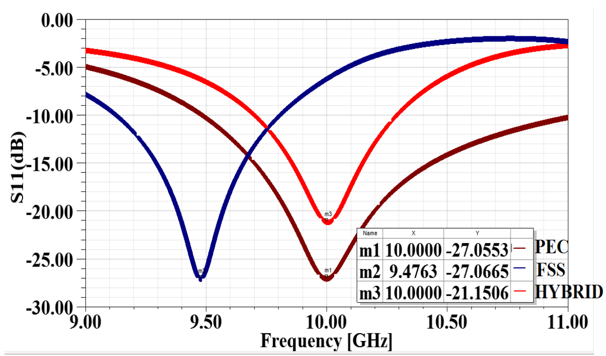


Fig.13. Comparison of the magnitude of the S_{11} of the array with PEC, FSS and hybrid ground plane

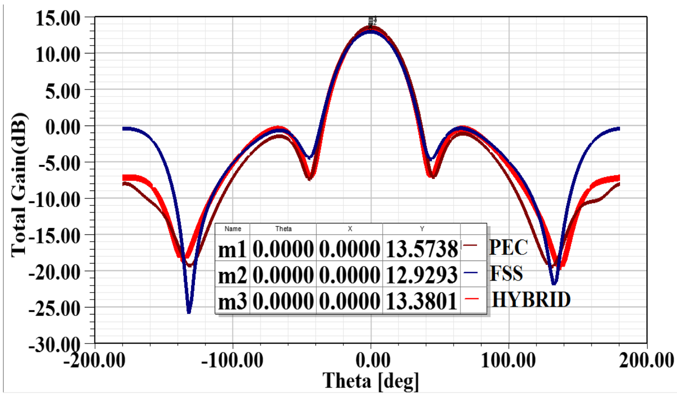


Fig.14.Comparison between the gain of the array with PEC, finite FSS elements and the hybrid ground plane.

B. Reduction of Radar Cross Section

The main aim of the design reported in this section is to decrease the structural RCS of a (2×2) MSPAA in the out-of-band frequencies from 16GHz. to 26 GHz. by modifying the ground plane with HGP. Fig. 15 gives the comparison between the monostatic RCS of the antenna array with PEC and the HGP.

The simulated RCS exhibited by the antenna array with the hybrid FSS ground plane is compared with the microstrip antenna with solid metallic ground plane for monostatic RCS and is shown in Fig.15. It is observed from the Figure that a very good structural RCSR has been achieved attributed to the design of HGP with JCS FSS elements for maximum RF transparency. The design of HGP has been optimized for best structural RCSR from 16 GHz. to 26 GHz. This is a departure from realizing the RCSR at the operating frequency of JCS FSS at 38 GHz. The design of HGP was optimized by a judicious combination of the copper patch and JCS FSS elements by including maximum possible JCS FSS elements to achieve the required RCSR in the desired frequency range without degrading the MSPAA performance.

Fig. 16a .shows the photograph of the top layer of (2×2) MSPAA with co-axial feed and Fig.16.b gives the photograph of the fabricated (2×2) MSPAA bottom layer with HGP.

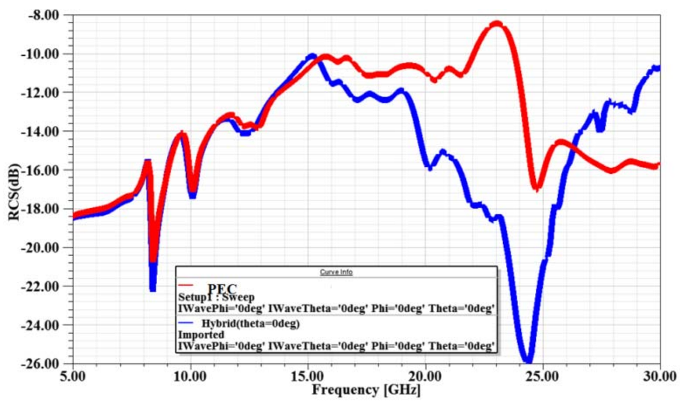
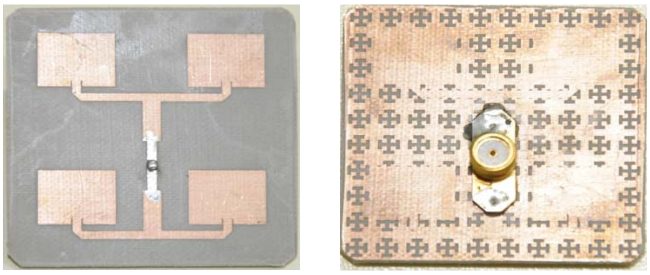


Fig.15. Comparison between the monostatic RCS of the antenna array with PEC and the hybrid ground plane (HGP).



(a) (b)

Fig. 16a.Photograph of the top layer of fabricated (2×2) MSPAA with co-axial feed and Fig. 16.b bottom layer of (2×2) MSPAA with HGP.

C. Study of Superstrate Effects

A structural superstrate becomes crucial in an airborne application to protect the antenna from harsh operating environment. Hence, a study of the effects of the prescribed superstrate is presented in this section. A superstrate with ε_r = 2.5 and $\tan\delta$ = 0.0019 with thickness 5 mils has been used for the study as the same substrate used for fabrication of the MSPAA needs to be used as a protective top cover but with minimum thickness. Fig. 17 gives the simulated plot of $\bar{E}$ and $\bar{H}$ plane radiation patterns with and without superstrate. Since a shift in the resonant frequency [7, 8] of MSPAA on HGP is predicted, it is observed that the resonant frequency of the MSPAA on HGP shifts to 9.8 GHz. The antenna was re-optimized for operating frequency of 10 GHz., with no degradation in gain, retaining 13.38 dB, with the superstrate.

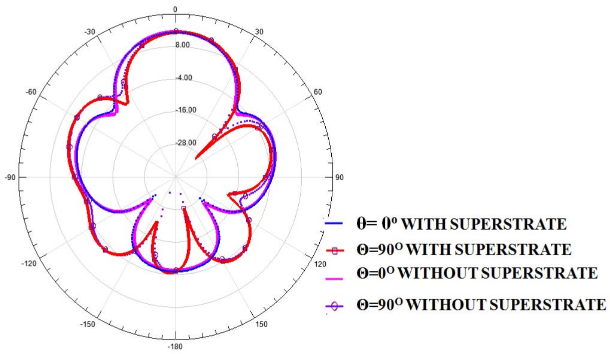


Fig. 17. Comparison of radiation patterns with and without superstrate of (2×2) MSPAA on HGP.

V. CONCLUSION

A (2×2) microstrip patch antenna array with reduced structural RCS over a 10 GHz. band from 16 GHz, to 26 GHz. is described in this paper. The patch array radiation characteristics are preserved with no degradation in performance. The design and implementation of the low profile MSPAA with RCS reduction assumes significance as the patch antennas on board an aircraft/UAV need to be essentially designed for stealth. The patch antenna array design with reduced structural RCS in the out of band frequency band of the antenna satisfies all the desired requirements and can be integrated on an aircraft structure. The array antenna can be used with thin, structural superstrate top layer, protecting it from the environment and with no degradation in radiation performance. With its low profile, good gain and bandwidth properties with structural RCS reduction over 10 GHz. bandwidth, the MSPAA is suited for applications in aircraft stealth.

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