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Design of a Low Profile Archimedean Spiral Antenna using Compact Defected Ground Structure as a Reflector

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ABSTRACT

In this paper, design and realisation of a low profile Archimedean spiral antenna is presented. The low profile Archimedean spiral antenna is printed on a substrate and backed by a reflector consisting of DGS. The DGS unit cell consists of a parallel combination of meander line inductors and inter-digital capacitors. This, DGS is one of the forms of electromagnetic band gap (EBG) structures providing electromagnetic band gap characteristics. It is used as a reflector with spiral antenna to achieve unidirectional radiation properties and a low profile of antenna. A modified version of uniplanar EBG cell is used as a DGS cell. This cell is used for configuration of the DGS ground plane. This ground plane is evaluated for its electrical characteristics and used as a reflector for the spiral antenna. Archimedean Spiral antenna is designed and simulated in the frequency band of 1-6GHz with DGS as a reflector. The antenna characteristics are studied for physical parameters of the antenna. These parameters are optimized for better electrical characteristics. The performance of the proposed antenna is also compared with conventional metallic (PEC) reflectors. Simulated results of an antenna are validated by measurement. Antenna height reduction of 60 % is achieved compared to conventional cavity-backed spiral antennas.

Keywords: Antenna; Cavity; DGS; EBG; Inter-digital capacitor; Meander line inductor; PEC

1. INTRODUCTION

Electromagnetic Band-Gap (EBG) structures are artificially engineered materials. Such types of materials provide special electromagnetic properties which are not available in natural materials. Electromagnetic band gap structures are the periodic structures with cell size much smaller than the free space wavelength[1]. Such materials exhibit a frequency band gap. In the frequency band of operation, the surface waves are suppressed at the metal-dielectric interface. This results in electrical performance improvement of planar antennas as surface waves are transformed into useful radiation. These structures also provide high impedance in frequency band of operation. The high impedance surface reflects the incident waves in the same phase. For the in-phase reflection property of these structures, they are known as perfect magnetic conductors (PMC) or artificial magnetic conductors (AMC). These properties of structures can be used to place radiating antenna elements very close to the EBG/AMC ground plane/ reflector. Mushroom-like[2] and uniplanar compact photonic band gap (UC-PBG)[3] are the two important types of 2D EBG structures. Such structures have their own merits and demerits based on construction and electrical performances. An EBG Ground plane consists of EBG Cells arranged periodically on a substrate and it can be structured in the following manners:

- Metallic ground plane on opposite side of the substrate with via connecting the EBG cells to the ground plane is called the Mushroom-like EBG ground plane[2].
- The metallic ground plane on opposite side of a substrate without via and cells are inter- connected with thin strips is called a uniplanar compact photonic band gap (UC-PBG)[3] EBG ground plane.
- No metallic ground plane on opposite side of the substrate and inter-connected cells themselves are used as a ground plane called defected ground structure (DGS)[4].

In this design, the EBG cell[5] is taken as a basic cell to configure it as a DGS to form a 2D DGS ground plane. This ground plane is used as a reflector for the spiral antenna. The proposed structure provides better bandwidth and low-frequency coverage.

Spiral antennas are the popular choice for airborne platforms and space applications. Such types of antennas can be flush mounted on the skin of the vehicles. The electrical attractive features of these antennas are wide bandwidth, good gain, and circular polarisation capability. The geometries of these antennas are defined in terms of angles. In case of Archimedean spiral antennas, antenna elements are placed in complementary form structures providing constant antenna impedance over a large frequency band. The radiation patterns of a spiral antenna are bidirectional with beam maxima perpendicular to plane of the spiral. This type of antennas is

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made unidirectional using a metallic cavity behind the radiator. This metallic cavity, being PEC reflects the energy 180º out of phase causing destructive interference with the main beam. The following implementations are incorporated to solve this problem:

- The cavity is placed at a distance of λ/4 to get constructive interference between direct and reflected waves causing better directivity in desired direction. The λ/4 physical spacing is constant at corresponding single frequency resulting narrow band of operation.
- The electrical spacing between the cavity and spiral will vary over the frequency band and consistent radiation characteristics cannot be achieved over the frequency band. The above problem is solved by filling the cavity with RF absorbers to absorb interfering backward radiations. But this solution lowers the antenna efficiency due to power absorption in absorbers and antenna gain may reduce substantially.

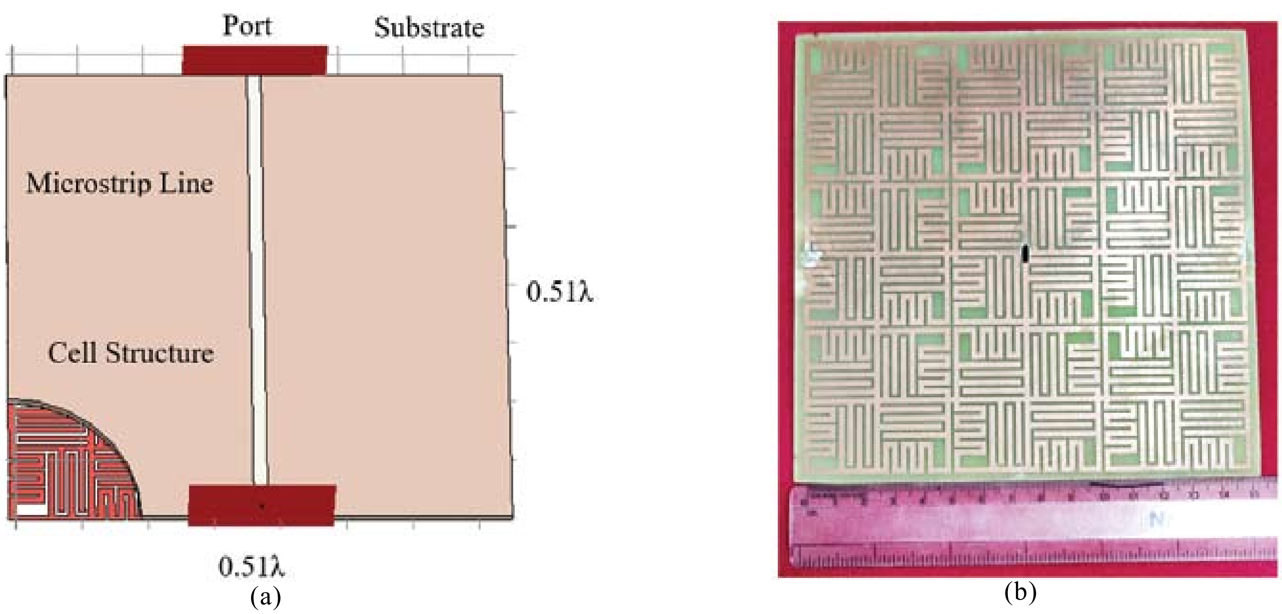
In-phase reflection properties of EBG reflector allow placing the spiral antenna very close to the reflector. This type of arrangement makes the antenna compact and electrical performance is also improved. In this proposed design, the working frequency range of DGS ground plane is 1-7 GHz. The bandwidth for the spiral antenna with DGS ground plane as a reflector is 1-6 GHz.

2. DGS GROUND PLANE AS A REFLECTOR FOR SPIRAL ANTENNA

2.1 Design, Modeling and Realisation, and Performance Evaluation

The EBG Cell design[5] is adopted for the design of the DGS ground plane. The proposed cell is suitable to work at lower frequencies with lesser overall dimensions. The electrical evaluation of this cell is carried out only at cell level up to 3GHz. The electrical characteristics include, electromagnetic band gap and reflection phase. For configuration of the DGS finite- sized ground plane, this cell is used as a unit cell. For square ground plane, N x N number of cells is used on the substrate to form the ground plane. The 2D ground plane is modeled using 3x3 cells on a FR4 substrate with ε_r= 4.3 and height=3 mm, in an FDTD-based simulation tool[6]. The inter-cell spacing is kept at 2 mm and the cells are inter-connected with a strip length of 2 mm to form a DGS. The size of this DGS ground plane is 0.51λ x 0.51λ, where λ is the free space wavelength at lowest frequency of operation (1GHz). For the simulation of S-parameter, a 50Ω microstrip line is modeled on the other side of the substrate[7]. The simulation model for the DGS ground plane with dimensional details is shown in Fig. 1(a). This DGS ground plane is realised in planar form with FR4 substrate using printed circuit technology. For S-parameters testing a 50Ω microstrip line is printed on the opposite side of the substrate. The SMA connectors are used as feed ports for this line. The photograph of the proposed DGS ground plane is shown in Fig.1 (b). A DGS ground plane should provide a large drop in S_{21} with magnitude of S_{11} near 0 dB to exhibits its electromagnetic band gap properties.

The S-parameters are measured using M/s Agilent E5071C Vector Network Analyser. An overlay of Simulated and Measured transmission coefficient (S_{21}) is shown in Fig. 2(a). The magnitude of measured transmission coefficient S_{21} is more than 10 dB in the frequency band of interest. This is the bandwidth that can be considered as the operational band width of the DGS ground plane. For verification of the S-parameter simulation setup, the simulation of S-parameters for conventional microstrip lines by replacing the DGS with perfect electrical conductor (PEC) ground plane. A 50Ω microstrip line is modeled over a grounded FR4 substrate having similar parameters to DGS substrate, for this verification. The simulated S-parameters for this line are shown in Fig. 2(b). The value of the magnitude of S_{11} is more and S_{21} is lesser, as expected. These results show the characteristics of a low-loss-matched transmission line.



(a) (b)

Figure 1. (a) Simulation model of DGS ground plane, and (b) Photograph of realised DGS ground plane.

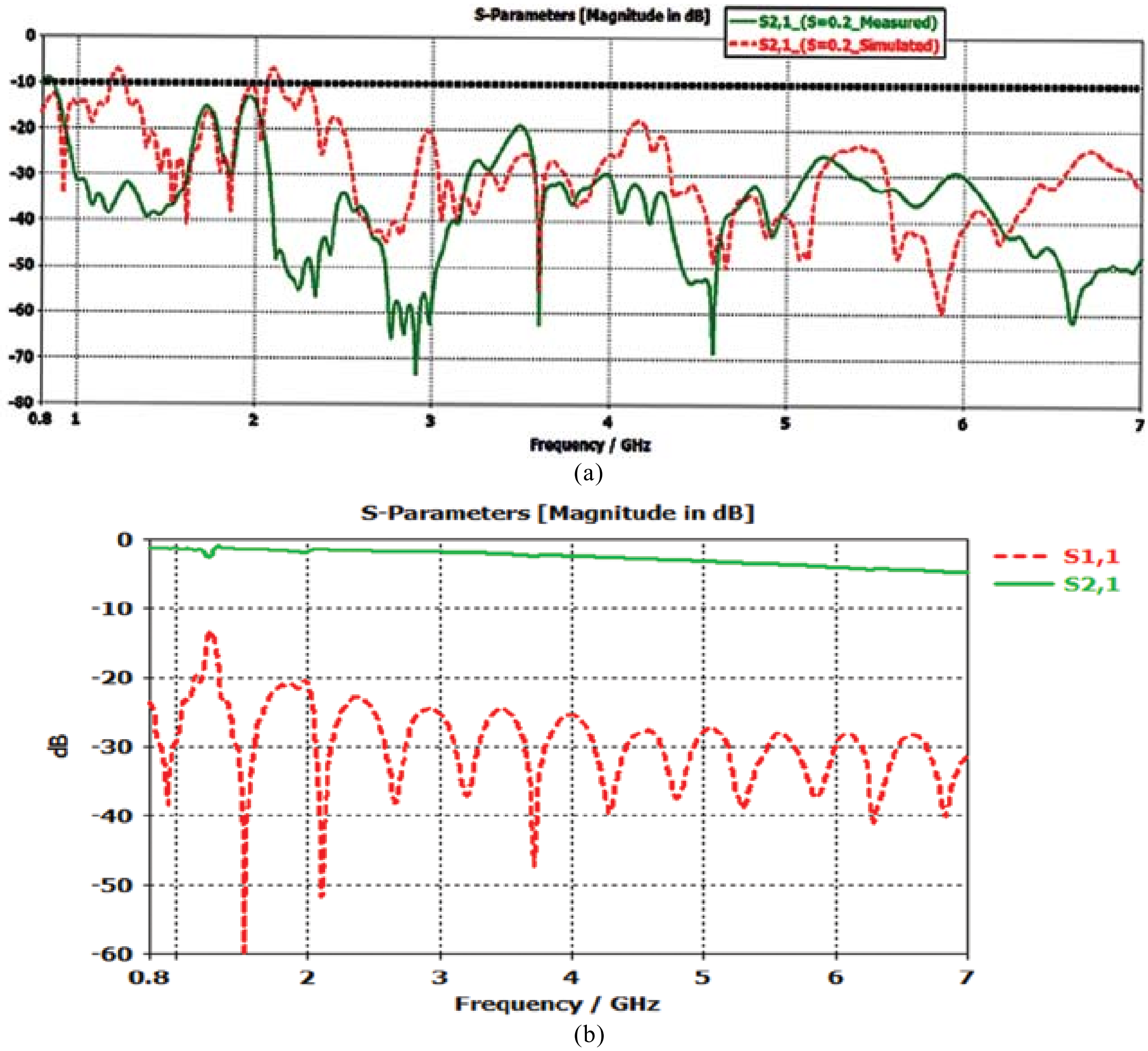


Figure 2. (a) Overlay of simulated and measured S21 for proposed DGS ground plane, and (b) Simulated S-parameters for 50Ω microstrip line.

3. THE ARCHIMEDEAN SPIRAL ANTENNA WITH DGS AS A REFLECTOR

3.1 Design and Modelling of Archimedean Spiral Antenna

The Archimedean spiral antennas are wideband. It is because the antenna elements are defined in terms of angles[8]. The arms of the spiral are flared out as a function of angle. The radius of spiral arm is defined as:

$$r = a\varphi + r_1 \quad (1)$$

Since the other arm of spiral is angularly displaced by 180º (π rad.), the radius for this second arm is defined as:

$$r = a(\varphi - \pi) + r_1 \quad (2)$$

where, r_1 = initial radius of spiral, r = instantaneous radius of spiral and a=constant, controls the flaring rate of spiral.

The low and high-frequency responses of the spiral are decided by the maximum radius $r = r_2$ and minimum radius $r = r_1$ respectively. The low and high frequencies of operation in terms of these radii are defined as follows-

$$f_{LOW} = c / (2\pi r_2) \quad (3a)$$

$$f_{HIGH} = c / (2\pi r_1) \quad (3b)$$

where, c is velocity of EM wave.

If W= width of spiral conductor, S= Spacing between two adjacent conductors and N= Number of turns of spiral then these parameters are related as follows:

$$W = [(r_2 - r_1)/2N] - S \quad (4)$$

For complimentary structures, S=W and

$$S = W = (r_2 - r_1))/4N \quad (5)$$

By Babinet's principle, the characteristics impedance of a spiral antenna with its complementary is 188.5Ω. In practical antennas, this value may range from120 to 150 Ω.

The Archimedean spiral antenna is modeled on an FR4 substrate of thickness 1.6mm. Antenna parameters are: S=W=3 mm, r_1=4 mm, r_2=76 mm and N=6.This antenna modeled is simulated for its impedance and radiation characteristics in frequency range of 0.5-10 GHz. Simulation of impedance is carried out with a fixed port impedance of a fixed port impedance of 150Ω which is assigned as a port impedance.

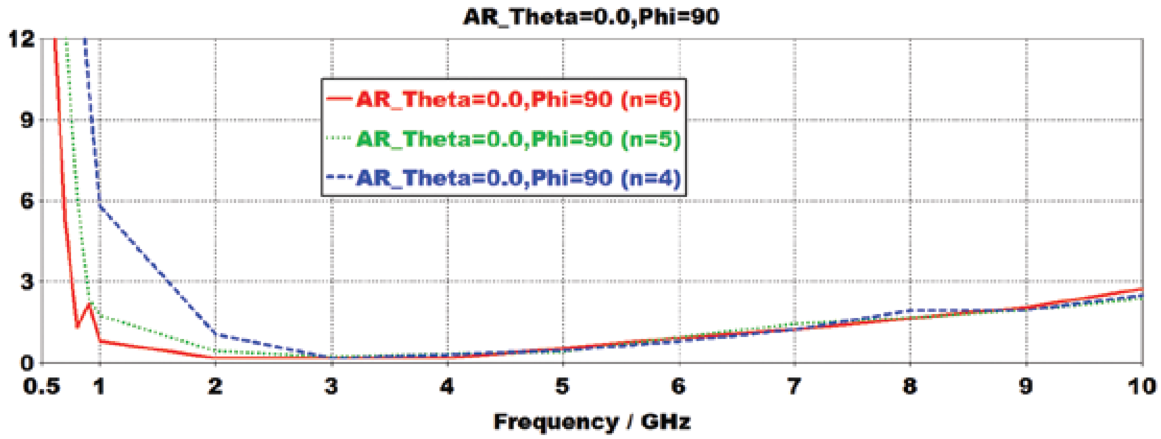


Figure 3. Variation of on-axis axial ratio of archimedean spiral antenna as a function of N.

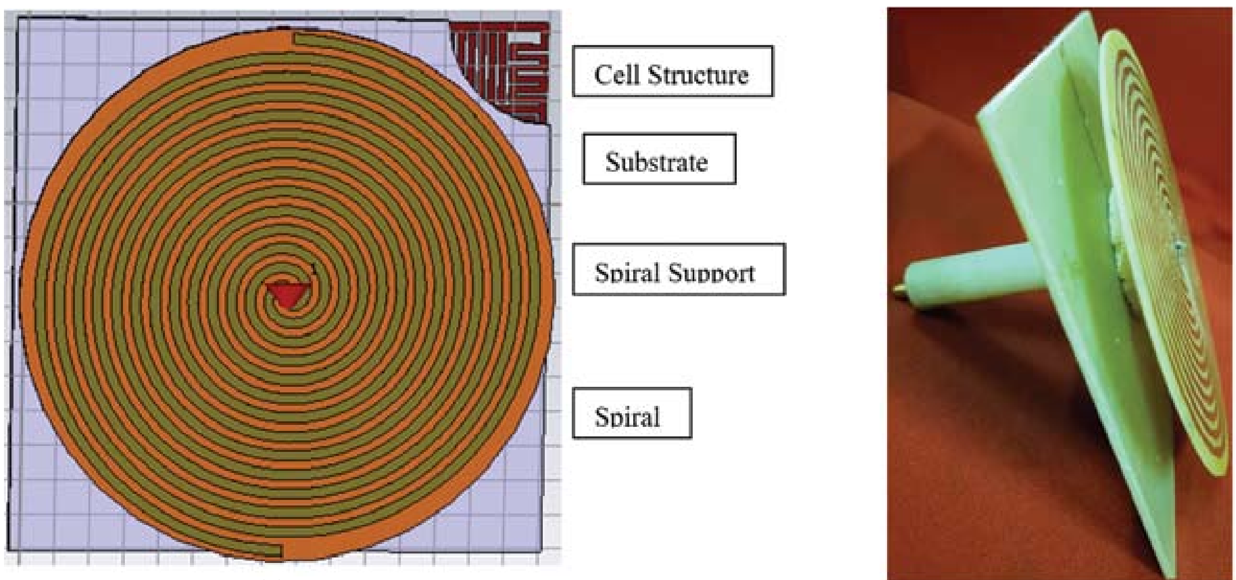


Figure 4. (a) Simulation model of proposed antenna, (b) Photograph of the proposed antenna.

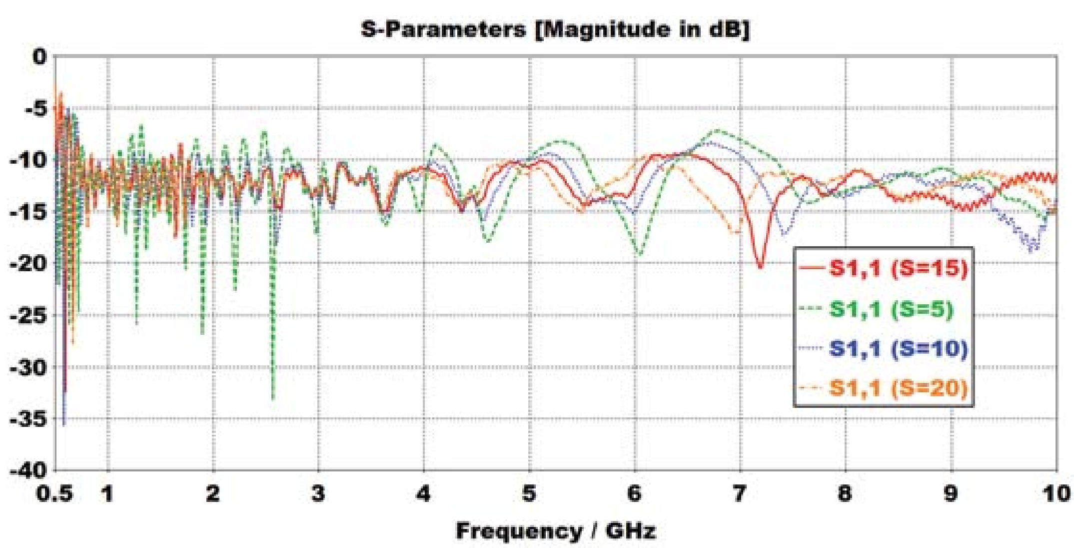


Figure 5. Simulated return loss plots over the frequency band for different spacing.

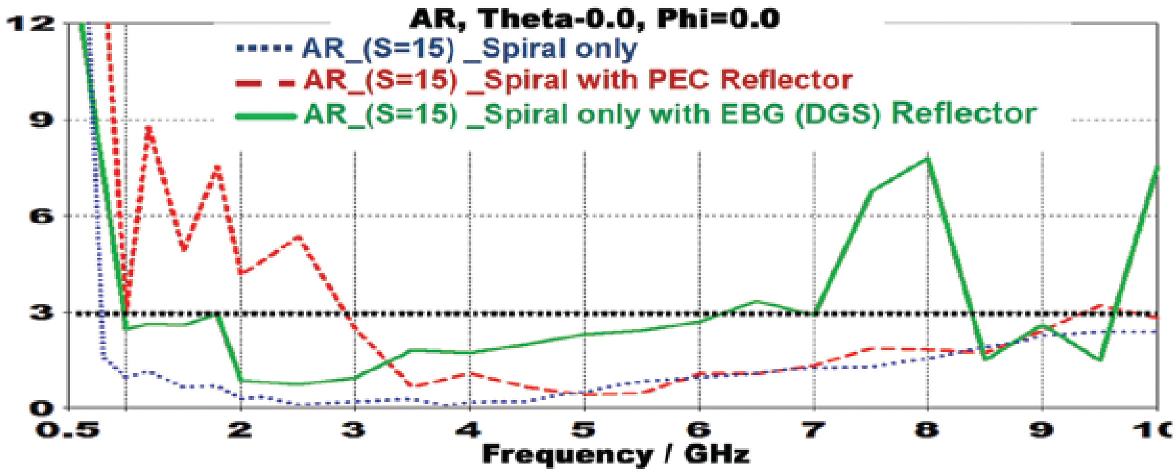


Figure 6. Simulated axial ratio comparison over the frequency band.

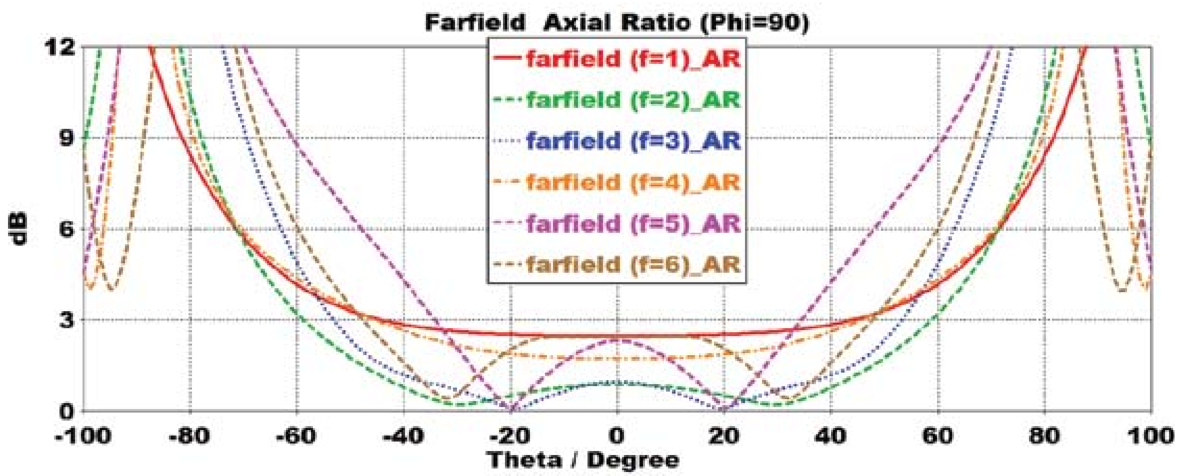


Figure 7. Simulated axial ratio variation of proposed antenna as a function of direction.

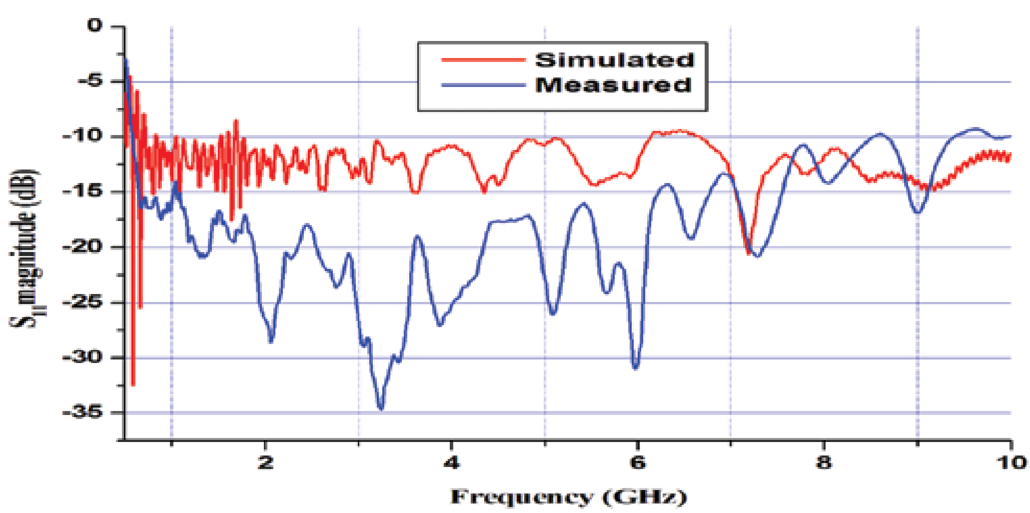
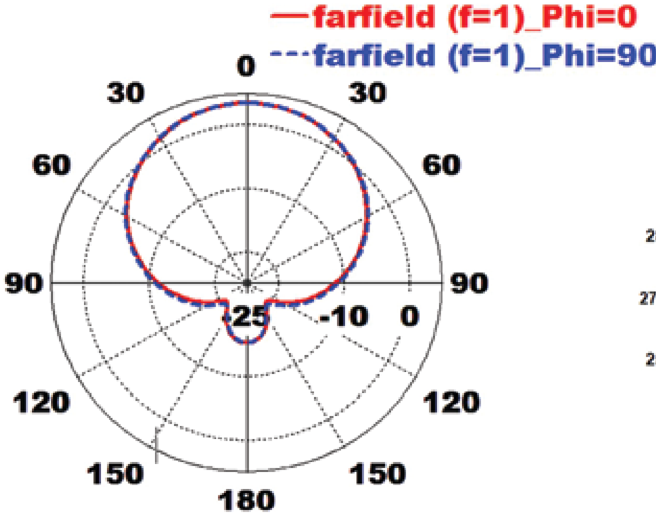


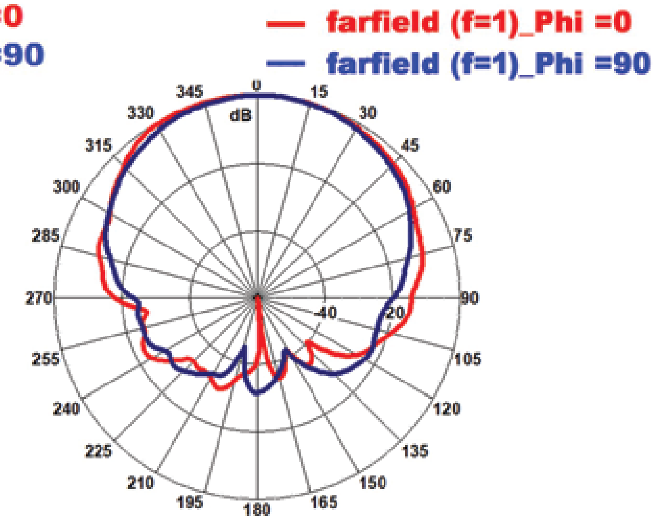
Figure 8. Simulated and measured S11 magnitude of proposed antenna.

Antenna return loss is plotted as a function of number of turns (N) of the spiral while keeping other parameters constant. The optimised number of turns for 10 dB return loss is N=6.

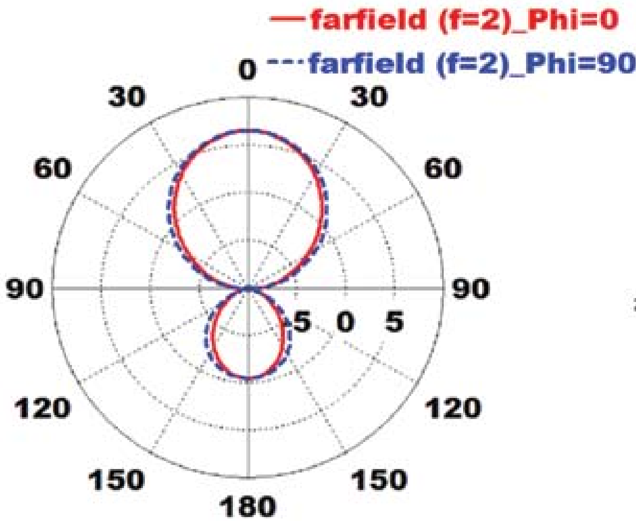
Simulated return loss is more than10dB above 1 GHz for all the three cases (N=4 to N=6). The effect on the boresight axial ratio is also studied as a function of number of turns of



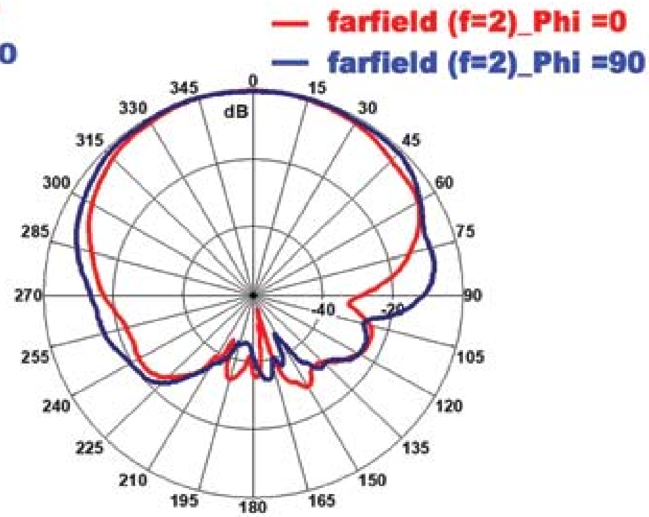
(a) Simulated, f=1 GHz.



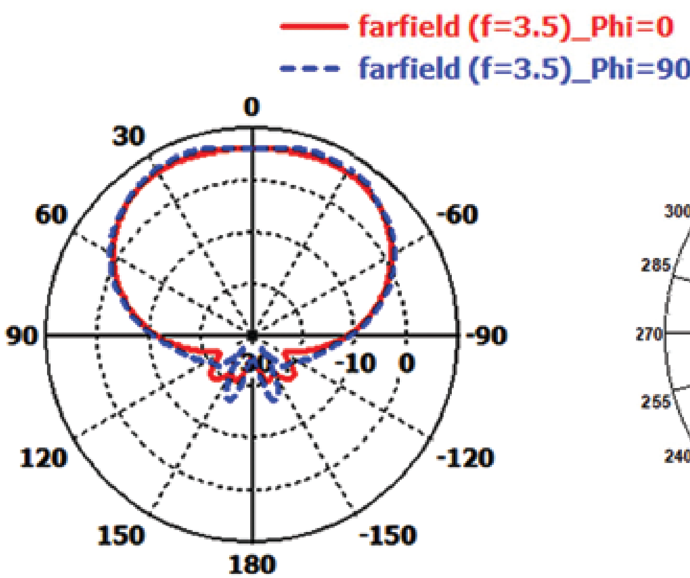
(a) Measured, f=1 GHz.



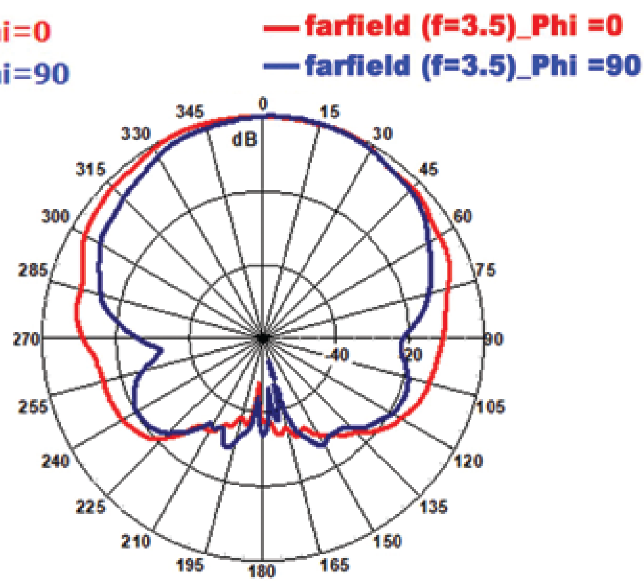
(b) Simulated, f=2 GHz.



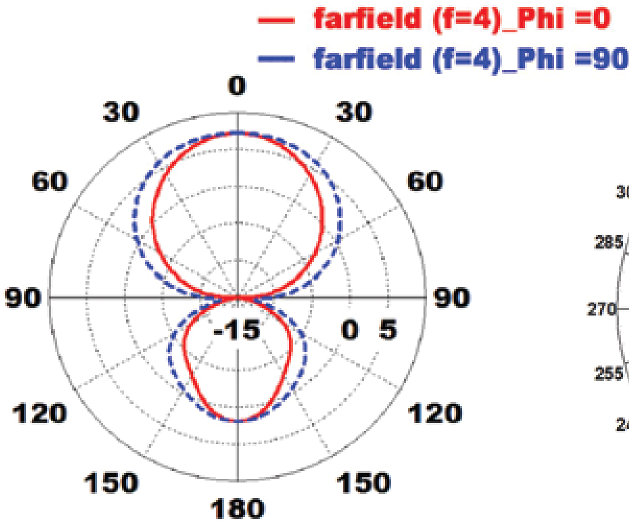
(b) Measured, f=2 GHz.



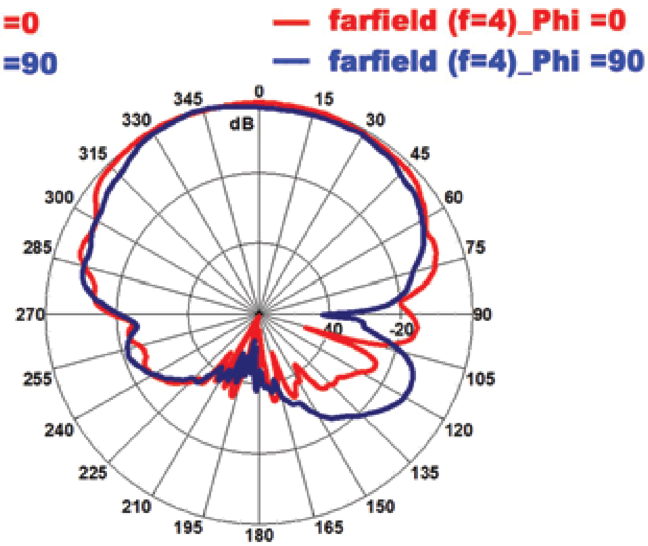
(c) Simulated, f=3.5 GHz.



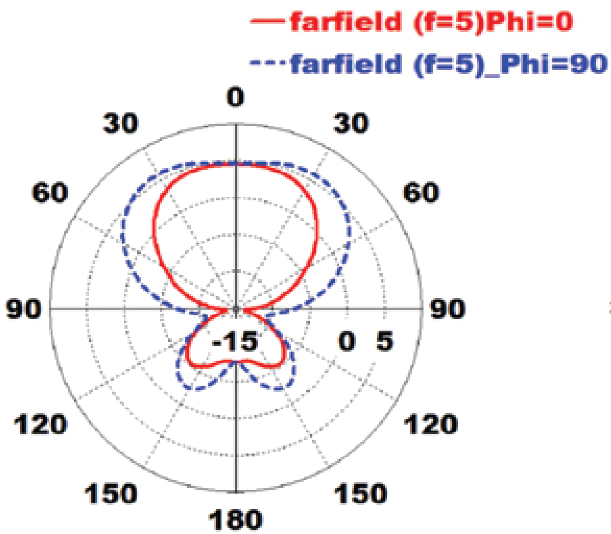
(c) Measured, f=3.5 GHz.



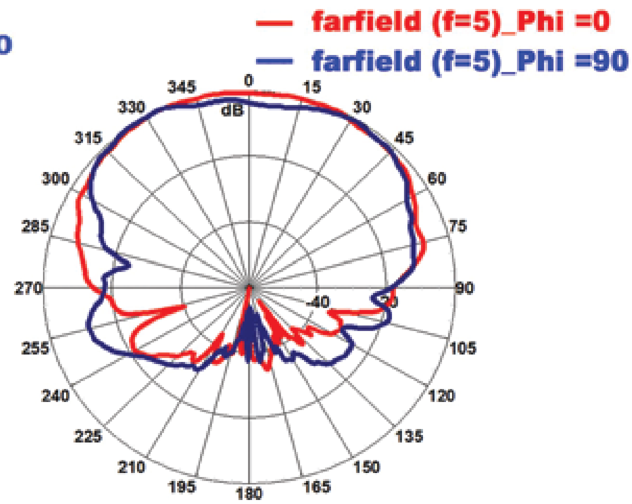
(d) Simulated, f=4 GHz EBG.



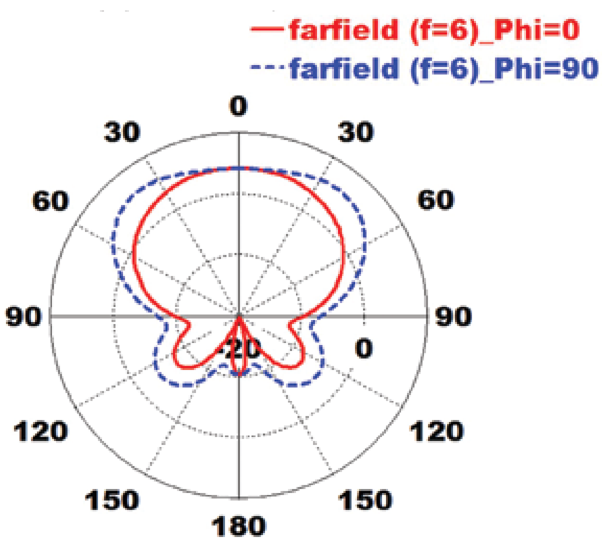
(d) Measured, f=4 GHz.



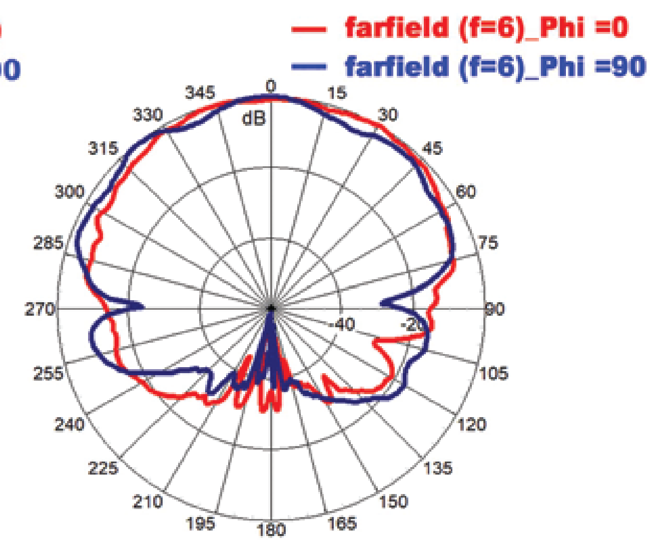
(e) Simulated, f=5 GHz EBG.



(e) Measured, f=5 GHz.



(f) Simulated, f=6 GHz EBG.



(f) Measured, f=6 GHz.

Figure 9. (a-f) Simulated radiation patterns of proposed antenna EBG.

Figure 10. (a-f) Measured radiation patterns of proposed antenna EBG.

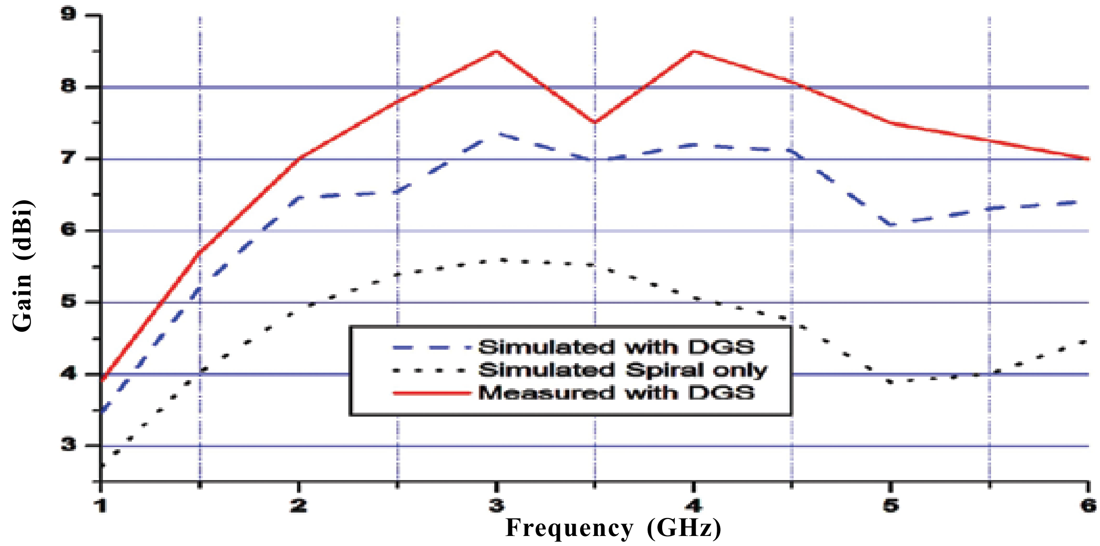


Figure 11. Comparison of gain plots for proposed antenna EBG.

Table 1. Comparison of performance of proposed antenna with similar antennas

Ref.	Radiating element	Reflector parameters	Element to reflector spacing	Mid-band freq. (f0) (GHz)	Bandwidth (%)	
					Impedance	3dB AR
9	Square spiral	Mushroom-like EBG, size: 2.18 λ x2.18 λ	0.1λ	6	-------	11 (Boresight)
10	Archimedean spiral	Mushroom-like EBG, size: 1.1 λ x1.1 λ	0.02λ	12	42	-------
11	Archimedean spiral	Resistively loaded metallic patches, size:0.43 λ x0.43 λ	0.006 λ	5.5	163.6	-------
12	Equiangular spiral	Modified mushroom-like EBG, size: 5.5 λ x4 λ	0.06λ	3	66.7	-------
13	Equiangular spiral	Mushroom-like EBG, size: 2.23 λ x2.23 λ	0.07λ	6.5	76.9	76.9 (Boresight)
14	Archimedean spiral	Mushroom-like EBG, size: 0.93 λ x0.93 λ	0.02λ	15	66.7	-------
15	Archimedean spiral	Frequency selective surface, size:0.78 λ x0.78 λ	0.14λ	5.1	136.6	88.3 (Boresight)
This work	Archimedean spiral	DGS, 0.51 λ x0.51 λ	0.05λ	3.5	70	70 (Boresight) 70 (Off-axis)

the spiral. The corresponding study is shown in Fig. 3 for N=4 to 6. The axial ratio in the main beam direction is not good for number of turns 4 or lesser. It is observed that for N=5 or more axial ration is ≤3 dB above 1 GHz. The axial ratio improves at lower frequencies with the increasing number of turns. The antenna radiation patterns deteriorate at higher frequencies with more turns. N=6 numbers of turns is the optimised value in this design, based on the above observations.

3.2 Archimedean Spiral Antenna on DGS

The spiral antenna is backed by EBG (DGS) reflector to transform it into a directional antenna. The simulation model with dimensional details is given in Fig. 4 (a). The photograph of the proposed antenna is shown in Fig. 4(b). The effect of spacing (S) between spiral and DGS is studied for impedance bandwidth, radiation patterns, and axial ratio (AR). It is varied from S=5 to S=20 mm. The simulated return loss variation as a function of spacing is shown in Fig. 5. The optimized spacing is 15mm; electrically it is 0.05λ at lowest frequency of operation. The focus was on better results of radiation patterns, boresight axial ratio, and 3 dB axial ratio beam width with acceptable return loss, in these simulation studies. The boresight axial ratio for proposed antenna is also compared with a spiral antenna without reflector and with PEC reflector, for optimized spacing S=15 mm. The 3 dB axial ratio is chosen as acceptable value in this comparison. This comparison for boresight axial ratio at a fixed angle (0º) over the frequency band is given in Fig. 6. Frequency bands for axial ratio ≤3 dB for spiral without any reflector backing, with PEC reflector and with DGS reflectors are 0.75-10 GHz, 3-9.5 GHz and 1-6 GHz respectively. The boresight axial ratio for PEC reflector at higher frequencies is better than the proposed DGS reflector but radiation patterns bandwidth with PEC reflector is limited to1- 1.8 GHz. The off-axis performance of the proposed antenna is studied by plotting the variation of off-axis AR, as a function of direction. It is plotted over an angular sector with a maximum 3 dB axial ratio as an acceptable value. The overlay of these plots for different frequencies is shown in Fig. 7. The beam width for 3 dB axial ratio varies from 72º to 120º.

In practical realisation, the spiral antenna is placed on DGS. The spacing between these two is maintained at 15 mm using a foam spacer. For balance to unbalance transformation and impedance matching, a tapered balun of length 100 mm is designed. The antenna is fed with an SMA connector connected at one end of the balun. Owing to gradual impedance transformation, further improvement in measured return loss is achieved. This comparison of return loss is shown in Fig. 8.

The radiation characteristics of the antenna are measured in an anechoic chamber. Simulated and measured radiation patterns are given in Fig. 9 (a-f) and Fig. 10(a-f) respectively. The comparison of antenna gain without and with DGS is given in Fig.11. An improvement in measured gain is observed due to the improvement in front to back ratio in radiation patterns. This improvement is attributed to unavoidable antenna mounting plate attached to measurement system.

3.3 Results Comparison with Existing Designs

The achieved results are compared with the designs[9-15] available in literature. This comparison is shown in Table 1. The off-axis 3 dB axial ratio is an important parameter for circularly polarised antennas. This is the measure of polarization purity of circularly polarised antennas and accordingly it is included in this work.

4. CONCLUSION

A low profile, broadband archimedean spiral antenna with DGS reflector has been designed and realised. The simulated results of the antenna are validated with measurements. The proposed antenna works in frequency range of 1-6 GHz with for all the antenna parameters such as return loss, radiation patterns, gain, on-axis and off-axis axial ratios, etc. the proposed antenna has lesser, weight and volume compared to conventional cavity-backed spiral antennas. The proposed antenna is a good candidate for EW systems, communication systems, and law enforcement.

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Contribution in the current research: He carried out the literature survey for the similar works available. He identified the gaps and conceptualised the design accordingly. He predicted the results by simulation and validated by measurements.

Dr Amara Prakasa Rao obtained his PhD degree from National Institute of Technology Warangal, India, in the year 2018. He is working as an Associate Professor at Department of Electronics and Communication Engineering as an National Institute of Technology, Warangal, India. His areas of interest include: Signal processing, smart antenna systems, and optimisation techniques.
Contribution in the current research work: He has supervised the research work, contributed for theoretical correlation with simulation results and organisation of the research paper.

Dr Mada Chakravarthy obtained his PhD degree from Andhra University, Visakhapatnam. He is working as Sc'G' at DRDO-DLRL. Presently, he is steering Antenna Group as Additional Director for indigenous development of variety of state of the art wideband EW antennas and Radomes covering HF to MMW frequency ranges for all three services.
Contribution in the current research work: He has provided overall guidance and support in testing and analysis of results, measurement setup and review of the research paper.