Original Article

An Unconventional Circularly Polarized Cylindrical Dielectric Resonator Antenna for GPR Applications

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Abstract - An ultra-wideband (UWB) antenna is designed, which is fed by a coplanar waveguide along with Dielectric Resonator Antenna (DRA) is discussed. The patch of ultra-high-frequency antenna structure comprises many full circles and half circles, rearranging the two focal point orientation and dimension of radius such that the antenna works in ultra-wideband frequency range and a rectangular slot in the middle of the antenna patch to change the orientation of current distribution. The antenna is resonating at 8.9GHz with a reflection coefficient (S_{11}) of -15.39dB, Gain is negative at resonating frequency, and Polarization at resonating frequency is linear. The proposed antenna is designed by mounting Cylindrical Dielectric Resonating Antenna (CDRA) on the rectangular slot made on the patch. By mounting a cylindrical DRA structure on the patch, the antenna is resonating at 3.6 GHz with a reflection coefficient (S_{11}) value - 22.54dB, achieving a Gain of 3.44dB at resonating frequency. The Polarization achieved by placing cylindrical DRA is circular Polarization which is more useful in Ground Penetrating Radar (GPR) applications. The proposed antenna is practically designed, and performance characteristics are measured and verified with simulation results.

Keywords - Ultra wide band, Coplanar waveguide, Dielectric resonating antennas, Polarization and ground penetrating radar.

1. Introduction

Ground Penetrating Radar (GPR) is a noncorrosive tool for non-intrusive exploration [1]. GPR is a geographical practice that can be used to examine and record the dielectric properties of the underground [2]-[3]. The working of the GPR system mainly depends on the antenna employed. The antenna transmits electromagnetic signals into the earth's subsurface and receives the reflected signals, which can be viewed on the display unit. The reflected signal depends on the contrast of materials[4]-[5]. Reflectivity depends on different underground materials like dry sand, wet sand, water, rocks, ice, etc., with different dielectric constants[6].

The frequency of operation of the antenna and depth of penetration of radar signal from the antenna plays a significant role in detecting the pollutants beneath the ground [7].To confine the range, outline, direction, and electrical properties of hidden things in GPR, Polarization is a significant concern in antenna design. These polarizations, dependent on scattering distinctiveness, can be used to categorize different classes of targets for the finest object recognition.

On the contrary, ignoring the polarization aspects of GPR can lead to a false evaluation of the Physical outline and inclination of objects in the field, especially in the case of buried objects where there is a chance of interpretation missing. The direction of magnitude can strongly impact the resulting image. Even elementary features, like immersion layers, can mask the individual objects that are the target of a survey [8].

Generally, the GPR frequency range of operation is between 10MHz to 3GHz. However, if the antennas are designed at the wide band or ultra-wideband range, the image's resolution will be superior, which helps to study the properties of buried objects perfectly [9].

2. Literature Survey on DRA

There are many different models of antenna designed for GPR applications. In this paper antenna design is accomplished with Dielectric Resonator Antenna (DRA) which has many advantages like high Q factor, low insertion loss, high dielectric constant, no conduction losses and compact in size, etc. [2][23-29].

Table 1. Literature survey

Sl. No.	Resonant Frequency	S11	Polarization	Gain
[13]	857MHz-885MHz	-30dB to -40dB	LP	3.75dBi
[14]	2.34GHZ	-28dB to -35dB	LP &CP	positive
[15, 16]	2GHz	-30dB to -40dB	CP & LP	13.3dBi
[17]	5.2GHz	-30dB to -40dB	LP	4.1dBi
[18]	60GHz	-30dB	LP	8.6dBi
[19]	2.65GHz	-20dB to -22dB	LP	0.62dB
[20]	2.31 GHz -2.61GHz	<-10dB	LP	-
[21]	2.82GHz-3.83GHz	<-10dB	CP	5.5dBi
[22]	6.125GHz	-26dB	LP	10.14dBi

Table 2. Comparison of feeding techniques

Characteristics	Coaxial Probe Feeding	Microstrip Feeding	Aperture Feeding	CPW Feeding
Bandwidth	Better	Good	Fair	Better
CP bandwidth	Difficult	Easy	Better	Better
Polarization purity	Poor	Good	Good	Good
Impedance Matching	Easy	Easy	Easy	Easy
Ease of Fabrication	Soldering and Drilling Required	Easy	Alignment Required	Alignment Required
Reliability	Poor	Better	Good	Good
Configuration	Non-polar	Coplanar	Planar	planar

Over the last three decades, the geometrical models of DRA have been studied. The following table shows the recent performance parameters of different geometric models of antenna designed using DRA. From the above Table 1. It can be concluded that DRA gives suitable performance parameters. The frequency of operation of CDRA is given by

$$f_r = \frac{c}{2\pi r \sqrt{\varepsilon_{DRA}}} \left[1.71t\frac{r}{h} + 0.1578\left(\frac{r^2}{h}\right) \right]$$

Where, r = radius of CDRA
h = height of CDRA
c = velocity of light (3x10^8m/sec)
ε = dielectric constant of CDRA

The above equation is valid for hybrid mode. CDRA also supports TE and TM modes, resonant frequencies are given by,

$$f_{TE_{npm}} = \frac{c}{\left(2\pi\sqrt{\varepsilon_r\mu_r}\right)} \sqrt{\left(\frac{X_{np}}{a}\right)^2 + \left(\frac{(2m+1)\pi}{2h}\right)^2}$$

$$f_{TM_{npm}} = \frac{c}{\left(2\pi\sqrt{\varepsilon_r\mu_r}\right)} \sqrt{\left(\frac{X_{np}}{a}\right)^2 + \left(\frac{(2m+1)\pi}{2h}\right)^2}$$

There are different feeding techniques for CDRA; among them, the Coplanar waveguide feeding technique has better characteristics. The following table shows the comparison of various feeding techniques.

3. Existing Antenna Design-1
The ultra-high frequency antenna structure patch comprises many full circles and half circles. Rearranging the two focal point orientation and dimension of radius such that the antenna works in ultra-wideband frequency range and a rectangular slot in the middle of the antenna patch to change the orientation of current distribution [5]. The distance of the coplanar waveguide (s_{02}) must be attuned to the suitable value such that an accurate match is achieved when s_{02} = 0.2mm antenna gets the exceptional resonance. The radiation patch incorporates many half-circles and circles that go beyond each other. To make the antenna work in an ultra-wideband frequency range, the radius of circle (a) and the radius of half circle(b) are adjusted.

Table 3. Dimensions of the proposed antenna

W2	28
L2	26
Wf2	1.5
W12	3
a	8.2
b	12.2
m	15
n	0.2
L02	10.3
S02	0.2
H	1.6
DRA	8x8
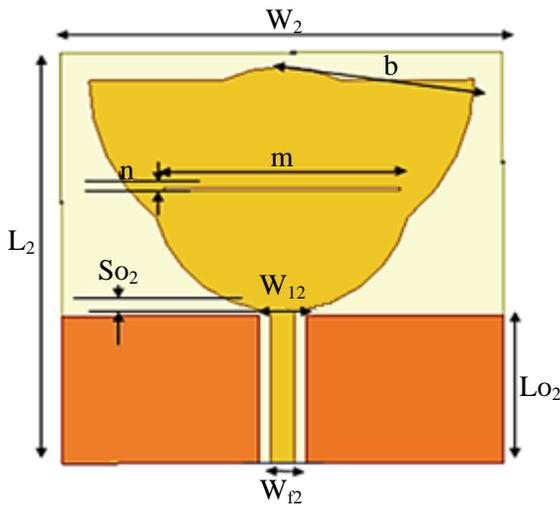
Fig. 1 Patch antenna with coplanar waveguide feed

(a) Stage-1   **(b) Stage-2**

(c) Stage-3

(d) Side view
Fig. 2 Proposed antenna design process with DRA

By increasing the value of 'a', the reflection coefficient in the frequency band moves down considerably. When the value of 'a' is 8.2mm, the antenna gets the optimal resonance. In order to change the distribution of current, a rectangular slit is made so that a notch function is achieved. The length of the gap mainly exaggerates the band-notched 'm'. As the value of 'm' increases, the band-notched noticeably shifts to the left. Finally, the value of 'm' is set at 15mm, so there will not be any problem with interference with other frequency bands.

4. Results Discussion for Existing Design

The performance characteristics of the existing antenna design are analyzed. The reflection coefficient is - 15.39dB at resonance frequency 8.9GHZ. Linear Polarization is observed at the resonant frequency by the axial ratio graph.
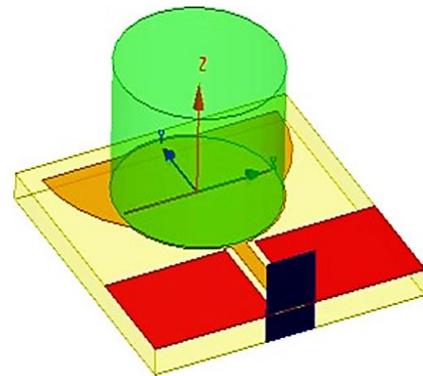
The Gain at the resonant frequency is negative. Since the Gain is negative, it is not used in GPR applications as the signal cannot penetrate more distance.

5. Proposed Antenna Design-2

To overcome the disadvantages of the existing design, the proposed design uses CDRA, which is mounted on the rectangular slot, to achieve better performance results (discussed in later sections). The proposed antenna design is shown Figure 2. The dimensions of the proposed antenna are shown in Table 3.

Table 4. Performance parameters of DRA of different sizes

Parameters	With DRA Cylinder height =22mm, radius =6.5mm	With DRA cube 5*5*2	With DRA cube 6*6*4
S11(dB)	-17.96	-17.8	-19.14
Frequency (GHz)	10.9	8.8 to 9.1 GHz	8.73 to 9.16GHz
VSWR	1.28	1.29	1.24
Gain(dB)	9.993	-1.83	-1.2498
(By Axial Ratio) Polarization	Linear Polarization	Linear Polarization except in 8.8 to 9.1 GHz	Linear Polarization, except in 8.73 to 9.16 GHz

The HFSS software verified the simulation results, and the antenna was fabricated. Different types of DRA are available, as shown below [10]-[13]. The simulation is carried out considering cube and cylinder DRA of different sizes. Table 4 shows the performance parameters of different CDRA and cube DRA sizes, which shows negative Gain for cube DRA and positive Gain for CDRA. The analysis was carried out considering only CDRA.

6. Simulation Results of CDRA of Different Sizes

The Cylindrical Dielectric Resonator Antennas mounted on the patch have experimented with dimensions like XxY, where X is DRA's radius, and Y is DRA's radius. The first case considered here is a change in X value, i.e. for different radius values like X=4, 5, 6, 8, 22. The performance characteristics are verified in all the cases. Similarly, the second case is changing the height of DRA Y=4, 5,6,7&8. The performance characteristics are verified. In this section, the performance of the proposed antenna is simulated and analyzed using HFSS.
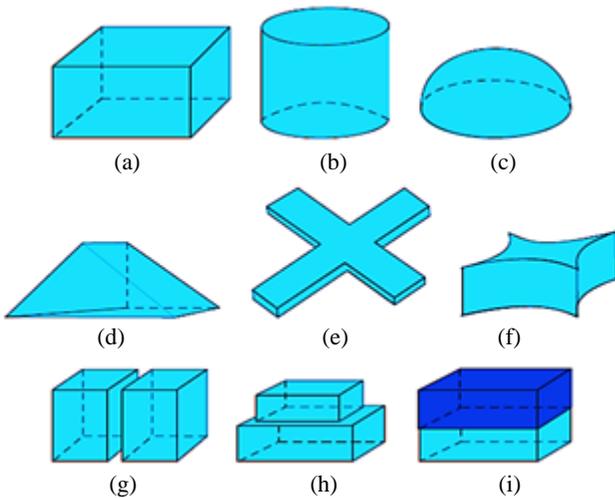

(a)   (b)   (c)

(d)   (e)   (f)

(g)   (h)   (i)

Fig. 3 Different models of DRA

The simulation results are compared to check the superiority in design for the existing antenna design (without DRA) and the Proposed antenna design (with Cylinder DRA). The essential parameters investigated for the analysis, namely Return loss or Reflection Coefficient(S11), Gain, Radiation Pattern, Axial ratio, Radiation efficiency and VSWR, are plotted for both antennas.

6.1. Reflection Coefficient

This parameter describes how much of an electromagnetic wave is reflected by an impedance discontinuity in the transmission medium. Generally, the reflection coefficient value should be a minimum of -10dB, representing $1/10^{th}$ power reflected, so the lesser the negative value will be the S_{11} value. The simulation results for the different dimensions of CDRA are analyzed by changing the radius and height of the CDRA. The CDRA considered here are 5x8, 6x8, 7x8, 8x8, 22x6.5, 8x4, 8x5, 8x6 and 8x8 which show variation in radius and height. The simulation results are shown in Figure 4(a) and Figure 4(b), which depict DRA with 8x8 has better performance results. The simulation results of the two designs are observed as -19.39dB at 8.9GHz without DRA and -23.5dB at 3.6GHz with cylindrical DRA of dimensions 8x8. The simulation graphs are shown in the following Figure 4(c).

6.2. VSWR

The parameter indicates the amount of contradiction between an antenna and the feed line connecting to it. The maximum and minimum value of VSWR is ∞ one, respectively. For most Antenna applications, the suitable VSWR value is less than 2. The two designs' simulation results are observed at 1.240 at 8.9GHz without DRA and 1.33 at 3.6GHz with cylindrical DRA. The simulation graphs are shown in Figure 5.

6.3. Gain

It is the product of the efficiency and directivity of the antenna. This parameter depicts the input power conversion to radio waves directed in a specific direction by the antenna.
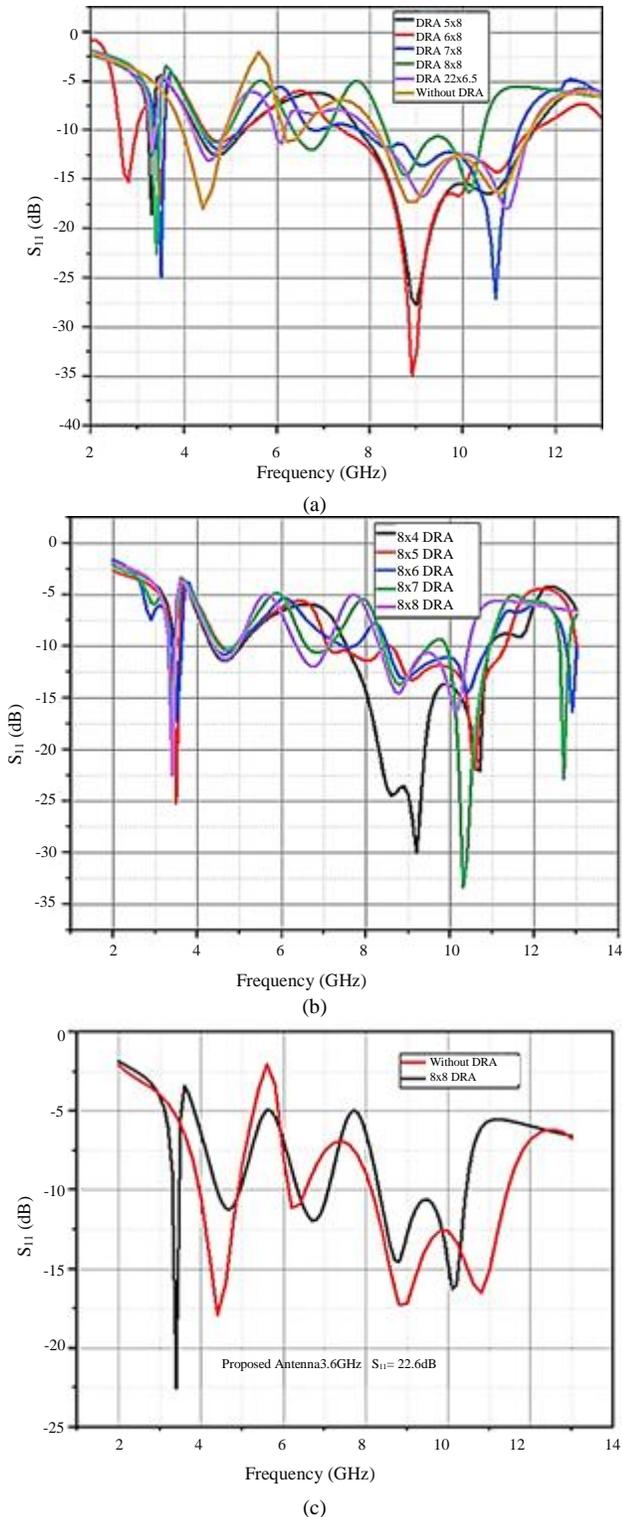
(a)

(b)

(c)

Fig. 4 Reflection coefficient graph with and without DRA(a,b,c)

Various parameters affect the antenna's Gain, like antenna substrate, antenna feed mechanism, frequency of operation, loading of materials on antenna, etc.

The two designs' simulation results are -3.059dB at 8.9GHz without DRA and 6.68 at 3.6GHz with cylindrical DRA. The simulation graphs are shown in Figure 6, where it is observed that other dimensions of DRA gain are negative.

6.4. Axial Ratio

It is the ratio of electrical fields along the orthogonal axis. There are three types of Polarization (i) Linear Polarization which indicates Axial ratio=∞ (ii) Circular Polarization which indicates Axial ratio=1 (iii) Elliptical Polarization which indicates Axial ratio ranging from 1 to ∞. Among different types of Polarization, circular Polarization is preferred.

The simulation results of two designs are observed where linear Polarization is achieved without DRA at 8.9GHz, and circular Polarization is achieved with cylindrical DRA at 3. 6GHz.The simulation graphs are shown in Figure 7(b).
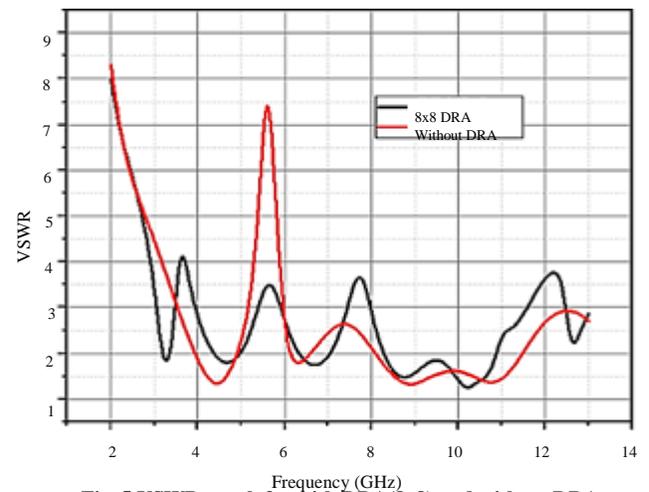

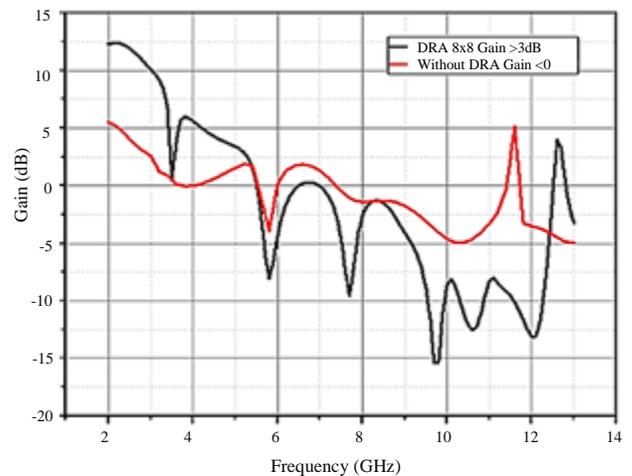**Fig. 5 VSWR graph for with DRA(8x8) and without DRA**

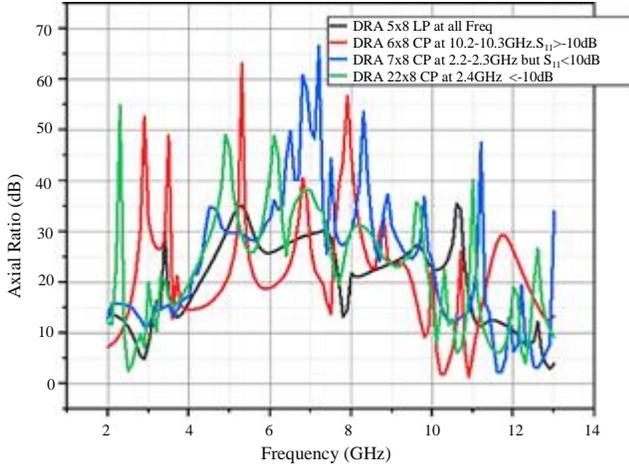**Fig. 6 Gain plot with DRA (8x8) and without DRA**

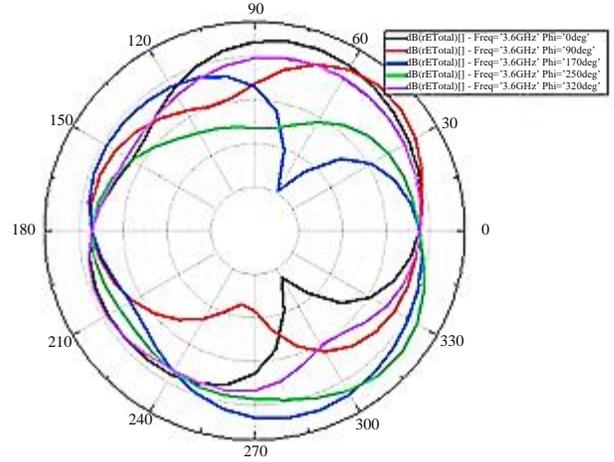**Fig. 7(a) Axial ratio plot with DRA**

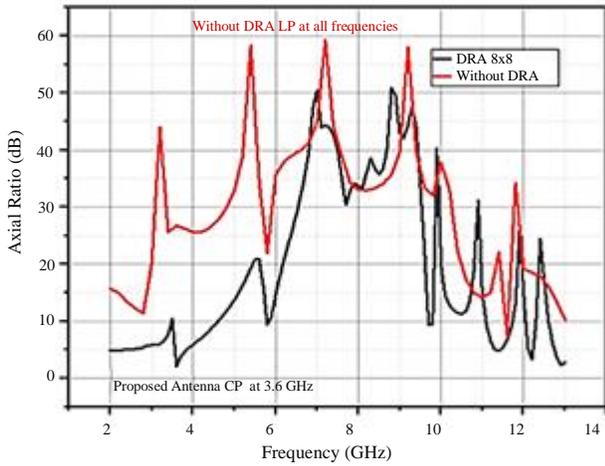**Fig. 9(a) Radiation pattern with DRA**

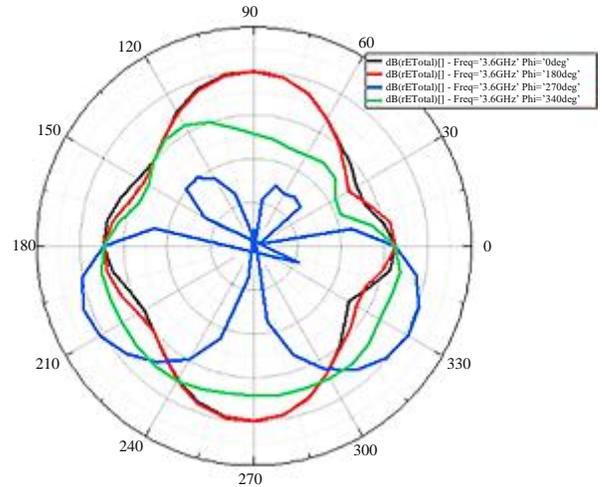**Fig. 7(b) Axial ratio plot without DRA**

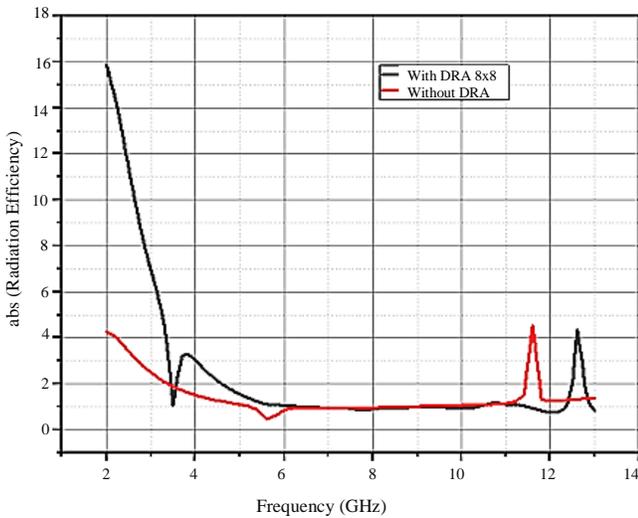**Fig. 9(b) Radiation pattern without DRA(b)**

Fig. 8 Radiation efficiency with and without DRA plot
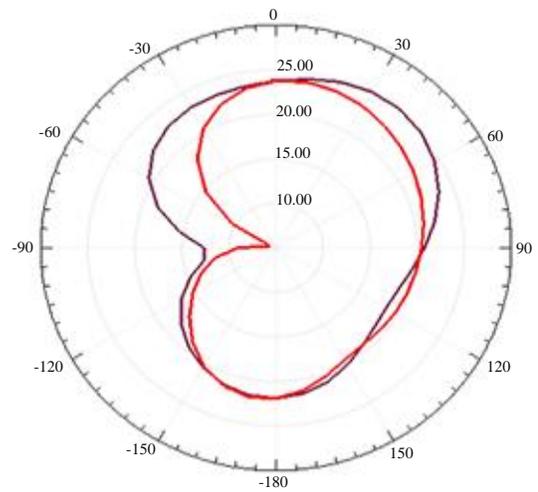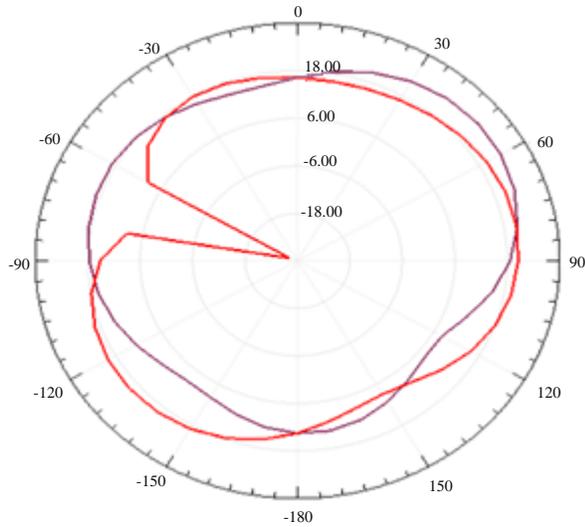

Fig. 10(a) LHCP and RHCP at 3.6GHz 0 degrees
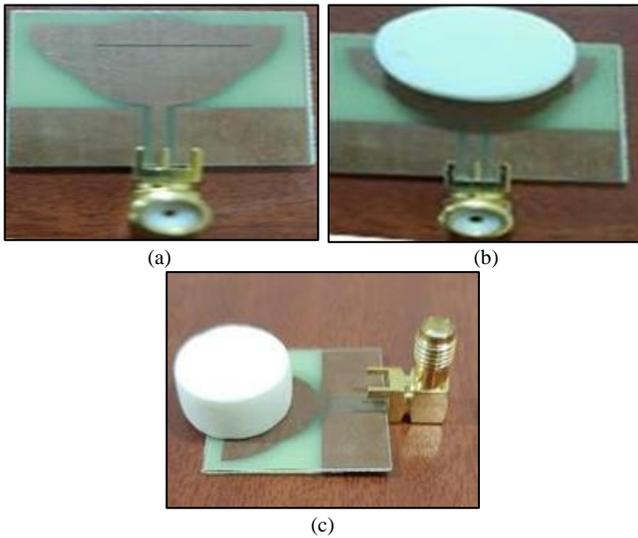
Fig. 10(b) LHCP and RHCP at 3.6GHz 90 degrees

(a)   (b)

(c)

Fig. 11 Overview of fabricated antenna

(a)   (b)

**Fig. 12 Testing fabricated antenna in VNA**

Fig. 13 Testing antenna in Anechoic Chamber

6.5. Radiation Efficiency

The ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter. The simulation results of Figure 8 show that the antenna designed with CDRA 8x8 has better efficiency than without DRA.

6.6. Radiation Pattern

The antenna pattern (or radiation pattern) is the geometric pattern of the relative strengths of the field emitted by the antenna. The radiation pattern reflects the 'sensitivity' of the antenna in different directions, and knowledge of this allows the antenna to be orientated in the optimum direction to ensure the required performance.
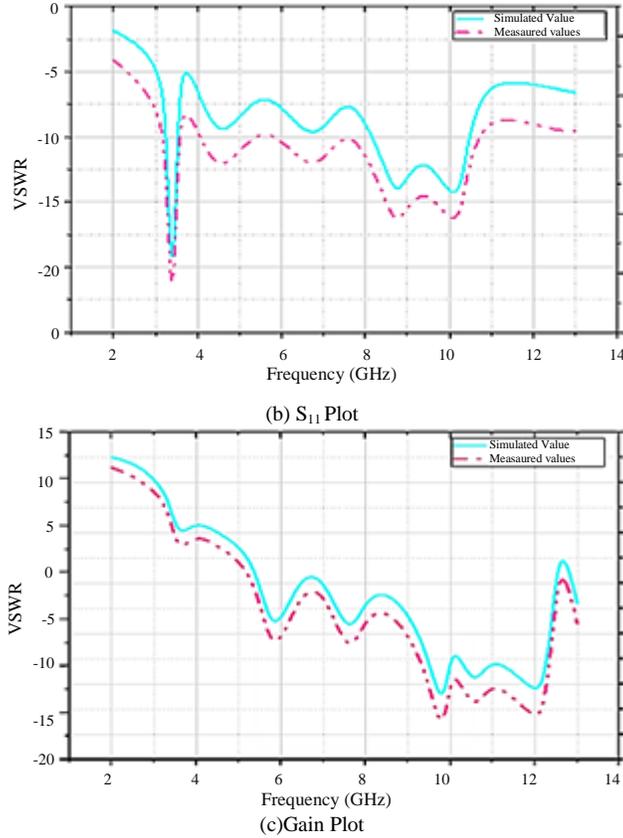

(a)   VSWR Plot

(b) S$_{11}$ Plot
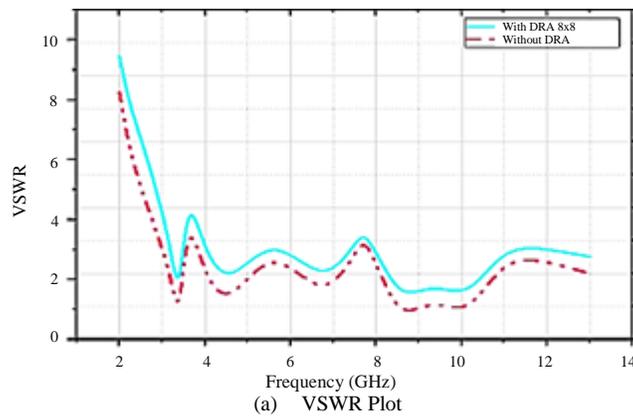
(c)Gain Plot

Fig. 14 Simulation and measured values plotting's

Table 5. Performance parameters of both antenna designs

Parameters (Present work done)	Antenna design-1 (Without DRA)	Antenna design-2 (With cylindrical DRA (8x8))
S$_{11}$(dB)	-15.39	-22.54
Frequency (GHz)	8.9	3.62
VSWR	1.240	1.710
Gain (dB)	-3.059dB	3.44 dB
Polarization (By Axial Ratio)	Linear Polarization at 8.9GHz	Circular Polarization at 3.6GHz

The radiated power is a function of the angular position and the radial distance from the circuit. The variation of power density with angular position is determined by the type and design of the circuit. It can be graphically represented as a radiation pattern. The simulation results of the two designs' radiation patterns are observed below in Figure 9, LHCP and RHCP at 3.6GHz are shown in Figure 10.

7. Antenna Fabrication and Experimental Results Discussion

This section presents the fabricated antenna without DRA and with CDRA (8x8), shown in Figure 11(a, b, and c).The performance characteristics of the fabricated antenna are verified using a Vector network analyzer, as shown in Figure 12(a, and b). Then fabricated antenna is tested in an anechoic chamber, as shown in Figure 13. Simulated and measured values are shown in Figure 14 (a, b, and c).

8. Conclusion

In this paper, the existing antenna design withoutDRA & Proposed antenna design with CDRA is designed. The simulation results of different sizes of CDRA are analyzed. When comparing the performance parameters of recommended designs. The proposed antenna design with CDRA (8x8) gives better results with a high Gain of around 3.44dB achieved at 3. 6GHz.By using CDRA, circular Polarization is achieved, which yields better image response from the antenna in the applications of GPR.

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