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ARTICLE

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SUPERSTRATE-BASED LOW RCS CAVITY-BACKED ARCHIMEDEAN SPIRAL ANTENNA

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Spiral antennas are frequency independent antennas with broadband operating frequency range and are used in fighter aircraft for direction finding applications. This work presents the electromagnetic (EM) design of low observable right-handed circularly polarized (RHCP) cavity-backed Archimedean spiral (CBAS) antenna with VSWR <2.3, axial ratio <3 dB and positive gain over 2-18 GHz. In order to reduce radar cross-section (RCS) of the designed spiral antenna, a three-layered metasurface-based superstrate have been placed at an optimum height. It is shown that addition of superstrate over the CBAS antenna has not degraded the antenna radiation performance in terms of reflection coefficient, VSWR, gain and axial ratio. The monostatic RCS of CBAS antenna with and without superstrate is simulated over 1-18 GHz for normally incident RHCP EM wave. On average, 3 dB RCS reduction has been achieved over 4-18 GHz.

Keywords: *Archimedean spiral antenna, superstrate, reflection coefficient, VSWR, axial ratio, gain, monostatic RCS*

Introduction

Spiral antennas are Electronic Warfare (EW) antenna which are used for direction finding and communication purposes. They are frequency independent wideband antenna (1-18 GHz) with high gain and low axial ratio. Spiral antenna is the preferred choice for direction finding radar applications, because of its low-profile (planar) structure, wideband characteristics and circular polarization. The main challenge in ultra-wideband (UWB) spiral antenna design is to achieve wide operational bandwidth, simultaneously maintaining antenna gain (greater than 3dBi), radiation efficiency and axial ratio (<3 dB) over specified frequency range. These EW antennas used in fighter aircraft are also required to be of low radar cross-section (RCS). Spiral antenna has a complex structure comprising of spirals, balun feed, and cavity whichneed to be optimized to achieve the required radiation and scattering performance over 1-18 GHz. There are multiple methods of RCS reduction like usage of radar absorbing material (RAM), structural modification of the antenna, or placement of superstrate over the antenna.

A superstrate consists of a dielectric substrate with frequency selective surface (FSS) elements or metasurfaces. It is placed at an optimum height from the antenna in order to maintain required antenna radiation performance, but with low structural RCS. Thus one can infer that superstrates are the structures mounted over antenna, for RCS reduction without any adverse effect on antenna radiation characteristics[1]. In fact, an efficiently designed superstrate can enhance the antenna gain and improve VSWR and axial ratio of the antenna[2]. In this paper, a novel three-layered superstrate has been designed for two-

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arm cavity-backed Archimedean spiral (CBAS) antenna. The main objective is to reduce RCS of CBAS antenna without any disturbance in the antenna structure and hence its radiation performance (Reflection coefficient, VSWR, axial ratio, gain, radiation pattern).

EM Design and Performance Analysis of Cavity Backed Archimedean Spiral (CBAS) Antenna

The CBAS antenna has been designed in CST Microwave Studio for 1-18 GHz.

Details of Design Parameters of CBAS Antenna: The proposed CBAS antenna has a diameter of 60.4mm and has a two complimentary phased spirals over a dielectric substrate. A 13-turn spiral antenna has a balun as a feed, a frustum shaped cavity also acting as the ground plane, and an absorber ring, as shown in Fig. 1. An Archimedean spiral section consists of two spiral coil arms with 180º phase difference, placed on a dielectric substrate. The feeding to these spiral coils is done through the balun. One spiral arm has been connected to signal trace patch of the balun and another spiral arm to the ground plane patch. The same substrate as that of balun has been chosen for Archimedean spiral section, so that, the intrinsic impedance remains same throughout the antenna and no signal loss within the antenna can take place due to partial reflections. The design parameters of the CBAS antenna have been provided in Table I. The constituent materials used in the antenna design are given in Table II. The balun helps in impedance matching of the coaxial cable to the input of the CBAS antenna so that there is maximum transfer of EM waves from the cable to the antenna[3]. It converts EM signals from an unbalanced structure to that of a balanced one. The absorber ring over the antenna surface is made of Eccosorb (ε_r=2.5, tanδ=0.5) which absorbs the EM waves that are emitted sideways and hence helps in providing directivity to the radiation of the antenna. The cavity provides mechanical support to the antenna and reduces the back lobe in the antenna radiation, and hence helps in gain enhancement of the CBAS antenna.

Table 1. Design parameters of CBAS antenna.

Parameter	Dimension
Thickness of Substrate	0.787mm
Length of Balun	25mm
Width of Balun	20mm
Width of signal trace unbalanced port	10.043mm
Width of microstrip	0.5mm
Gap between coils	0.5mm
Beginning radius of innermost spiral coil	0.4mm
Inner radius of outer ring	28mm
Width of outer ring	2.2mm
Diameter of spiral section	53.8mm
No. of turns in each coil	13
Height of cavity	7.4mm
Outer top radius of frustum in cavity	27.5mm
Inner top radius of frustum in cavity	27mm
Outer bottom radius of frustum in cavity	1.5mm
Inner bottom radius of frustum in cavity	1mm
Thickness of absorber strip	2mm
Width of absorber strip	2.2mm
Outer radius of absorber strip	30.2mm

Table 2. Materials used in EM design of CBAS antenna

Antenna Part	Material
Spiral coils, microstrip of balun and outer ring	Copper (Annealed)
Substrate (balun and spiral section)	FR4 (lossy) (ε_r= 4.3, tanδ = 0.025)
Back Cavity	Copper (annealed)
Absorber	Eccosorb MCS(ε_r=2.5, tanδ=0.5)

EM Performance Analysis of CBAS Antenna: The designed CBAS antenna is simulated to check its EM performance using full wave simulation software. The radiation pattern of the antenna at 10 GHz is shown in Fig. 2. The reflection coefficient, VSWR, gain and axial ratio of the antenna is shown in Fig. 3. It may be observed that the reflection coefficient of the antenna is less than -10 dB for 3-18 GHz and VSWR is less than 2.2 for 1-18 GHz. This shows that the reflection of EM waves back into the coaxial cable is kept to a minimum, which is required for any antenna to have a good performance.

The axial ratio (Fig. 2c) is less than 3 dB for 3-18 GHz which means that the waves being emitted by the spiral antenna are indeed circularly polarized. Moreover, the gain of the antenna is positive for most of the frequency range 1-18 GHz. Thus the designed CBAS antenna performs well over 1-18 GHz.

Superstrate for RCS Reduction of CBAS Antenna

The scattering from antenna structure needs to be controlled without degrading the radiation performance.

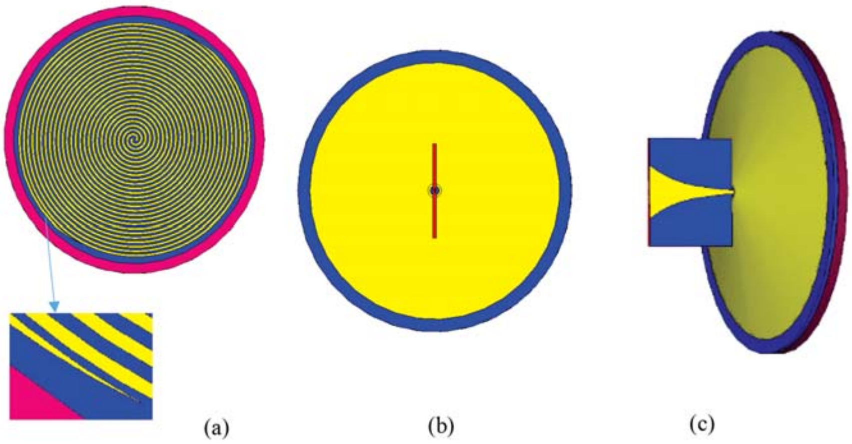

Fig. 1: CBAS antenna: (a) Front view (b) Back view (c) Side view

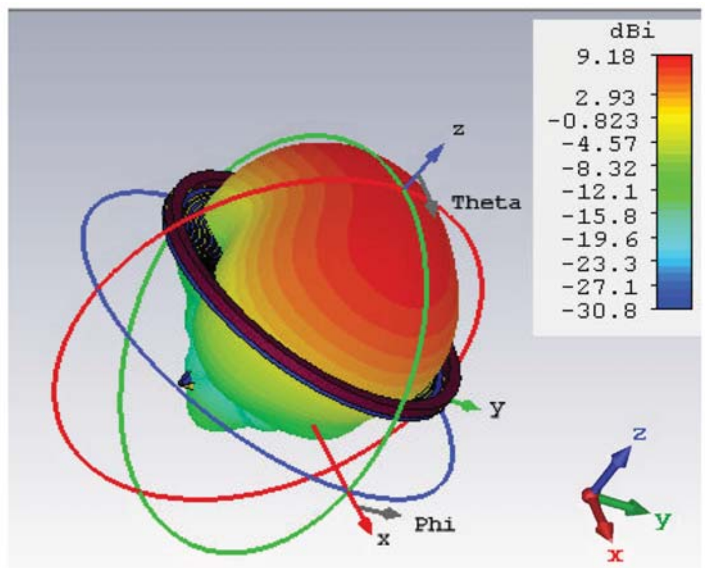

Fig. 2: Radiation pattern of designed CBAS antenna at 10 GHz.

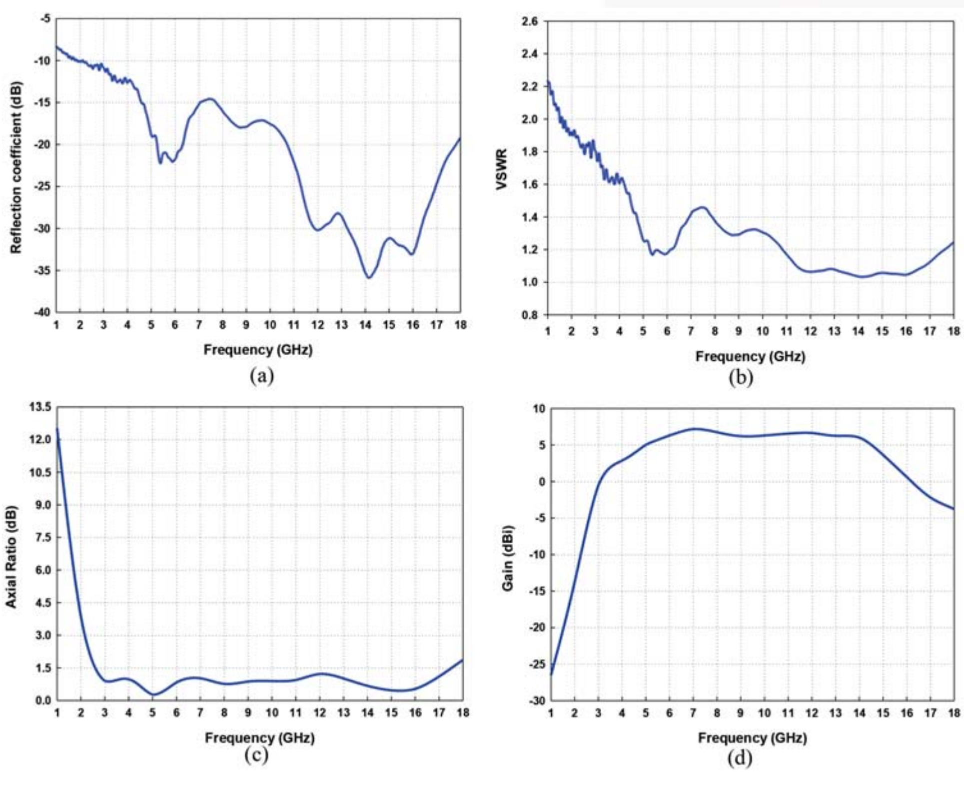

Fig. 3: EM performance of designed CBAS antenna. (a) S_{11} (b) VSWR (c) Axial ratio (d) Gain

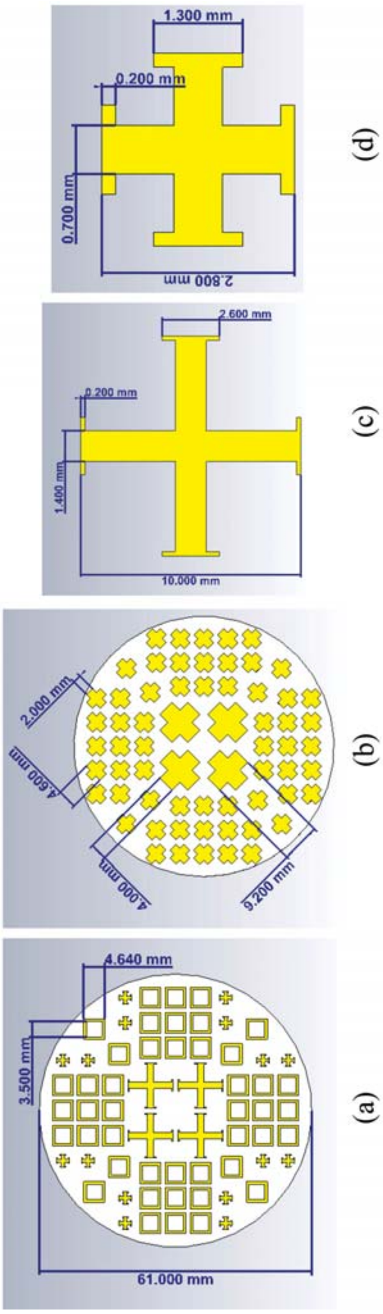

Fig. 4: EM design of superstrate: Version 1. (a) front view (b) back view (c) dimensions of JC at the centre (d) dimensions of surrounding JC

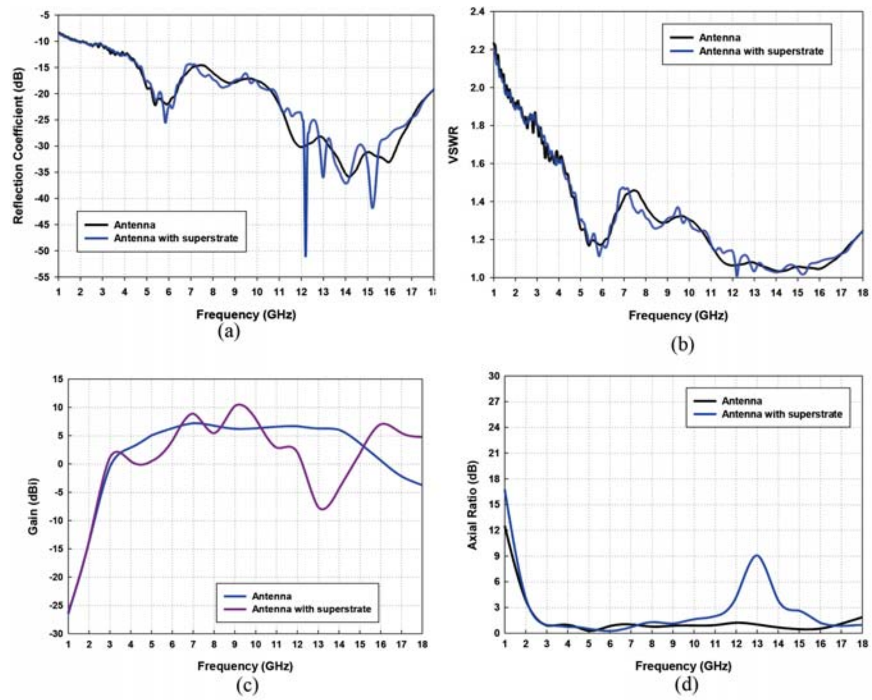

Fig. 5: EM performance of CBAS antenna with superstrate: Version 1. (a) S_{11} (b) VSWR (c) gain (d) Axial ratio

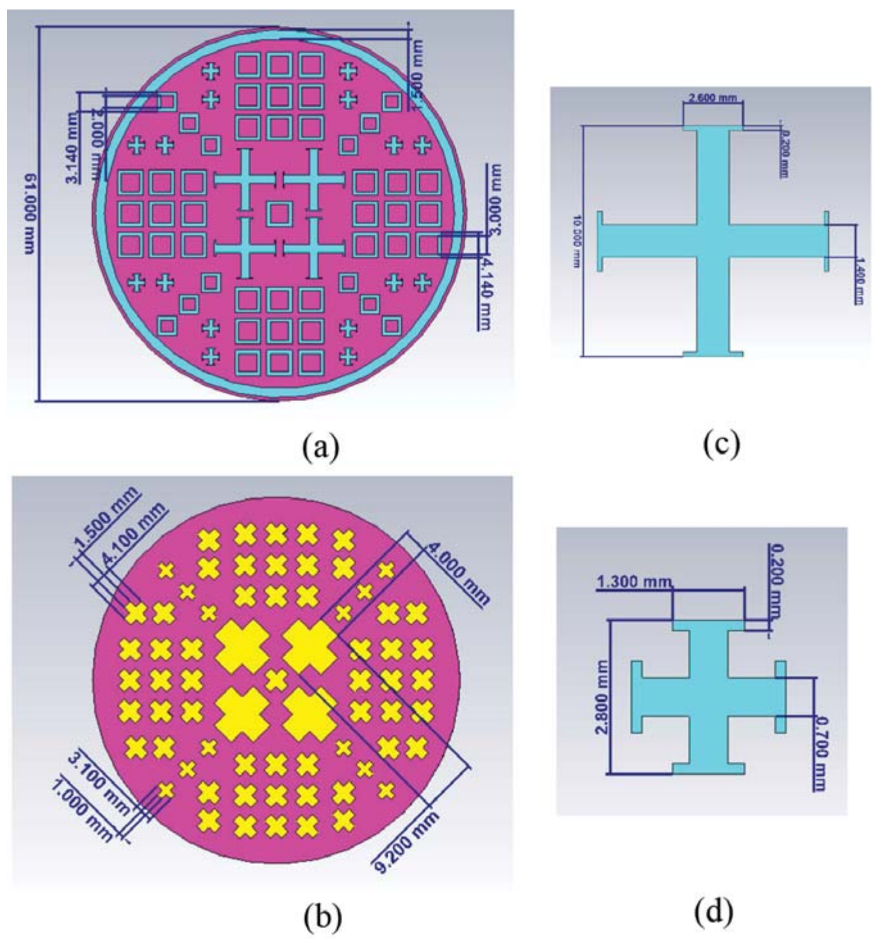

Fig. 6: EM design of superstrate: Version 2. (a) Front view (b) Back view (c) Dimensions of central JC (d) Dimensions of surrounding JC

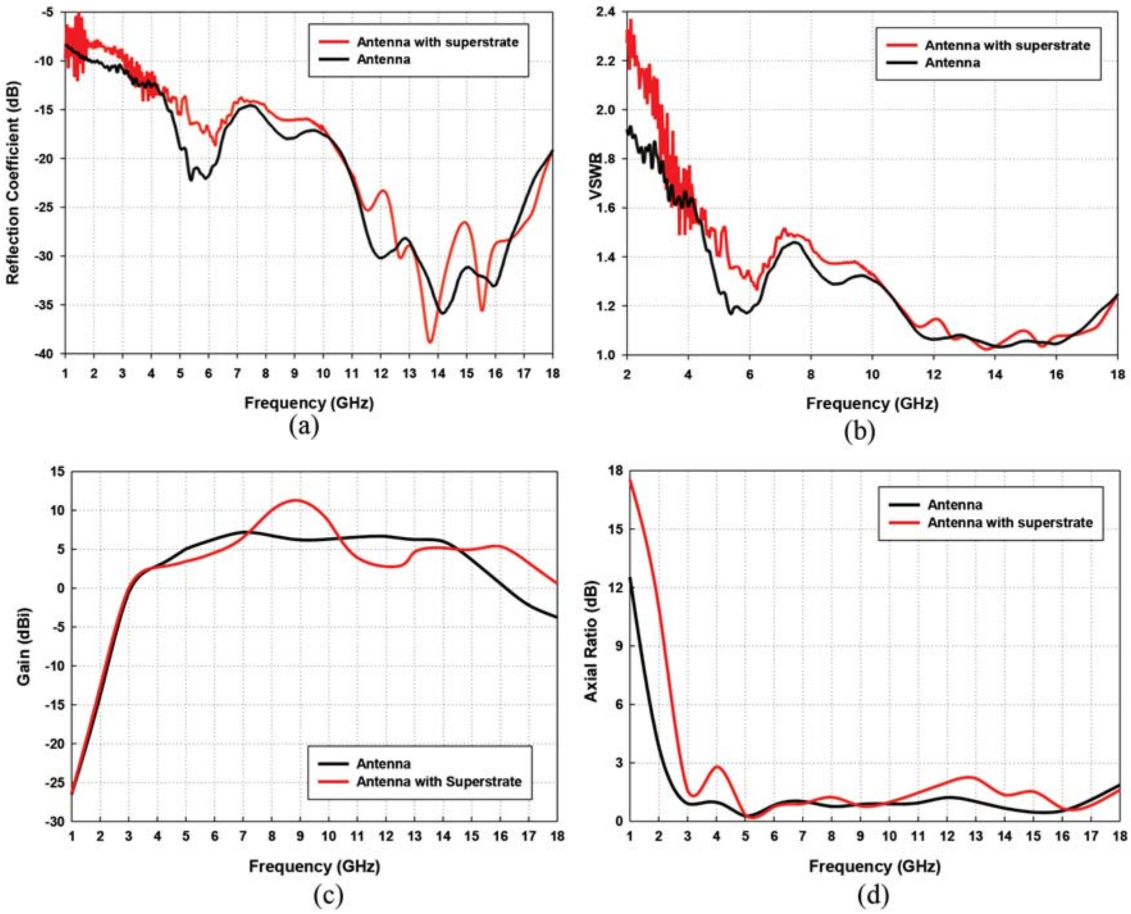

Fig. 7: EM performance of CBAS antenna with superstrate: Version 2. (a) S_{11} (b) VSWR (c) gain (d) Axial ratio

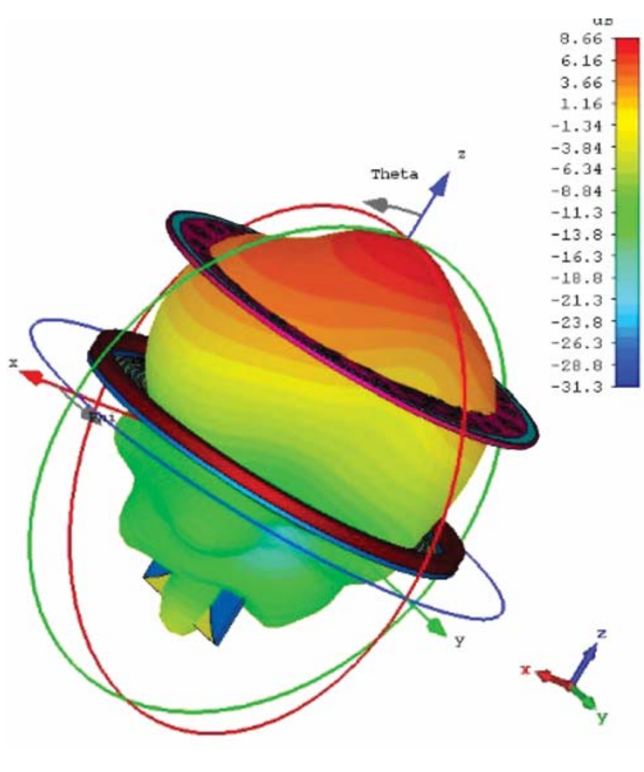

Fig. 8: Radiation pattern of CBAS antenna with superstrate: Version 2.

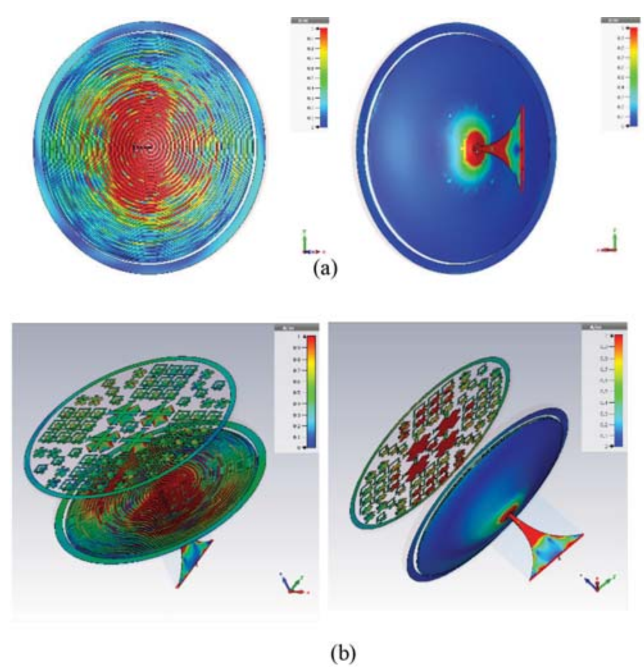

Fig. 9: Surface current distribution over CBAS antenna with superstrate: Version 2. (a) Antenna alone (b) Antenna with superstrate

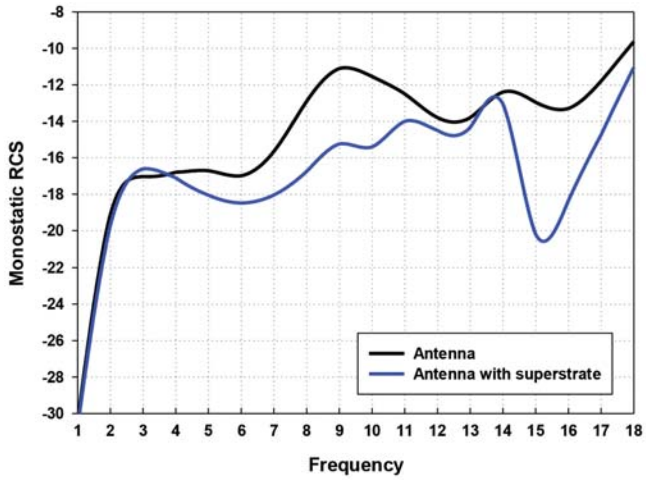

Fig. 10: Monostatic RCS of CBAS antenna with superstrate: Version 2.

There are several constraints regarding the antenna structure. Thus, without altering the antenna design, RCS of antenna can be controlled only by putting one layer of superstrate over the antenna at an optimum height.

EM Design of Superstrate: Version 1: A three layered superstrate is designed using FR4 substrate (1.575 mm) and FSS pattern etched over its top and the bottom surface. The FSS pattern is of annealed copper (0.018mm). The bottom pattern has cross-shaped patches while the top pattern consists of square loops and Jerusalem cross (JC) of arranged in a specific pattern, as shown in Fig. 4. Here, the copper top has a combination of square loops and JCs of different sizes. Jerusalem crosses, square loops and cross slots are the FSS elements used to achieve RCS reduction[4].

The principle of superstrate in controlling the antenna scattering[5] is that the ray incident on the surface is reflected but with different phase. Here, the phase of the waves reflected off the square loop and that from Jerusalem cross are phase apart. Hence, they tend to destructively interfere thereby reducing the antenna RCS. While designing the superstrate, several configurations were attempted using these FSS unit cells but the gain and axial ratio of the CBAS antenna was affected adversely. To counter this problem, the slots on the back of superstrate were replaced by metallic patches. Also the size of crosses at the center was increased in hope of achieving satisfying EM performance of CBAS antenna with superstrate. This led to the design presented here. Further, the varying sizes of the FSS unit cells used does not make sure of whether the waves that will be reflected off these FSS unit cells will be in opposite phases or not. This may affect RCS of CBAS antenna too. These problems indicate that optimization of dimensions of these unit cell geometry and arrangement is very critical in achieving the desired performance.

EM Performance of CBAS antenna with Superstrate: The superstrate was placed above the CBAS antenna at an optimal height of 22 mm. The performance of CBAS antenna with the proposed superstrate is shown in Fig. 5. The reflection coefficient, VSWR, gain and axial ratio of CBAS antenna with the superstrate are compared with that of antenna alone. The reflection coefficient and VSWR remain intact even after the placement of superstrate. The reflection coefficient is less than -10 dB for 3-18 GHz and VSWR is less than 2.2 for 1-18 GHz. However, it is observed

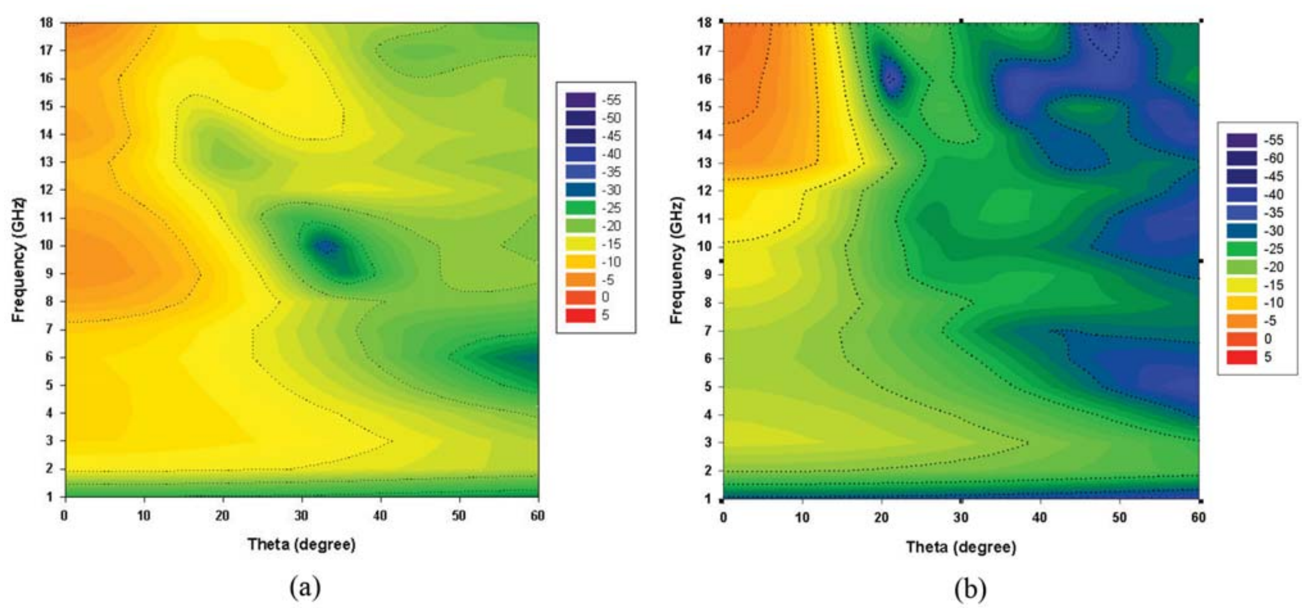

Fig. 11: Bistatic RCS for RHCP plane wave incidence. (a) CBAS antenna alone (b) CBAS antenna with superstrate: Version 2.

that the gain and axial ratio of the antenna got affected at certain frequencies. The gain and axial ratio are deteriorated for 12-14 GHz. This necessitates the improvement in the design of superstrate.

Improved Superstrate Design For CBAS Antenna

EM Design of Superstrate: Version 2: In this version of superstrate, certain changes have been made in the design in order to achieve better EM performance with RCS reduction. The substrate is changed to RO4835. A specific design of resistive sheet (377 ohms/sq) is used on the top surface while cross patches of annealed copper are designed oin the bottom surface, as shown in Fig. 6. The thickness of RO4835 substrate is 0.787 mm and both the copper and resistive layers on the top and bottom surface have thickness of 0.018 mm. As compared to the previous version, the material of the top surface has been changed from copper to resistive sheet. This would enhance the impedance matching on the top surface and hence contributes in gain enhancement. Also, a resistive ring has been added at the edge of the superstrate in order to improve the axial ratio. The dimensions of square loop and cross patches on the top and bottom surface were varied, so that more number of unit cells could be included, which helped in the gain improvement at higher frequencies. These changes in the configuration of superstrate also helped in RCS reduction.

The change of materials changed the physics behind RCS reduction of antenna by the superstrate[5,6]. The top layer of 3-layered superstrate acts as a partial absorbing surface (PAS) while the bottom layer of the superstrate (Copper layer) acts as a partial reflecting surface (PRS). When incident rays fall upon the superstrate, the partial absorbing surface absorbs the frequencies that are out of its operating band while the other frequencies pass through to the partial reflecting surface. The PRS then reflects the out-of-band frequencies and only few frequencies pass through to the antenna surface.

These remaining frequencies now undergo multiple reflections between the antenna surface and the superstrate and eventually get diffracted in different directions. These multiple reflections can result in the gain enhancement of the CBAS antenna if the superstrate is placed at the optimum height. This absorption of frequencies by the PAS and reflection by the PRS contribute to the gain enhancement and overall RCS reduction of the antenna[7].

EM Performance Analysis of CBAS antenna with Superstrate: Version 2: The designed superstrate has been placed on the CBAS antenna at the optimum height of 22 mm. The EM performance, i.e. reflection coefficient, VSWR, gain and axial ratio of the CBAS antenna has been simulated and compared with that of antenna alone (Fig. 7). The reflection coefficient of CBAS antenna with superstrate (v2) is less than -10 dB for 3-18 GHz and VSWR is less than 2.2 for entire range of 1-18 GHz. The axial ratio of the CBAS antenna with superstrate is still less than 3 dB for 3-18 GHz. It can be observed that the gain of the antenna has improved for higher frequencies (16-18 GHz) and also for 7-10 GHz. For other frequencies, the gain of antenna with superstrate follows that of antenna alone. The radiation pattern of antenna with superstrate is shown in Fig. 8. It can be observed that it is similar to that of antenna alone (Fig. 2). The EM performance of CBAS antenna with superstrate has not affected. Moreover, there is gain enhancement for some frequencies. The surface current distribution over the CBAS antenna with superstrate: Version 2 is shown in Fig. 9. The surface current over the antenna alone is also included. It can be seen that surface current over the FSS pattern on the bottom surface of superstrate is concentrated over the metallic patches, thereby contributing in improvement in radiation performance of underlying CBAS antenna.

The monostatic RCS of CBAS antenna and antenna with superstrate: Version 2 was simulated for RHCP plane wave incidence. The simulated RCS of antenna alone and antenna with superstrate are compared in Fig. 10. It is apparent that RCS reduction of 3 dB (on average) is observed for frequencies 4-18 GHz. The contour plot of bistatic RCS of CBAS antenna with superstrate: Version 2 for RHCP plane wave incidence is shown in Fig. 11. The bistatic RCS of antenna alone over 1-18 GHz are also included for the sake of comparison. It can be seen that RCS reduction has been achieved by placing the superstrate over the CBAS antenna at 22mm distance from the antenna aperture.

Conclusions

In this paper, a cavity backed Archimedean spiral antenna has been successfully designed to work in the wideband frequency range of 1-18 GHz. A three-layered superstrate is presented for CBAS antenna consisting of resistive sheet based top pattern and metallic bottom pattern. The designed CBAS antenna with superstrate shows reflection coefficient less than -10 dB, VSWR less than 2.2, axial ratio less than 3 dB, and gain greater than 5dBi on average over 1-18 GHz. Both monostatic RCS and bistatic RCS has been simulated for RHCP plane wave incidence. The proposed superstrate is shown to provide 3 dB (on average) RCS reduction without degrading the EM performance of the antenna. Moreover, the superstrate facilitates the gain enhancement at certain frequencies. Such low observable CBAS antenna can be used for designing spiral array for interferometry and direction finding applications.

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