Comparative study of DRAs

Sanjeev Kumar[1], Dr. (Mrs.) Taran Kumari[2], Dr. Ravindra Kumar[3] & Mr. Dinesh Kumar [4]
[1]Research Scholar, University Department of Physics, B.R.A.Bihar University, Muzaffarpur
Bihar,India,
[2]Associate Professor, University Department of Physics, B.R.A.Bihar University,Muzaffarpur
Bihar ,India ,
[3]Demonstrator, University Department of Physics, B.R.A.Bihar University,Muzaffarpur, Bihar ,India
[4]Department of Physics, B.R.A.Bihar University,Muzaffarpur, Bihar, India.

Abstract-

In this paper, we have established the fact that RDRA (in terms of parameters like impedence bandwidth, degree of freedom, resonant frequency - simulated and calculated) may be the best choice for further improvement in the design of Dielectric Resonator Antena. The rudimentary geometries of DRA are rectangular, cylindrical and hemispherical, which are used for investigation of DRA performance. These rudimentary geometries of DRA give a best understanding of design parameters of an antenna and their effect on return loss, impedance bandwidth, benefit and resonant frequency. It was found that the rectangular DRA provide best resonance level as compared to another geometries.

Keywords- *RDRA, CDRA, HDRA, Impedance bandwidth, Resonant frequency, Degree of freedom.*

I. INTRODUCTION

A DRA is a high radiation efficiency radiator, which is made up of high permitivity lossless dielectric material called dielctric resonator (DR). Initially, the DRs were particularly used as an option to waveguide cavity resonators that are enclosed in metallic cavities to maintain high Q factor and to prevent radiation. After the study by S.A.Long et. al., DRs were assumed to be a potential option for DRA.

Various shapes of DRA can be used to radiate electromagnetic wave Fig.-1 shows the various shapes of DRs, which include rectangular, cylindrical and hemispherical. Various shapes possess various modes of resonance, and hence various field distribution, radiating features and resonant frequencies. So shape is also major factor for the study of DRAs : out of the various shapes, three shapes mentioned are discussed in this paper.

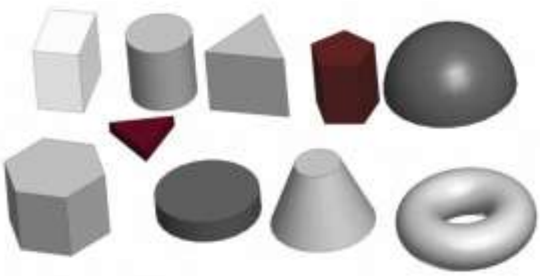


Fig. 1 Different shapes of DRAs

The purpose of this paper is to provide a comparative analysis of DRAs of various shapes. This chapter illustrates the achievable performance of DRAs designed for wide impedance bandwidth; low profiles, various polarization, compactness and high profit. The versatility in choice of shape, radiation patterns, bandwidths, relative permittivity and size enables a whole spectrum of operating frequency ranges (1-100GHz).

The DRA is an open resonating structure, fabricated from a low loss microwave dielectric material. Dielectric resonators (DR's) have proved themselves to be ideal for antenna applications by virtue of their high radiation efficiency, flexible feed arrangement, simple geometry, small size and the ability to produce various radiation pattern using various modes. Feeding techniques such as probe feed, aperture slot, microstrip line and coplanar line can be used with the DRAs, which enables them for integration with technology.

Additionally, DRA's avoid some limits of the patch antenna including the high conductor losses at millimeter-wave frequencies, sensitivity to tolerances, and narrow bandwidth. DRA's of cylindrical, hemispherical and rectangular shapes are most broadly used and investigated. The rectangular shape is much easier to fabricate and one or more dimensional parameters are present as additional degrees of freedom for the design. Impedance bandwidth varies over a broad range with resonator parameters. It can be as small as a few percent with high ε_r material or over 20 % with small ε_r in conjunction with certain geometries and resonant modes. Various far field radiation patterns are supported. For a given DRA geometry, the radiation pattern can be made to change by exciting various modes.

Systematic study on dielectric resonator antennas (DRA's)were first carried out by Long *et al.*. Since then, theoretical investigations have been reported by many investigators on DRA's of different shapeslike spherical, cylindrical, rectangular and other.

DRAs offer a high degree of flexibility and versatility over a wide frequency range, allowing for designers to suit many requirements. DRAs come in simple geometries like circular cylinder, hemisphere, rectangular etc. are readily present and can be easily fabricated. The DRA size is proportional to $\frac{\lambda_0}{\sqrt{\varepsilon_r}}$, where λ_0 is the wavelength at resonant frequency and ε_r is the dielectric constant of the DR. Thus for the same frequency there is a natural reduction in size, compared with their conventional counterparts such as microstrip antennas. Also, various values of ε_r (ranging from 4 to 100) can be used, thus allowing the designer the flexibility in controlling the size and bandwidth. Depending on the resonator shape, different modes can be excited within the DRA element. These modes can produce various radiation patterns for different coverage requirements. Also, the Q-factor of some of these modes will depend on the aspect ratio of the DRA, thus allowing one more degree of flexibility in the design. Many of the existing feeding schemes can be used (like slots, probes, microstrip, coplanar waveguides, dielectric image guide, etc.). This makes them easy to integrate with existing technologies. Compared with the microstrip antenna, DRA has a much broader impedance bandwidth. This is because the microstrip antenna radiates only via two narrow radiation slots, whereas the DRA radiates through the whole antenna surface except the grounded part. Moreover the operating bandwidth of a DRAcan be varied by suitably selecting the dielectric constant of the resonator material and its dimensions. So ε_r is the major factor for DRA. DRAs have been designed to operate over a broad frequency range (1 GHz to 44 GHz) compared with another antennas. DRAs have a high dielectric strength and hence higher power handling capacity. Moreover the temperature-stable ceramics enable the antenna to operate in a broad temperature range. There is no inherent conductor loss for a DRA. High radiation efficiency is thus possible in case of DR antennas. It is especially attractive for high frequency millimeter wave applications, where the loss from metallic antennas can be high.

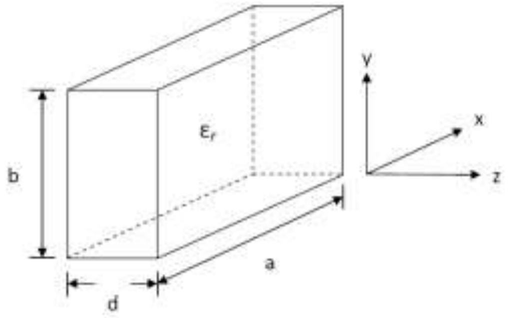
II. DRA Development

(i) Rectangular DRA

Rectangular DRAs offer practical benefits over cylindrical and spherical shape. For example, the mode degeneracy can be avoided in the case of rectangular DRA's by properly selecting the three dimensions of the resonator. It may be noted that mode degeneracy always exists in the case of a spherical DRA and in the case of hybrid modes of a cylindrical DRA. The mode degeneracy can enhance the cross polarlevels of an antenna, thus limiting its performance. Further, for a given resonant frequency, two aspect ratios of a rectangular DRA (height/length and width/length) can be chosen independently. Since the bandwidth of a DRA also depends on its aspectratio(s), a rectangular-shaped DRA provides more flexibility in terms of bandwid thcontrol.

A rectangular DRA support two type modes, TM and TE, but TM modes have never been observed. Therefore the existence of TM modes presents to be doubtful. Figure 3.2 shows a rectangular DRA with the corresponding coordinate system. The resonant modes can be TE to either dimension, denoted as TE^x, TE^y, or TE^z.A rectangular DR has three independent dimensions. The modes of a DR can therefore, be TE to any of three dimensions.

Referring to the DR and co-ordinates system shown in figure-2, the modes with lowest order indexes are TE$^z_{111}$, TE$^y_{111}$ and TE$^x_{111}$. The figure -3 represents the simple geometry of RDRA. If the dimensions of the DR are like a > b > d, the modes in the order of increasing resonant frequency are TE$_{111}$,TE$^y_{101}$ and TE$^x_{011}$. The analysis of all the modes is same. For example, for TE mode, the analysis for the field components inside the resonator can be done from the directed magnetic potential ϕ^h.



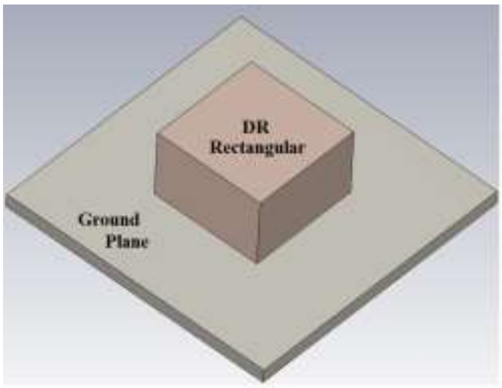


Figure 2: Isolated rectangular DRA. **Figure 3:** Simple geometry of RDRA.

The wave numbers along xyz direction with dielectric constant ε_r inside DR for rectangular DRA is related by the equation (1).

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2$$ .... (1)

The dimensions of the radiating portion of the DR can be determined using the equation (2) developed for the dielectric waveguide model (DWM) for a rectangular resonator in free-space.

$$k_x = \frac{\Pi}{a}; k_y = \frac{\Pi}{b}; k_o = \frac{2\Pi f_o}{C}; C = 3\times10^8 m/S$$ .... (2)

Figure -4 shows the rectangular resonator with length a, breadth b and height d, where resonances can occur at the following frequencies

$$f_{mnp} = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2}$$ .... (3)

where ϵ is the permittivity, μ is the material permeability, and m, n and p are integers. In this configuration, TE^x_{011} mode is the dominant mode, because it occurs at the lowest frequency at which a cavity resonance can exist. From equation (3) it can be seen that the frequency at which this dominant resonant mode can exists (the cutoff frequency) is inversely proportional to the square root of the product of material parameters, ϵ and μ.

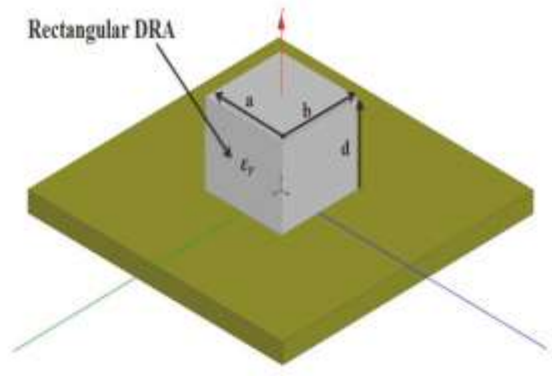


Fig. 4 : Rectangular DRA with length (a), width (b) and height (d)

The broadly reported shape of DRA is rectangular DRA, which has one more degree of freedom as compared to cylindrical DRA. This is the most versatile basic shape of DRAs. Fig. 4 illustrates the schematic view of the rectangular DRA with length (a), width (b) and height (d). Rectangular DRAs offer more design flexibility (degree of freedom) since two of the three dimensions can be varied independently for a fixed resonant frequency. The shape is characterized by a permittivity (ε_r), height (d), width (b) and depth over an "infinite" plane of perfect conductor. For this particular shape, the modes will also have an orientation dependency, due to symmetry. Hence, the lower energy modes will be the $TE^{x}_{\delta 11}$, $TE^{y}_{\delta 11}$ or $TE^{z}_{\delta 11}$. These modes radiate similar to a short magnetic dipole in the *x*, *y* or *z* direction, which makes RDRA more appropriate.

The initial dimensions of DRA can be calculated by using the dielectric waveguide model (DWM) for a rectangular resonator in free space. Therefore by matching the fields at boundaries, the wave propagation number and the resonant frequency can be calculated by using the following equations (4).

In equation (4) ε_r is permittivity of material and k_0 is the free-space wave number given by :

$$k_0 = \frac{2\pi f_r}{c} \qquad \text{...............................(4)}$$

where *c* is the speed of EM wave in free space, f_r is the resonant frequecy. For well-guided modes, the fields are confined within the guide and a further approximation can be made.

This approximation is equivalent to the assumption that the magnetic walls exist at $x = \pm a/2, y = \pm b/2$ from equation (2) resonant frequency (f_r) of a rectangular DRA is given as :

$$f_r = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{k_x^2 + k_y^2 + k_z^2} \qquad \text{...............................(5)}$$

(ii) CYLINDRICAL DRA

The next common shape analysed and reported is the cylindrical DRA. In order to analyze analytically, infinite perfectly conducting plane is supposed in these DRAs. Cylindrical DRAs have attracted much attention owing to their broad applicability in wireless communication techniques. As compared to hemispherical shape, cylindrical DRA possess one more degree of freedom. Fig. -5 illustrates the schematic view of the cylindrical DRA with radius (*a*), diameter (*D*) and height (*h*). While Fig. -6 represents the easy geometry of CDRA. The parameters for this shape are the permittivity (ε_r), the height of the cylinder (*h*) and the radius of the cylinder (*a*). The assumption of the infinite perfectly conducting plane is used in order to simplify the calculations regarding this interesting shape. In cylindrical DRA, TE_{01} and $TM_{01\delta}$ resonant modes are radiated but other higher order modes excitation is also possible.

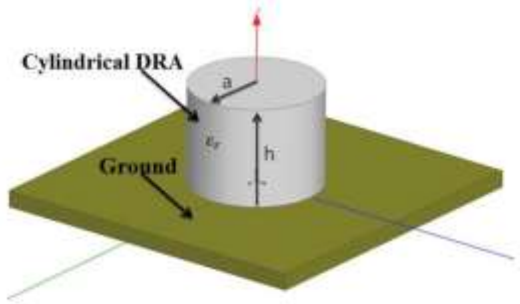


Fig. 5 Cylindrical DRA with radius (*a*), diameter (*D*) and height (*h*),

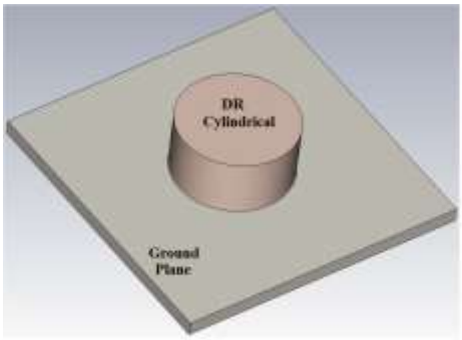


Fig. 6 Simple geometry of CDRA.

(Three degrees of freedom in CDRA)

In early 1980's, Long et. al. showed that certain low-Q radiating modes could be excited from some DRAs when it is placed on finite ground plane in an open space environment.

The two parameters (Q) - quality factor and resonant frequency *f* for the various modes are taken into consideration for CDRA.

$$f_{TE_{01\delta}} = \frac{2.327}{\sqrt{\varepsilon_r + 1}}\left(1 + 0.2123\frac{a}{h} - 0.00898\left(\frac{a}{h}\right)^2\right).\frac{4.7713}{a} \qquad \text{..................(6)}$$

$$Q_{TE_{01\delta}} = 0.078192.\varepsilon_r^{1.27}\left(1 + 17.31\frac{h}{a} - 21.57\left(\frac{h}{a}\right)^2 + 10.86\left(\frac{h}{a}\right)^3 - 1.98\left(\frac{h}{a}\right)^4\right) \qquad \text{.......(7)}$$

$$f_{TM_{01\delta}} = \frac{\sqrt{14.6689 + \left(\frac{\pi a}{2h}\right)^2}}{\sqrt{\varepsilon_r + 2}}.\frac{4.7713}{a} \qquad \text{..................(8)}$$

$$Q_{TM_{01\delta}} = 0.008721.\varepsilon_r^{0.888413} e^{0.0397475\varepsilon_r} \times \left(1 - \left(0.3 - 0.2\frac{a}{h}\right)\left(\frac{38 - \varepsilon_r}{28}\right)\right)$$

$$\times\left(9.498186\frac{a}{h} + 2058.33\left(\frac{a}{h}\right)^{4.322261} e^{-3.50099\left(\frac{a}{h}\right)}\right) \qquad \text{..................(9)}$$

Kishk et. al. presented an accurate analysis of the radiation characteristics of the cylindrical DRA using the method of moments. They presented the effect of the permittivity, ground plane size and resonator's dimensions on the radiation patterns of antenna. It was also confirmed that it is possible to improve the performance of a DR antenna by using a coaxial probe coated with a low permittivity material. A appropriate expression for an effective permittivity has been used to compute the resonant frequency of the $TE_{01\delta}$ mode of a dielectric resonator placed in an MIC environment. A new antenna configuration that uses a microstrip line-slot feed scheme for exciting the half split DR antenna structure has been explained. The feed scheme readily allows for the excitation of the "magnetic dipole" mode of the resonator. Chow et. al. studied a two-element linear CDRA array compared with a single element and improved from to back ratio. Drossos et. al., investigated various structures of broadside DRA arrays theoretically and experimentally using various array techniques. These structures include two cylindrical DRAs excited by coaxial, four-element linear broadside arrays using microstrip-coupled CDRAs, two linear four-element linear aperture-coupled cylindrical dielectric and hence reported enhanced directivity, benefit and bandwidth.

(iii) HEMISPHERICAL DRA

The common shape that was analyzed by most of the antenna researcher is hemispherical DRA. One of the reasons for this was that an analytical solution can be obtained for this geometry, considering certain assumptions. The degrees of freedom present in this particular geometry are : the permittivity of the material ε_r and the radius of the half sphere. For analysis, the shape is mounted on a perfect conductor plane of infinite length. The fields present in the hemispherical DRA shape can be divided into two distinct modes : TE_{111} and TM_{101}. However, some variations of the hemispherical DRA might be having more interesting parameters and design freedom that can be achieved by additional engineering and modification of the shape. Fig. -7 illustrates the schematic view of the hemispherical DRA with radius (*r*), diameter (*D*) and height (*H*). While Fig.-8 represents the simple geometry of HDRA.

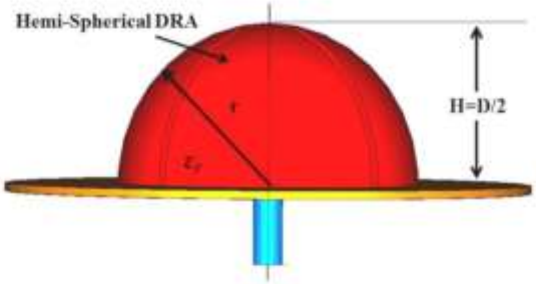


Fig. 7 Hemispherical DRA with radius (*r*), diameter (*D*) and height (*H*).

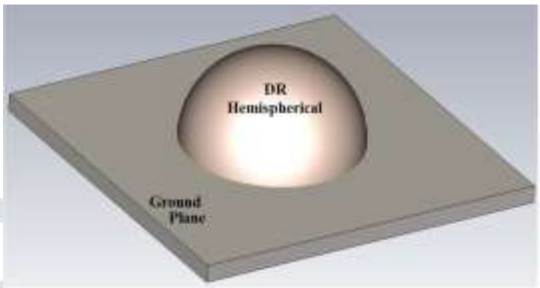


Fig. 8 Simple geometry of HDRA.

Two degree of freedom HDRA.

The resonant frequecy, f_r (in GHz) and radiation Q-factor of hemispherical DRA for TE_{111} and TM_{101} modes can be found using following equations.

$$f_{r(GHz)} = \frac{4.7713\,\mathrm{Re}(kr)}{r\sqrt{\varepsilon_r}} \qquad \text{.............................(10)}$$

$$Q = \frac{\mathrm{Re}(kr)}{2\,\mathrm{Im}(kr)} \qquad \text{.............................(11)}$$

For TE_{111}Mode :

$$\mathrm{Re}(kr) = 2.8316\ \varepsilon_r^{-4.47829} \qquad \text{.............................(12)}$$

$$Q = 0.08 + 1.796\varepsilon_r + 0.01226\varepsilon_r^{\ 2} - 3.10^{-5}\varepsilon_r^{\ 3} \qquad \text{.............................(13)}$$

For TM_{101}Mode :

$$\mathrm{Re}(k_r) = 4.47226\ \varepsilon_r^{-0.505} \qquad \text{.............................(14)}$$

For $\varepsilon_r < 20$ $$Q = 0.723 + 0.9324\varepsilon_r - 0.0956\varepsilon_r^{\ 2} - 0.00403\varepsilon_r^{\ 3} - 5.10^{-5}\varepsilon_r^{\ 4} \qquad \text{.................(15)}$$

For $\varepsilon_r > 20$ $$Q = 2.621 - 0.547\varepsilon_r + 0.01226\varepsilon_r^{\ 2} - 2.59*10^{-4}\varepsilon_r^{\ 3} \qquad \text{.............................(16)}$$

K.W.Leung and K.M.Luk carried out the bulk of the research focused on analysingdifferent modes of excitation of DRAs with examining a variety of fed mechanisms of DRAs. They also applied analytical and numerical techniques to determine the input impedance, Q factor, and radiation patterns of DRA. They proposed technique to standardize the mode nomenclature being used to characterize the DRAs. As ε_r increases, the input resistance increases initially, attain a maximum value and then it starts decreasing sharply with increase in ε_r. This shows that a very high permittivity material is a bad radiator. It has been seen that material with low permittivity (ε_r =9.8)for Roger TMM10 is considered as the better material for DRA development as its permittivity is low compared to another Roger materials. They also provided a set of simple equations for predicting the resonant frequency and Q factors for various modes of various DRAs. Hemispherical DRA is also rigorously using other feeding techniques like coaxial probe and aperture-coupled for its best performance, but feeding approach is not discussed here.

IV. RESULT & DISCUSSIONS

RESULT

Table -1

Comparison of the Numerical Results for Various Geometries of DRA

Rudimentary Geometries	***Rectangular***	***Cylindrical***	***Hemispherical***
Dimensions (mm) (Optimized)	a=b=30,d=15	r=18, h=15	hr=18.61
Resonant Frequency (Simulated)	3.2 GHz	3.2 GHz	3.3 GHz
Resonant Frequency (calculated)	2.5 GHz	2.3 GHz	2.4 GHz
Bandwidth Range ($\|S_{11}\|$<-10dB)	2.9 - 4.7 GHz	2.9 - 4.7 GHz	3 - 4.5 GHz
Bandwidth (Simulated)	56%	50%	46%
Total Peak Gain	1.56 dBi	1.50 dBi	1.54 dBi

Table -1 summarizes all the numerical results for various geometries of DRA. It can be seen that the simulated impedance bandwidth (for return loss below - 10dB) of the DRA is 56%, 46% and 50% for rectangular, hemispherical and cylindrical respectively. It can be observed that the rectangular antenna not only achieves broader impedance bandwidth, but also its benefit is considerably higher than other DRAs. Also as compared to another DRAs, rectangular DRAs make it simple to fabricate. So in this paper, we have established the fact that RDRA (in terms of parameters like impedence bandwidth, degree of freedom, resonant frequency - simulated and calculated) may be the best choice for further improvement in the design of Dielectric Resonator Antena (DRAs).

DISCUSSIONS

The rudimentary geometries of DRA are rectangular, cylindrical and hemispherical, which are used for investigating the DRA performance. These geometries of DRA are shown in Fig. -9. DRA is designed on symmetrical ground plane having the dimension of 60 × 60 mm^2. The dielectric material used for rudimentary geometries is TMM10, Roger material is not explained in detail here. A ceramic thermoset polymer composite material of the Rogers high-frequency laminates having the permittivity (ε_r) of 9.8, the dissipation factor (tanδ) of 0.002, and the density of 2.8 gm/cm^3. The DRA is designed to operate around 3.2 GHz (predicted). However, the resonant frequency may alter due to different rudimentary geometries. CST (Microwave Studio transient) solver is used to design and simulate the different rudimentary geometries of DRA. The characteristics of the antenna are obtained in terms of reflection coefficient, gain and impedance bandwidth; and are compared with the computational values (Rectangular, Cylindrical and Hemispherical).

The rectangulr shape is much easier to faricate and one or more dimensional parameters are present as additional degrees of freedom i.e. to design RDRA, flexibility between the lengths to width or width to height ratio can be selected. Fig. -9 (a) shows the geometry of a probe fed rectangular DRA. The rectangular DRA has dimensions$a = b = 30$ mm and $d = 15$ mm and permittivity, $\varepsilon_r = 9.8$ (Roger TMM10 is taken), whereas the feeding probe length from ground plane is 7mm and radius of probe is 0.33 mm.

The resonant frequency (f_r) of a RDRA is given as eqn. (5):

$$f_r = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{k_x^2 + k_y^2 + k_z^2}$$

where "ε_r" is the permittivity of the RDRA, "c" is the speed of light in free space and symbol "k_x", "k_y" and "k_z" represents the wave number in the x, y and z directions respectively.

The theoretical resonant frequency is 2.5 GHz while simulated resonant frequency is 3.2 GHz and bandwidth is 56% (for return loss below - 10dB) for RDRA as shown in Fig. -10.

Fig. -9(b) shows the geometry of probe fed Cylindrical DRA (CDRA). This antenna offers one degree of freedom i.e. radius (r) to height (h) ratio in terms of physical dimensions. For analysis of CDRA, radius is taken as 18 mm and height is taken as 15 mm, and the feeding probes length is considered as 7mm. The resonant frequency of CDRA for $TE_{01\delta}$ is given by Eq. (6). The calculated resonant frequency is 2.3 GHz while simulated resonant frequency is 3.2 GHz and bandwidth is 50% (for return loss below - 10dB) of CDRA, as depicted in Fig. -10.

Hemispherical DRA (HDRA) offers zero degree of freedom. For HDRA the dimension of radius is hr (hr = 18.61 mm) as shown in Fig. -9(c) whereas the feeding probe length is 7mm. The resonant frequency, f_r (in GHz) of HDRA can be found using following equation (10).

The calculated resonant frequency is 2.4 GHz while simulated resonant frequency is 3.3 GHz and bandwidth is 46% (for return loss below - 10dB) of HDRA, as shown in Fig.-10.

The corresponding $|S_{11}|$ variations for various rudimentary geometries of DRAs are shown in Fig. -10. The simulated result shows that impedance bandwidth (for return loss below - 10dB) of rectangulr, cylindrical and hemispherical DRAs are 56%, 50% and 46% respectively.

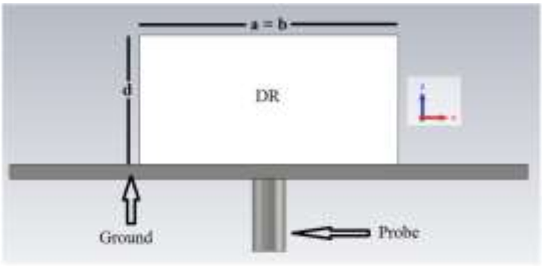


Fig. -.9 (a) : Geometry of a probfed RDRA

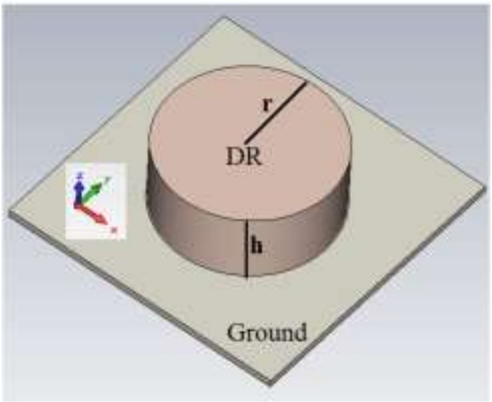


Fig.-9 (b) : Geometry of a probfed Cylindrical DRA (CDRA)

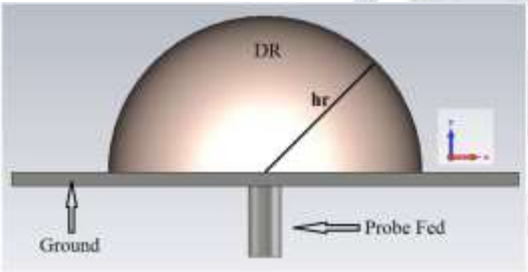


Fig. 9 (c) : Geometry of a probfed Hemispherical DRA (HDRA)

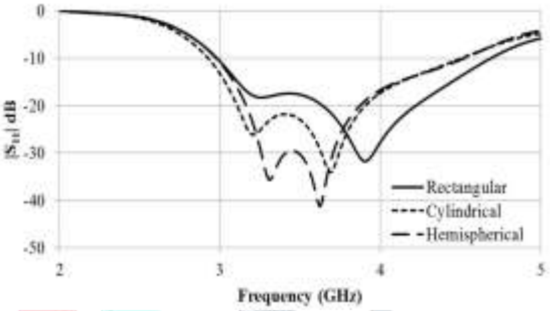


Fig. 10 : Variations of $|S_{11}|$ verses frequency for different rudimentary geometries of DRAs

CONCLUSION

The rudimentary geometries of DRA are rectangular, cylindrical and hemispherical, which are used for investigation of DRA performance. These rudimentary geometries of DRA give a best understanding of design parameters of an antenna and their effect on return loss, impedance bandwidth, benefit and resonant frequency. It was found that the rectangular DRA fed by coaxial probe provide best resonance level as compared to another geometries. simulated result shows that impedance bandwidth (for return loss below - 10dB) The result shows that impedance bandwidth of rectangulr, cylindrical and hemispherical DRAs are 56%, 50% and 46% respectively.

REFERENCES

[1] Long S.A. et al., “The resonant cylindrical dielectric cavity antenna,” IEEE Trans. Antennas Propagation, vol. 31, pp. 406–412, 1983.

[2] D. Guha,Archita Banerjee, C. Kumar and Yahia.M.M Antar “Higher Order Mode Excitation for High Gain Broadside Radiation from Cylindrical Dielectric Resonator Antennas” *IEEE Transactions on Antennas and Propagation*,vol.60, no.1, pp. 71 - 77, Jan. 2012.

[3] T.A. Denidni and Z. Weng, “ Rectangular dielectric resonator antenna for ultra wideband applications,” Electronics Letters, vol. 45, no. 24, Nov. 2009.

[4] McAllister M., Long S.A., Conway G.L. "Rectangular dielectric resonator antenna" Electronics Letters. 1983. 19: 219-220.

[5] McAllister M., Long S.A., Conway G.L. "Resonant hemispherical dielectric antenna" Electronics Letters. 1984. 20: 657-659.

[6] S.N.Singh, Pappu Paswan & Neeraj Kumar, "Analysis of Different Waveguide Modes of a Cylindrical Dielectric Resonator Antenna for Wireless Communication", IJERT, Vol.4, Issue 07, pp. 861-864, July-2015

[6] Mongia, R.K. "Theoretical and experimental resonant frequencies of rectangular dielectric resonators." In IEE Proceedings H (Microwaves, Antennas and Propagation), 1992, 139: 98-104 IET Digital Library.

[7] Kishk, A.A., H.A.Auda, B.C.Ahn. "Accurate prediction of radiation patterns of dielectric resonator antennas. "Electronics Letters, 1987, 23 : 1374-1375.

[8] Drossos, G., Z. Wu, L.E. Davis. "Two planar arrays using four probe-fed cylindrical dielectric resonator antennas." IEEE International Conference on Antennas and Propagation, York, UK 1999 : 283-286.

[9] CST Microwave Studio. Computer Simulation Technology, Framingham, MA, USA, 2010.

[10] Luk, K.M., K.W. Leung, K.Y. Chow. "Bandwidth and gain enhancement of a dielectric resonator antenna with the use of a stacking element." Microwave and Optical Technology Letters, 1997, 14:215-217.