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Circularly Polarized Cylindrical Dielectric Resonator Antenna with Fractal Cross-Slot: Design, Analysis, and Performance Evaluation

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Abstract: This work focuses on the development and design of a Circularly Polarized Cylindrical Dielectric Resonator Antenna (CDRA) incorporating a Fractal Cross Slot. The antenna is planned for applications requiring enhanced performance in wireless communication systems. The proposed design unites the advantages of circular polarization for reduced signal fading and the unique characteristics brought about by the incorporation of a fractal cross slot. The results in the simulation are showed that it has wonderful impedance bandwidth and radiation efficiency that it is a kind of good performance. But due to the advantages of Fractal-slot-aperture coupled DRA antennas in the wireless application, it is designed further. In this innovative design, a Circularly Polarized (CP) Dielectric Resonator Antenna (DRA) is coupled with a fractal cross-slot, effectively enhancing radiation efficiency. Through meticulous adjustment of the fractal cross-slot dimensions, resonance from both the fractal cross-slot and the dielectric resonator can be merged, leading to a significantly wider Axial Ratio (AR) bandwidth. This novel approach allows for the creation of an antenna meticulously tailored for optimal performance, leveraging the benefits of the fractal cross-slot coupled CP DRA element. The cylindrical dielectric resonator serves as the radiating element, providing a compact and efficient structure. Circular polarization is achieved through careful design considerations, optimizing the orientation and configuration of the dielectric resonator. The use of fractal geometry introduces additional resonances and modifies the radiation characteristics of the antenna. Fractals are employed to enhance the antenna's bandwidth, reduce size, and achieve multi-band capabilities. The resulted patterns are utilized to calculate the antenna's radiation pattern, gain, VSWR, return loss, axial ratio, directivity. Measurements include radiation pattern analysis, and circular polarization verification. The experimental results are compared with simulation predictions, validating the effectiveness of the proposed design. The integration of circular polarization and fractal geometry contributes to improved performance metrics, making the antenna well-suited for modern communication systems requiring compact, high-performance antennas. The findings of this research may advance the state-of-the-art in antenna design and pave the way for practical applications in emerging wireless technologies.

Keywords: *Ultra-wideband, Circular polarization, Fractal cross-slot, Micro-strip antenna, Return-loss, Radiation pattern, Axial-ratio and Dielectric resonator.*

1. Introduction

Dielectric Resonator Antennas (DRAs) operate effectively in microwave frequencies and higher, leveraging a ceramic block called the dielectric resonator situated above a metal surface or ground plane. Radio waves fed into this resonator from a transmitter induce standing waves within, and the semi-transparent walls of the resonator permit the release of energy into the environment. By appropriately exciting the dielectric structure, it can function as an effective radiator at certain frequencies, with the resonator size being inversely proportional to the material's relative permittivity. The initial studies on DRAs primarily addressed linearly polarized configurations until the landmark introduction of Circularly Polarized (CP) DRAs by Herneisha and Takizawa in 1985 through modifications to a rectangular DRA, which has since spurred numerous developments in CP DRA designs [1].

Subsequent enhancements in CP DRA array performance have been influenced not only by the feeding networks but also by the characteristics of individual array elements [2], [3]. Researchers have devised several methods to expand the axial ratio (AR) bandwidth of single DRAs, including the use of multiple-feed techniques, traveling wave excitation, and innovative DRA shapes [4], [5]. These advancements, however, can introduce complexities that complicate DRA array designs, potentially reducing radiation efficiency or creating inefficiencies in the design process [6], [7].

In a specific advancement, a CP rectangular DRA with a relative permittivity (εr) of 9.2 was developed, featuring a fractal cross slot on the ground plane beneath the resonator. This design achieved an effective AR bandwidth of approximately 12%, notable for its simplicity as it avoids the need for dual feeds or two-layer substrates. The correlation between the measured results and the simulated outcomes for this fabricated DRA antenna confirms the viability of this straightforward design approach [2].

2. Related Work

The design and analysis of a Circularly Polarized Cylindrical Dielectric Resonator Antenna (CP CDRA) with

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a fractal cross-slot for enhanced performance in wireless communication systems incorporate several innovative techniques and materials. The CP CDRA leverages the inherent advantages of dielectric resonator antennas (DRAs), such as wide bandwidth, high gain, high efficiency, low losses, and a low profile, which are crucial for modern wireless applications [8]. The use of a cylindrical dielectric resonator, as discussed in various studies, is particularly effective for achieving circular polarization, a key feature that minimizes multipath distortion and polarization mismatch losses [9]. The integration of a fractal cross-slot in the CP CDRA design is a novel approach to improve impedance matching and circular polarization (CP) purity. This technique is inspired by the use of cross slots and parasitic elements to enhance the performance characteristics of DRAs, such as impedance bandwidth and axial ratio (AR) bandwidth, while also stabilizing the gain across the working passband [10].

The fractal design contributes to a more compact antenna size without compromising the bandwidth and gain, addressing the need for compact and effective radiators in wireless technology [11]. Performance evaluation of the proposed CP CDRA shows promising results, with a significant improvement in the impedance bandwidth and AR bandwidth, ensuring efficient operation over a wide frequency range. The antenna exhibits stable gain and excellent radiation suppression levels outside the passband, indicating its potential for high-performance applications [12].

Moreover, the circular polarization achieved by the antenna makes it suitable for applications requiring robust communication links, such as Ground Penetrating Radar (GPR) and multiple-input-multiple-output (MIMO) systems, where circular polarization can increase channel capacity, link reliability, and data rate [13]. In conclusion, the CP CDRA with a fractal cross-slot represents a significant advancement in antenna design for wireless communication, combining the benefits of DRAs with innovative structural modifications to meet the demands of modern communication systems.

The design and performance evaluation of a Circularly Polarized Cylindrical Dielectric Resonator Antenna (CDRA) with a fractal cross-slot incorporates various innovative techniques and materials to enhance its operational bandwidth, gain, and axial ratio (AR) characteristics. The proposed antenna amalgamates the principles of circular polarization, dielectric resonator antennas, and fractal geometry to optimize its performance for applications requiring wideband and high-efficiency communication. The use of a truncated conical dielectric resonator antenna (DRA) with a split-ring microstrip line and six probes demonstrates a significant improvement in the axial ratio bandwidth, achieving a 3-dB AR bandwidth of 24% and a peak gain of 9.48 dBic, which lays a foundational principle for enhancing circular polarization and gain in cylindrical DRAs [14].

The incorporation of orthogonal feeding mechanisms, as seen in rectangular DRAs, to excite mutually orthogonal radiation modes, further contributes to the circular polarization characteristics, offering a novel approach to achieving wide axial ratio beamwidths [15]. The application of fractal geometry, as demonstrated by a fractal antenna based on a circular spiral patch, introduces a method to improve antenna performance through the introduction of circular slots, which could be adapted to enhance the cross-slot design in cylindrical DRAs for better impedance matching and miniaturization [16]. The use of high dielectric constant materials, as explored in satellite application-focused CDRAs, suggests that materials with higher dielectric constants can produce higher gain and lower return loss, which is crucial for the design of efficient CDRAs [17].

Moreover, the employment of dielectric vias filled with barium strontium titanate nanoparticles in a compact and wideband CP DRA design offers insights into size reduction and bandwidth enhancement through effective dielectric constant manipulation. This technique could be pivotal in designing a fractal cross-slot CDRA by redistributing resonant frequencies of different radiating modes to achieve wide impedance and AR bandwidths [18]. In summary, the design and analysis of a Circularly Polarized Cylindrical Dielectric Resonator Antenna with a Fractal Cross-Slot should integrate the use of high dielectric constant materials, fractal geometry for slot design, and orthogonal feeding mechanisms to enhance its performance in terms of bandwidth, gain, and axial ratio. These strategies collectively contribute to the development of a high-performance CDRA suitable for wideband and efficient communication applications [19] [20] [21].

3. Design of Cp Cylindrical Dra Antenna

This research delves into the analysis of a Circularly Polarized (CP) Cylindrical Dielectric Resonator Antenna (CDRA) featuring enhancements enabled by fractal cross-slot coupling. This innovative design facilitates efficient radiation while simultaneously exciting the CDRA. Through meticulous adjustment of the fractal cross-slot dimensions, the resonances of both the cross-slot and the dielectric resonator merge, resulting in a broader Axial Ratio (AR) bandwidth and impedance bandwidth. Experimental validation confirms the functionality of the proposed CDRA across a frequency range spanning from 6.7GHz to 9.2GHz, with a noteworthy 3-dB axial ratio bandwidth extending from 7.7GHz to 8.65GHz.

Antenna Structure: This is the arrangement where a Rogers 5880 duroid (T) substrate with a dielectric constant of 2.2, dissipation factor of 0.0009 and thickness of 0.508mm was employed in the design process whereas the substrate dimensions were restricted to 50mm for both length and breadth. In the centre of the ground plane there stands an earth ceramic cylinder which measures 5.5 mm by radius, height being also 5.5 mm while on the base plane below this is an etched fractal cross-slot on it and under which attains a cubic ceramic .The length of the microstrip line designed at the bottom side of substrate with characteristic impedance Zo equals If1 + lf2, where lf1 is distance between port of impedance value equal to 50 ohms and center of cubic ceramic and If2 is from middle point of cubic ceramic upto terminal end on microstrip line having characteristic impedance equal to Zo = 50 ohms.

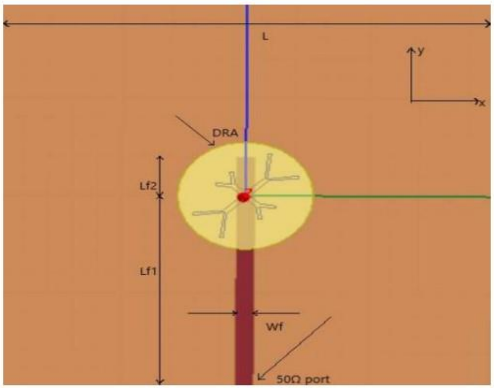


Fig. 1. Structure of Cylindrical Dielectric Resonator Antenna

The influence of the Fractal Cross-Slot is demonstrated in Figure 2 and Figure 3, showcasing the configurations of the fractal cross-slot at iterations n = 0 and 1. The fractal pattern originates from the initial cross-slot (n = 0), characterized by side lengths ls1 and ls2 (where ls2= ks × ls1) and a width of ws. During the iterative procedure, the slot width remains consistent, while the iterative angle is represented by Ψ, and the iterative length coefficient is maintained at 0.5.

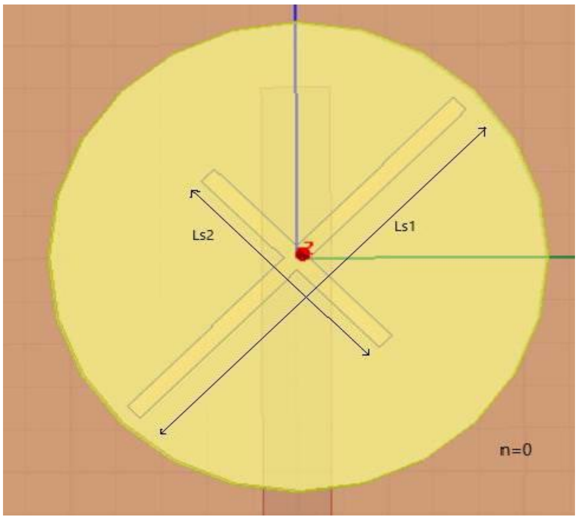


Fig. 2. Structure of fractal cross slot with n=0

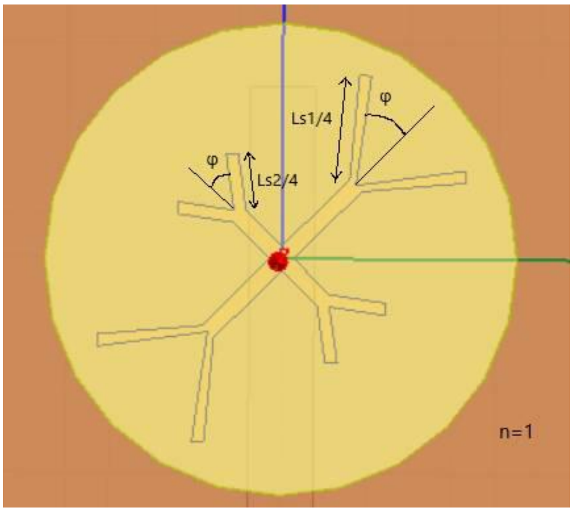


Fig. 3. Structure of fractal cross slot with n=1

4. Simulation Using Hfss

HFSS, short for High-Frequency Structure Simulator, represents a robust software solution tailored for the simulation and analysis of electromagnetic fields within high-frequency and high-speed electronics components. Utilizing a 3D full-wave Finite Element Method (FEM) field solver, HFSS accurately forecasts the electrical traits of intricate components, accommodating diverse shapes and user-defined material properties with precision. This tool is particularly valuable for engineers working on the design and analysis of components operating in the high-frequency and radio frequency (RF) ranges, providing a comprehensive solution for understanding and optimizing electromagnetic interactions in complex electronic systems. Ansys specializes in engineering simulation software. The design and analysis of different electronic and communication devices like microwave circuits, RF filters, antennas, and other high-frequency components are among the major uses of HFSS. To solve Maxwell's equations, the software utilizes finite element analysis (FEA) to predict and optimize electromagnetic behavior for engineers' designs. Engineers employ HFSS to analyze the electromagnetic features of different structures, measure their performance, and ensure that they comply with specific design criteria. This allows fine-tuning of designs by using simulation output from HFSS to optimize performance reducing the need for physical prototypes hence saving time as well as resources in product development process. The final testing and verification effort on such computer simulated high frequency behaviors mitigates system(errors) test requirement since multiple prototypes become unnecessary and reduce the cost in terms of both money and time while developing a product.

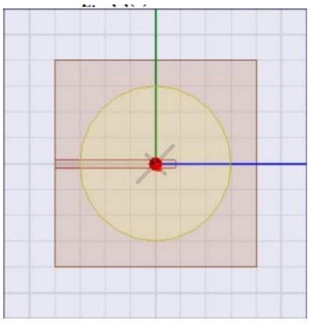


Fig. 4(a)

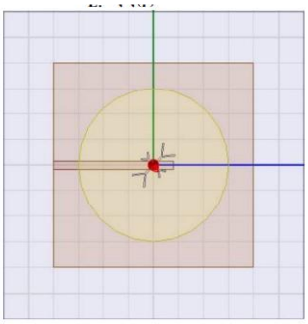


Fig. 4(b)

Fig. 4(a) Circularly Polarized Dielectric Resonator Antenna Featuring Fractal Cross-Slot at Initial Iteration (0th)

Fig. 4(b) Circularly Polarized Dielectric Resonator Antenna Featuring Fractal Cross-Slot at Initial Iteration (1st)

5. Simulation Results

5.1. Simulation Results of Circularly Polarized DRA with Fractal Cross-Slot of 0th iteration using HFSS

The return loss of the circularly polarized Dielectric Resonator Antenna with a Zeroth iteration Fractal Cross-Slot, as designed in HFSS and shown in Figure 4(a), is depicted in Figure5. The S11 value is observed to be-14.5348dB at 8GHz and -23.7826dB at 9.4GHz, and it remains below -10dB across two frequency bands. To consolidate these bands, an additional iteration, n=1, is considered.

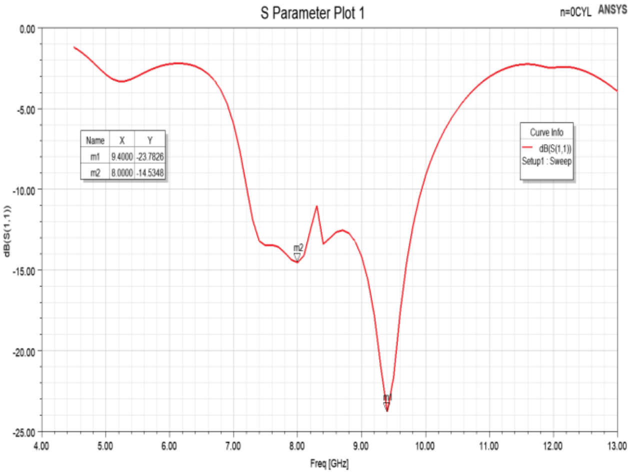


Fig. 5. Simulated return loss for the proposed antenna

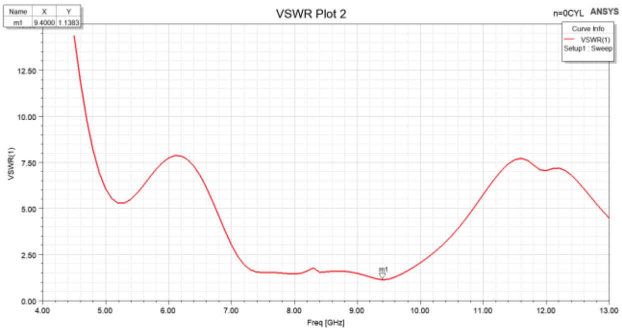


Fig. 6. simulated VSWR for proposed antenna

The VSWR values for the Circularly Polarized Dielectric Resonator Antenna with a Fractal Cross-Slot of zeroth iteration, designed in HFSS and shown in Fig 4(a), range between 1 and infinity. For practical use, the VSWR should ideally be between 1 and 2. Notably, the minimum VSWR observed is 1.1383 at a frequency of 9.4 GHz, indicating a strong match for the antenna in that configuration.

The antenna's gain, depicting the power transmitted per unit solid angle, is pivotal for its operational efficacy. In the instance of the Circularly Polarized Dielectric Resonator Antenna crafted using HFSS, corresponding in Fig 4(a), the 3-D gain registers at 5.8559dB, surpassing the commonly sought-after 3dB threshold across diverse applications.

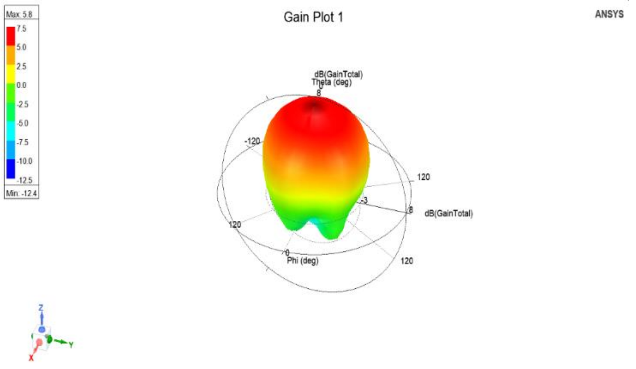


Fig. 7(a) Gain of Circularly Polarized Dielectric Resonator with Cross-slot of Zeroth iteration

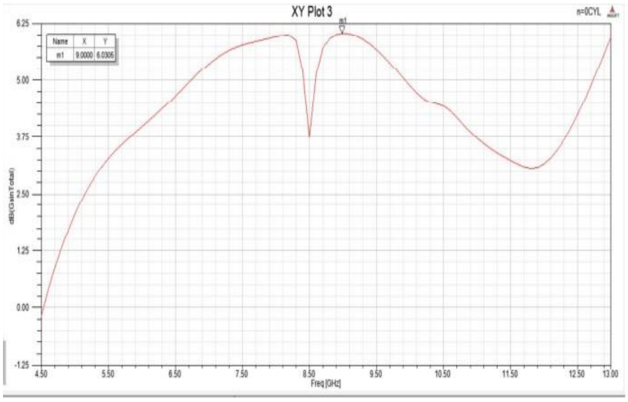


Fig. 7(b) Gain vs frequency plot of cylindrical DRA under zeroth iteration

The radiation pattern of the antenna, designed in HFSS and corresponding to Fig 4(a), visually demonstrates how the transmitted power changes with the direction away from the antenna. This directional power variation, observed in the antenna's far-field, is illustrated in both Fig 8(a) and Fig 8(b).

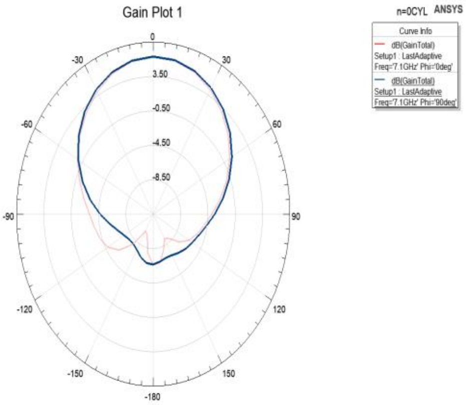


Fig. 8(a) - Radiation pattern of circularly Polarized DRA with Fractal Cross-Slot of Zeroth iteration at 7.1GHz).

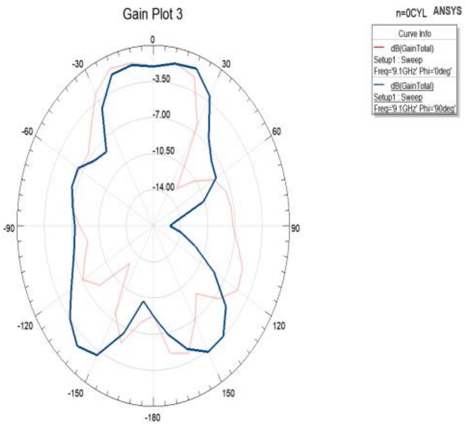


Fig. 8(b) - Radiation pattern of circularly Polarized DRA with Fractal Cross-Slot of Zeroth iteration(phi=9.1GHz).

The axial ratio (AR), representing the ratio between the minor and major axes of the polarization ellipse, is crucial for circularly polarized antennas. In practical terms, an axial ratio below the 3dB.The Axial Ratio of the Circularly Polarized Dielectric Resonator Antenna with a Fractal Cross-Slot, designed in HFSS and corresponding to Fig 4(a), is depicted in Fig 9 is observed at 1.2875dB at 7.1GHz which is below 3dB.

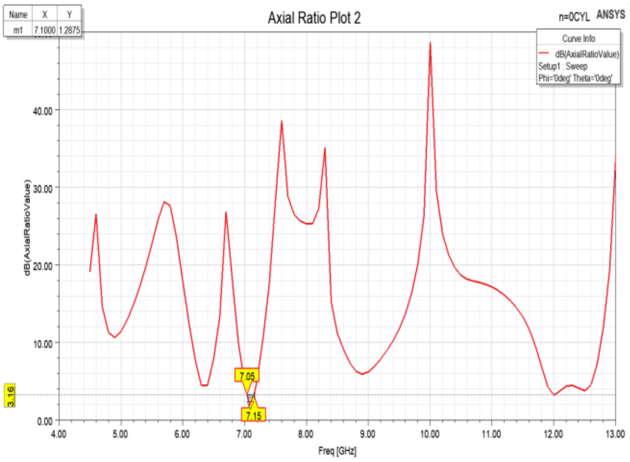


Fig. 9. Axial Ratio Analysis for Circularly Polarized Dielectric Resonator Antenna with Fractal Cross-Slot (0th Iteration)

Field Patterns:

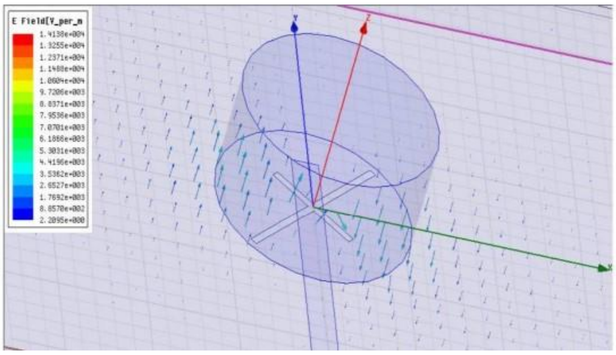


Fig. 10(a)

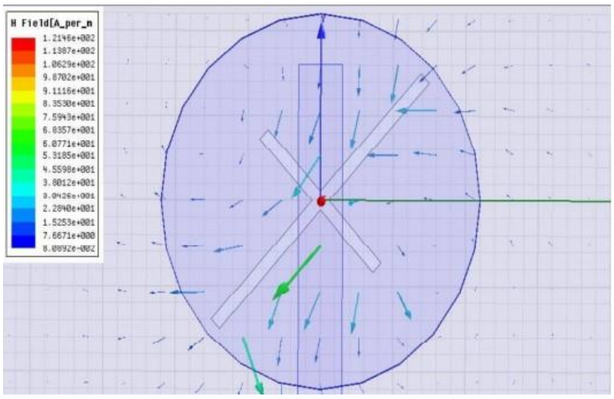


Fig. 10(b)

5.2. Simulation Results of Circularly Polarized cylindrical DRA with Fractal Cross-Slot of first iteration using HFSS

The return loss behavior of a Circularly Polarized Dielectric Resonator Antenna (CPDRA) featuring a Fractal Cross-Slot from the first iteration, as simulated through High-Frequency Structure Simulator (HFSS), is illustrated in Figure 11, corresponding to the configuration outlined in Figure 4(b). The graph reveals that the S11 parameter remains below -10dB across a broad frequency range, specifically spanning from 6.7 to 9. 5GHz.Notably, the minimum value of S11 is recorded at 7GHz, reaching -34.783dB.This suggests that the antenna exhibits effective impedance matching and resonant performance over the mentioned frequency band, making it suitable for applications within this range.

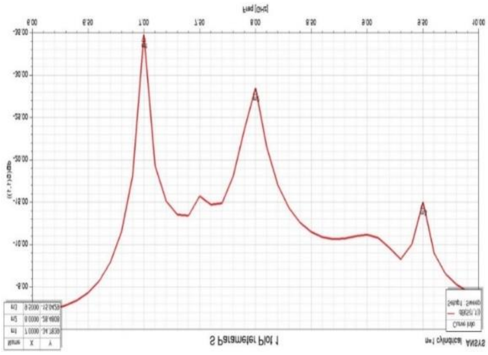


Fig. 11. Return Loss of Proposed antenna with Cross-slot of First iteration

The Voltage Standing Wave Ratio (VSWR) serves as an indicator of how well an antenna is matched to its transmission line. A perfect match is represented by a VSWR of unity. In the case of the Circularly Polarized Dielectric Resonator Antenna with a Fractal Cross-Slot of the First iteration, designed in HFSS and corresponding to Figure 4(b), the VSWR characteristics are depicted in Figure 12. The VSWR values for this antenna fall within the range of 1 to infinity, and for practical applications, it is desirable to have VSWR values between 1 and 2. The observed VSWR for this antenna remains below 2dB over a frequency range spanning from 7 to 9.5 GHz. The value of VSWR is recorded at 7 GHz is 1.0371, at 8 GHz is 1.0783 and at 9.5 GHz is 1.43. This suggests that the antenna maintains good impedance matching within this frequency band, making it well-suited for practical applications requiring reliable performance.

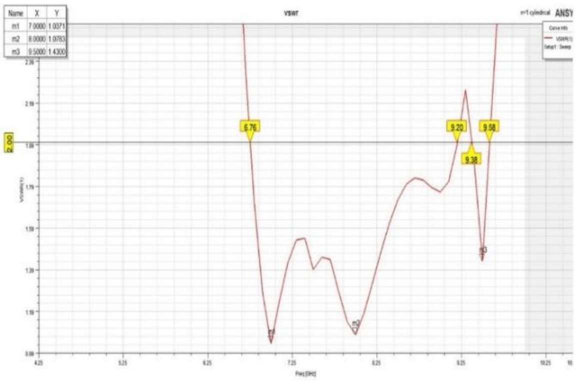


Fig. 12. VSWR for proposed CP-CDRA with First Iteration Fractal Cross-Slot

The antenna's gain signifies the power emitted per unit solid angle. Specifically, in the Circularly Polarized Dielectric Resonator Antenna incorporating a Fractal Cross-Slot from the initial iteration and designed through HFSS, this parameter is of paramount importance, and corresponding to Figure 4(b), the three-dimensional gain is a crucial parameter. For effective performance in various applications, it is generally preferred for an antenna's gain to exceed 3dB.In the specific case of this antenna, the observed gain stands at 6.4929dB, indicating that it surpasses the 3dB benchmark and is well-suited for applications requiring a higher level of transmitted power within its specified solid angle.

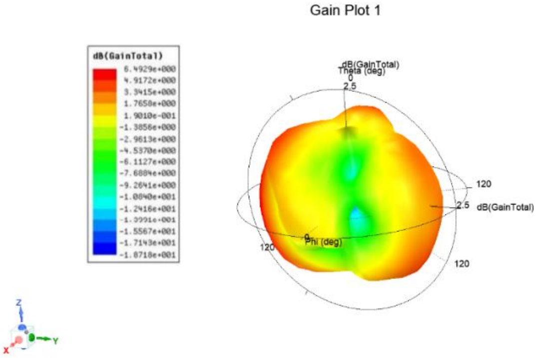


Fig. 13(a) Gain of Circularly Polarized Dielectric Resonator with Cross-slot of First iteration

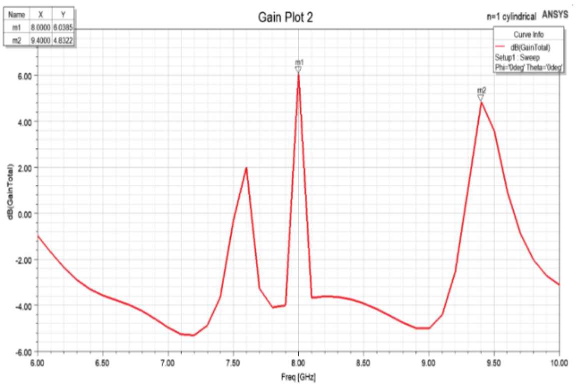


Fig. 13(b) Gain vs frequency plot of cylindrical DRA under First iteration

A radiation pattern depicts the distribution of power emitted by an antenna as it varies with direction away from the antenna. This change in power, discernible in the antenna's far-field region, provides insights into its directional properties. In the case of the antenna designed using HFSS and corresponding to Figure 4(b), the radiation pattern is visually represented in Fig.14. provide a graphical depiction of how the transmitted power changes with different arrival angles, offering insights into the antenna's performance and directional properties in its operational environment.

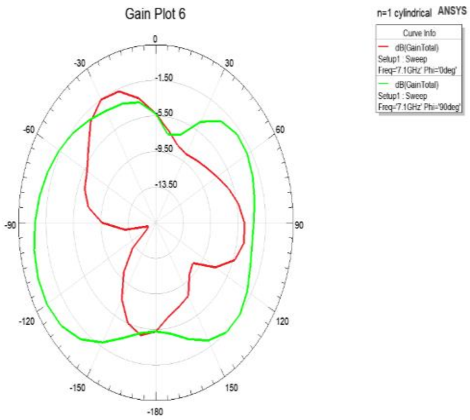


Fig. 14. Radiation Characteristics of Circularly Polarized Dielectric Resonator Antenna with First Iteration Fractal Cross-Slot at Phi = 0°and Phi = 90°

The axial ratio (AR) quantifies the ratio between the minor and major axes of the polarization ellipse. In the context of a circularly polarized antenna, a lower axial ratio is desirable, ideally approaching 0 dB. However, in practical scenarios, the axial ratio is typically considered satisfactory if it falls below the 3 dB line on a logarithmic plot. The axial ratio of the circularly polarized dielectric resonator antenna featuring the Fractal Cross-Slot from the First iteration, designed using HFSS and corresponding to Figure 4(b), is depicted in Fig.15, the Cylindrical DRA with n=1 iteration is showing a wide Axial ratio bandwidth i.e. from 6.7GHz to 7. 14GHz.The minimum value of axial ratio is found to be 0.9522dB at 7GHz.The axial ratio bandwidth is >6% for the proposed antenna.

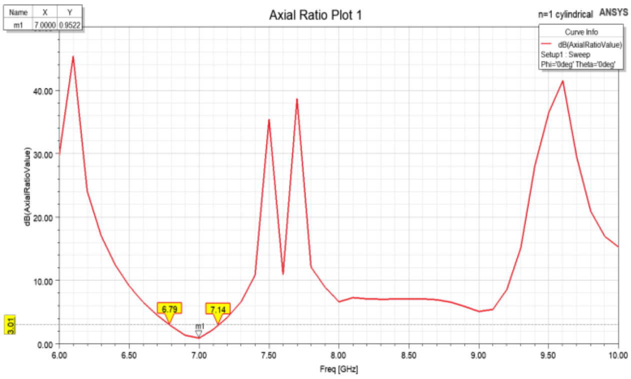


Fig. 15. Axial Ratio Analysis of Proposed-CDRA with First Iteration Fractal Cross-Slot

Field Patterns for First iteration:

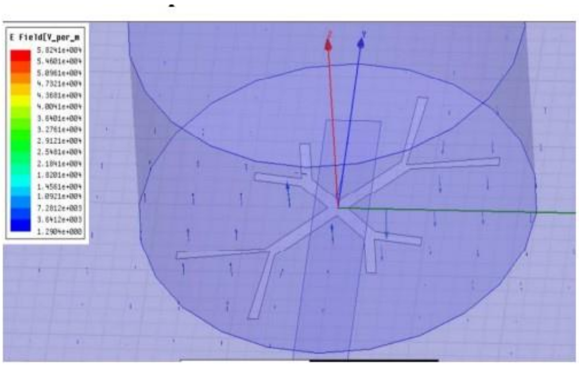


Fig. 16(a) E Field pattern

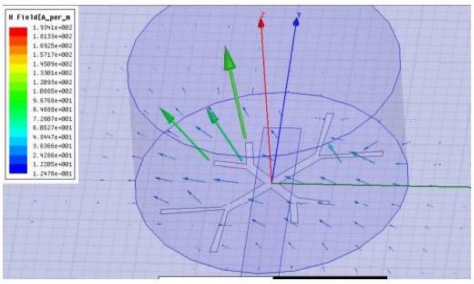
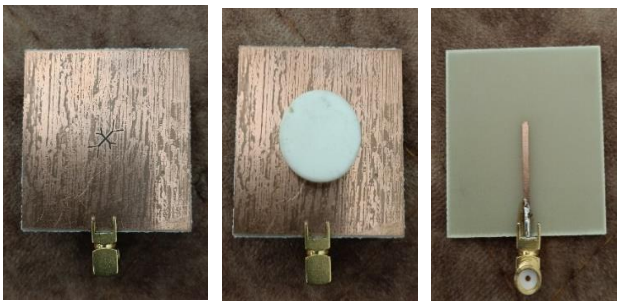


Fig. 16(b) H Field pattern

5.3. Fabrication model:

The suggested antenna was created on a FR 4 substrate using HFSS simulation.



(a) (b) (c)

Fig. 17. Fabricated Antenna (a) Front View without DRA, (b) Front View with DRA, (c) Back View

Fig. 18(a) Experimental setup with DRA

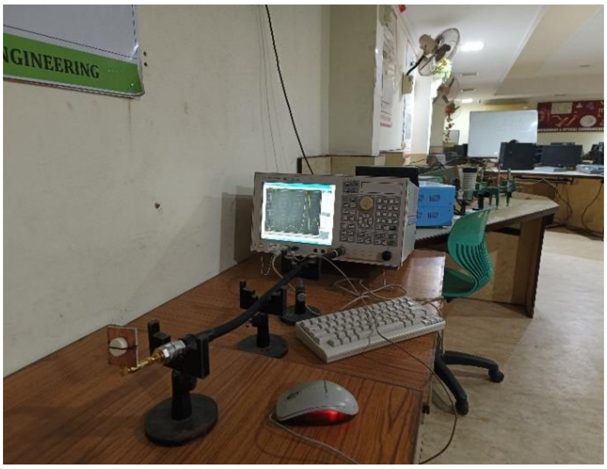
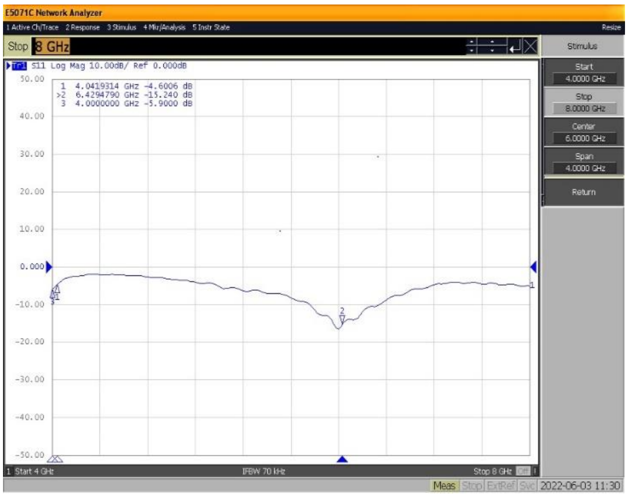


Fig. 18(b) shows the experimental set-up for measuring the parameters like resonant frequency, return loss and VSWR of the antennas

6. Measured Results

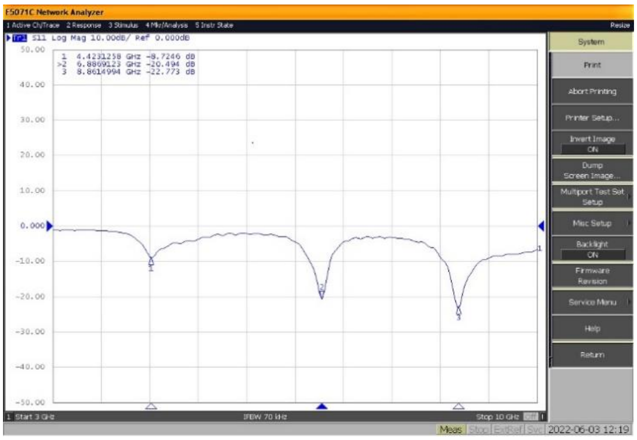
Fig.19 depicts the return-loss characteristics of the antenna coupled with the fractal cross-slot, excluding the dielectric resonator antenna (DRA), as measured using a vector network analyzer. The antenna exhibits resonance at two notable frequency bands: 4 GHz and 6.42 GHz, with corresponding return losses of -5.94 dB and -15.240 dB, respectively.



```
Tr1 S11 Log Mag 10.00dB/ Ref 0.000dB
 1   4.0419314 GHz -4.6006 dB
>2   6.4294790 GHz -15.240 dB
 3   4.0000000 GHz -5.9000 dB
```

Fig. 19. return-loss of fabricated antenna without DRA

Fig.20 shows the return-loss curve for the fractal cross-slot coupled antenna with dielectric resonator antenna (DRA), as measured by a vector network analyzer. The antenna resonates in two distinct frequency bands, specifically at 4.42 GHz, 6.88 GHz and 8.86 GHz, with return losses of -8.72 dB, -20.49 dB and -22.77 dB respectively.



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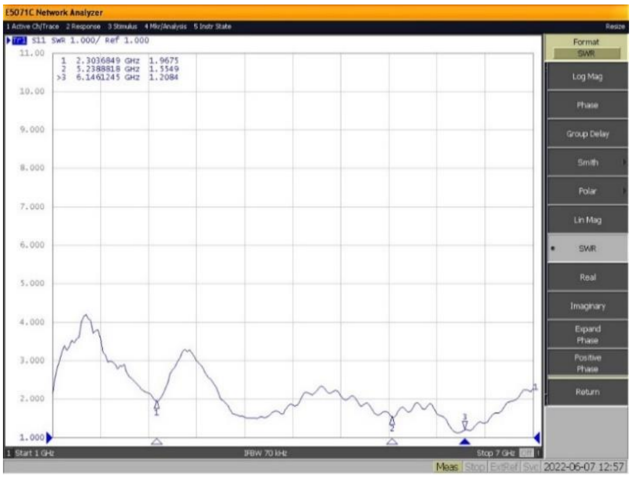
Tr1 S11 Log Mag 10.00dB/ Ref 0.000dB
 1   4.4231258 GHz -8.7246 dB
>2   6.8869123 GHz -20.494 dB
 3   8.8614994 GHz -22.773 dB
```

Fig. 20. return-loss of fabricated antenna with DRA

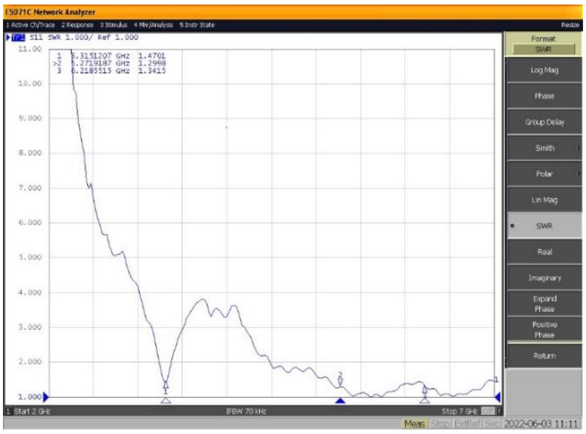
Figure 21 demonstrates the Voltage Standing Wave Ratio (VSWR) traits of the antenna paired with the fractal cross-slot, with the exclusion of the dielectric resonator antenna (DRA), obtained through measurements using a vector network analyser. The antenna exhibits resonance at three distinct frequency bands: 2.3 GHz, 5.23 GHz, and 6.14 GHz, with corresponding SWR values of 1.96 dB, 1.554 dB, and 1.208 dB, respectively.



```
Tr1 S11 SWR 1.000/ Ref 1.000
 1   2.3036849 GHz  1.9675
 2   5.2388818 GHz  1.5549
>3   6.1461245 GHz  1.2084
```

Fig. 21. VSWR of fabricated antenna without DRA

Figure 22 presents the Voltage Standing Wave Ratio (VSWR) curve for the antenna integrated with the fractal cross-slot and the dielectric resonator antenna (DRA), as determined through measurements conducted with a vector network analyzer. The antenna resonates in three distinct frequency bands, specifically at 3.3 GHz, 5.27 GHz and 6.21 GHz, with SWR of 1.47 dB, 1.29 dB and 1.341 dB, respectively.



```
 1  3.3151207 GHz  1.4701
>2  5.2719187 GHz  1.2998
 3  6.2185515 GHz  1.3415
```

Fig. 22. VSWR of fabricated antenna with DRA

The comparison of the simulated outcomes from the HFSS simulation, circularly polarized, cylindrical DRA having fractal slot for two iterations

Table1: simulated results summarization for proposed antenna

Iteration Value(n)	**Frequency (GHz)**	**Return Loss(dB)**	**Gain (dB)**	**VSWR**
0(1 Element)	9.1	-23.00	5.8559	1.1
1(1 Element)	7.0	-34.7839	5.5829	1.0371
	8.0	-28.4808	6.1403	1.0783

The table above summarizes the performance of the circularly polarized Cylindrical DRA with a fractal cross slot at various iteration values (n = 0 and 1). It is evident that the antenna's performance metrics, such as return loss, gain, Voltage Standing wave Ratio (VSWR), Axial ratio vary with different iterations. This information is essential for designers when optimizing the antenna for specific applications or frequency bands, as it helps identify the most suitable iteration value to achieve the desired performance.

7. Conclusion

This article concludes by discussing the design and simulation of circularly polarized cylindrical dielectric resonator antenna (CPCDRA) incorporated by fractal cross slot utilizing the High-Frequency Structure Simulator (HFSS). In terms of size, gain, radiation patterns, and bandwidth, the simulation results, which have been broadly discussed and illustrated, indicate a strong performance. The antenna operates effectively in the frequency range of 7 GHz to over 9 GHz, with optimal performance at 6.4 GHz and 8.4 GHz, where the VSWR is less than 2 and the return loss is less than -10dB. The designed antenna exhibits good impedance bandwidth and Axial ratio bandwidth of >6% in both iteration of fractal slot aperture couple. Consequently, this antenna design is well-suited for Aerospace, RADAR, and satellite communications applications at which high frequency, high gain is required.

Future research will investigate modifications to circularly polarized dielectric resonator antenna (CPDRA) arrays to further improve performance and optimize the design for applications. This research lays the groundwork for the development of more efficient and versatile fractal cross-slot-coupled antennas with circularly polarized dielectric resonator elements.

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