Progress In Electromagnetics Research C, Vol. 11, 69–79, 2009

DESIGN OF A COMPACT RECTANGULAR DIELECTRIC RESONATOR ANTENNA AT 2.4 GHz

G. D. Makwana and K. J. Vinoy

Microwave Laboratory, ECE Department
Indian Institute of Science
Bangalore 560012, India

Abstract—This paper presents the design of a compact rectangular dielectric resonator antenna (RDRA) for wireless applications. A metal plate has been attached to top surface of the RDRA to achieve significant reduction in the resonant frequency of the antenna. A simple microstrip feeding mechanism has been used to excite this compact rectangular DRA. Performance parameters such as resonant frequency, impedance bandwidth, and volume of this compact RDRA are compared with those of the conventional RDRA. Measured characteristics of these RDRAs are in good agreement with the simulated results. The size of the compact RDRA using a low dielectric constant ($\varepsilon_r = 10.3$) material resonant at 2.4 GHz is 30 mm × 10 mm × 6.3 mm with a ground plane size of 200 mm × 200 mm.

1. INTRODUCTION

Dielectric Resonator Antennas (DRAs) have been suggested as potentially efficient antennas for modern wireless systems. They offer advantages such as high efficiency, large bandwidth, low profile, ease of fabrication, and low production cost as compared to microstrip antennas. The resonant frequencies of a DRA are predominantly determined by its size and shape, relative permittivity of the material ε_r, and the selected mode of operation [1, 2]. DRAs can be excited using probe, microstrip line [3, 4], microstrip slot [5], and coplanar waveguide [6] coupling. Several DRAs with standard shapes (hemispherical, cylindrical, and rectangular) have been reported in the literature [1, 7, 8].

The use of low permittivity material in DRA results in a high impedance bandwidth operation, but with a large physical volume for

Corresponding author: G. D. Makwana (gmakwana@gmail.com).

the antenna. On the other hand, high permittivity yields compact [9] or low-profile design of DRA [2]. An alternative approach to design a compact DRA is by adding a conducting metal plate on the top surface of the DRA [10]. It has been shown that the resonant frequency and fractional bandwidth are reduced by adding this metal plate [10–12]. In [10] magnetic dipole modes of circular and rectangular DRA with a metal layer on the top, and fed by a probe were investigated for size reduction. Aperture coupled, circular shaped DRA also showed similar trends in resonant frequency [11]. More recently, rectangular DRA with a stepped microstrip line feed was investigated with a resonant frequency of above 5 GHz [12]. It has been shown that the impedance bandwidth is improved for a dielectric resonator on patch (DRoP) in [13, 14], while patch on DRA is decreased the impedance bandwidth.

In this paper, physical parameters of the proposed low-profile rectangular DRA have been optimized by extensive simulations using full wave electromagnetic simulator Ansoft HFSS. The antenna is designed to operate for the wireless band at 2.4 GHz with sufficient gain and bandwidth characteristics. Section 2 presents the theoretical aspects of the design of the compact rectangular DRA. Section 3 discusses the antenna geometry. Section 4 compares the experimental results of proposed antennas against the simulation results for validation.

2. THEORY

The resonant behavior of the simplified case of an isolated rectangular DRA (Figure 1) is analyzed here. The antenna is characterized by height b, width d, length w, as shown in the Figure 1 and is made of material with dielectric constant ε_r. This geometry is equivalent to a rectangular DRA of the same material placed over an infinite ground plane with dimensions w, d, height $h = b/2$. If the smallest dimension of the rectangular DRA is in the x direction, then the dominant lowest order mode will be the TE^x_{111} mode (w, $b > d$) [7]. The equations for calculating the resonant frequency are

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \tag{1}$$

$$k_0 = \frac{2\pi}{\lambda_0} \tag{2}$$

$$k_y = \frac{\pi}{w}, \quad k_z = \frac{\pi}{b} \tag{3}$$

$$k_x \tan\left(\frac{k_x d}{2}\right) = \sqrt{\left((\varepsilon_r - 1)k_0^2 - k_x^2\right)} \tag{4}$$

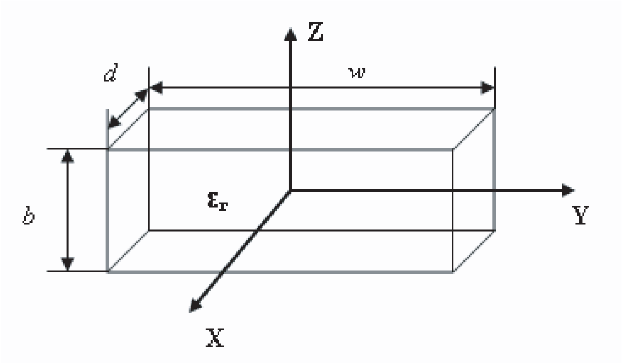

Figure 1. Geometry of an isolated rectangular dielectric resonator antenna.

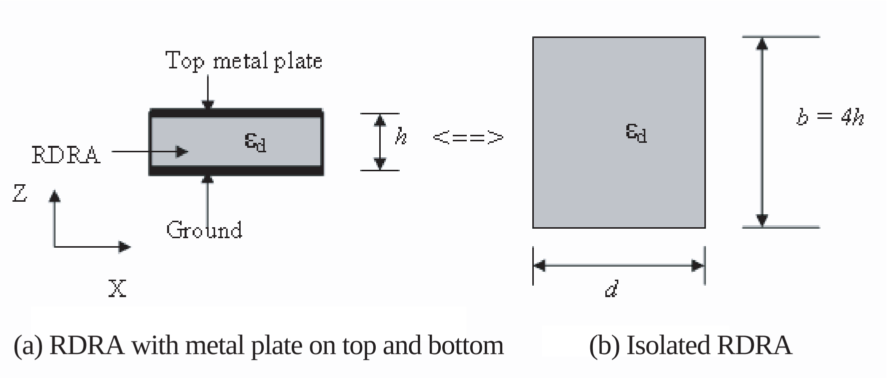

Figure 2. The compact DRA with metallic layers and its equivalent DRA in free space.

The cross sectional view of a compact rectangular DRA with metal plates on top and bottom surfaces is shown in Figure 2. Image theory may be used to replace the geometry with an isolated RDRA of height equal to four times of original height i.e., $b = 4h$. The above equations can therefore be used for calculating the resonant frequency of this antenna geometry also. It may however be noted that this model does not include the effects of the top metal layer being finite. Similarly the effects of dimensions of the feed microstrip line and the presence of the dielectric laminate beneath this are not considered here.

3. SIMULATION STUDIES WITH THE ANTENNA

Figure 3 shows the geometry of the proposed microstrip fed low profile rectangular DRA. As shown in Figure 3, a 50 Ω microstrip line having width of 4.45 mm and length of 45 mm is printed on a grounded substrate (dielectric constant of 2.5, thickness of 1.56 mm, and loss factor of 0.0017) with a size of $50 \times 50\,\text{mm}^2$. The antenna is made using microwave laminate material from Arlon with relative permittivity ε_r of 10.33, thickness of 0.76 mm, and loss factor of 0.0023 This placed symmetrically above the microstrip line for coupling. The dimensions of ground plane used in this structure are $200 * 200\,\text{mm}^2$. For the compact antenna, the conducting copper foil with the same cross-sectional area of rectangular DRA is placed on its top.

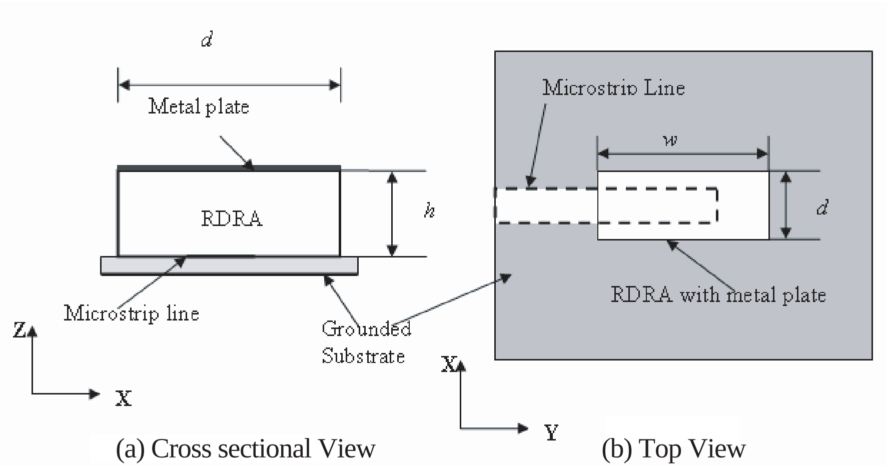

Figure 3. Geometry of the proposed compact RDRA.

Table 1. Simulated results for varying height of a conventional RDRA.

h (mm)	Calculated Fr. (GHz)	Simulated Fr. (GHz)	% of Error
8	5.145	5.52	7.28
7	5.433	5.80	6.75
6	5.838	6.16	5.51
5	6.442	6.62	2.76
4	6.704	7.20	7.70

Numerical studies were carried out by varying the height of the conventional and compact rectangular DRA fed by a microstrip line. All other parameters of these RDRAs are kept constant. The resonant frequencies calculated using the model developed in Section 2 are compared with those obtained by full wave simulations of the conventional and compact DRA are shown in Tables 1 and 2 respectively. Although these simulated resonant frequencies agree well with calculations in both cases, the modes of resonance in these cases differ. Analysis shows that the resonant modes of the conventional and compact DRA are for $TE^x_{\delta 21}$ and $TE^x_{\delta 10}$ mode respectively. It may be recalled that the presence of microstrip line and substrate are not included in the calculation based on the simplified model. Another factor for the error in compact RDRA is due to finite metal plate on top surface of RDRA. In calculation, infinite metal plate is assumed. A second order approximation is used to calculate the resonant frequency of conventional RDRA. Due to this, the simulated resonant frequency is higher than calculated resonant frequency. In compact RDRA, the $k_z = 0$ is assumed in calculated resonant frequency, because of which the simulated resonant frequency is lower than calculated resonant frequency.

Table 2. Simulated results for varying height of a compact RDRA.

h (mm)	Calculated Fr. (GHz)	Simulated Fr. (GHz)	% of Error
8	2.45	2.28	6.94
7	2.45	2.31	5.71
6	2.45	2.27	7.34
5	2.45	2.315	5.51
4	2.45	2.33	4.90

Table 3. Simulated results for varying width of a compact RDRA.

d mm	Calculated Fr. (GHz)	Simulated Fr. (GHz)	% of Error	S_{11} (dB)	BW (MHz)	% BW
16	2.13	2.14	0.46	−15.59	90	4.20
14	2.21	2.16	2.26	−16.58	90	4.17
12	2.31	2.22	3.89	−20.25	105	4.72
10	2.45	2.27	7.34	−21.03	120	5.28
08	2.63	2.36	10.26	−32.30	120	5.08
06	2.88	2.47	13.88	−20.30	115	4.67

For parametric study on width, d, of compact RDRA, fixed height of 6 mm and length of 30 mm have been chosen. The width d of the compact DRA were varied to study the effects, as shown in Table 3. From the Table 3, it is observed that the error in the prediction of resonant frequency increased to 13% as the width is decreased. This is partially due to the reduction in the area of the top metal plate. Location of open ended microstrip line is optimized for return loss less than 10 dB in each case. Based on simulations, the design physical parameter of RDRA are $w = 30$ mm, $d = 10$ mm, and $h = 6$ mm have been chosen for further validation.

4. EXPERIMENTAL VALIDATION AND DISCUSSION

Prototypes of the antennas with and without the top metal layers were fabricated using a microwave laminate material from Arlon with same ground plane size. These are made by stacking together eight layers, glued with wax to avoid air gap between the layers, of this material (dielectric constant of 10.33). The height of RDRA is 6.3 mm. The fabricated antennas are characterized by a PNA series vector network analyzer. The measured and simulated return loss characteristics of the conventional rectangular DRA without the metal layer on the top are shown in Figure 4. The difference in the measured and simulated responses of this antenna is due to fabrication error and the effect of finite thickness of the wax/glue layers. Measured response has a -10 dB return loss bandwidth starting from 5.56 GHz to 6.37 GHz (13.3%) [4]. The measured gain is 4.33 dB at resonant frequency.

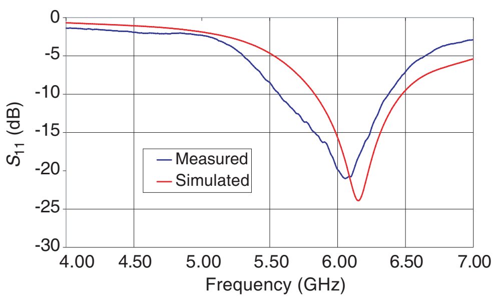

Figure 4. Measured and simulated return loss characteristics of a conventional RDRA.

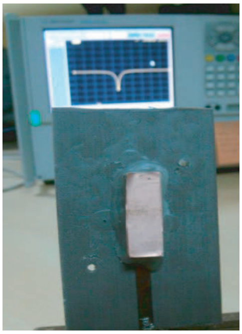

Figure 5. Photograph of fabricated proposed compact RDRA before attaching aluminum ground.

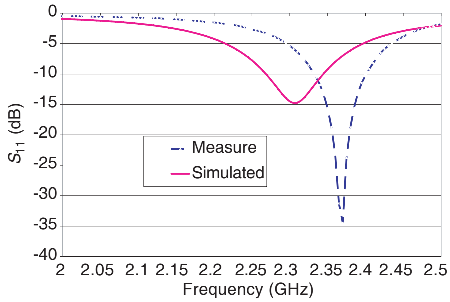

Figure 6. Measured and simulated return loss characteristics of a compact RDRA.

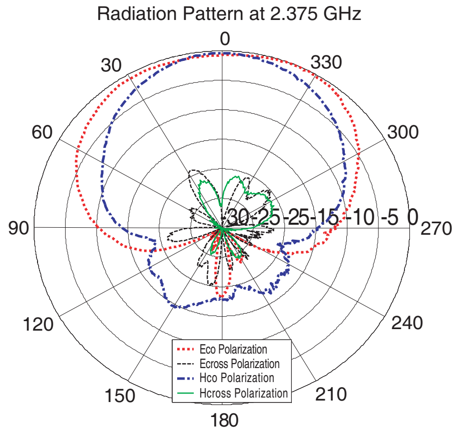

Figure 7. Measured radiation patterns for compact RDRA.

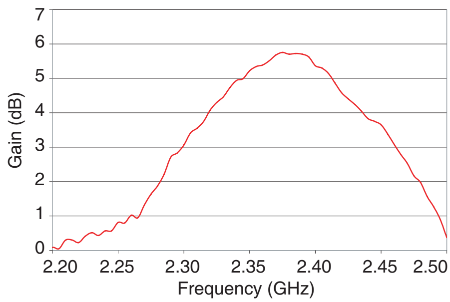

Figure 8. Measured gain for compact RDRA.

The proposed compact rectangular DRA is fabricated by attaching a copper foil with the same cross-sectional area of $30 * 10\,\mathrm{mm}^2$, and thickness of 20 µm on the top surface of conventional RDRA. Photograph of fabricated compact rectangular DRA is shown in Figure 5. The measured and simulated return loss characteristics for compact RDRA are found to be in reasonable agreement, except for minor difference due to fabrication error, is shown in Figure 6. Compact RDRA has a measured resonant frequency of 2.375 GHz. It has −10 dB return loss bandwidth of 65 MHz (−6 dB bandwidth of 120 MHz) which is sufficient for most wireless applications. The measured radiation patterns are shown in Figure 7. Radiation patterns are taken with aluminum ground of dimension 200 mm × 200 mm of this antenna. The cross polarization level is better than −25 dB at resonant frequency. The measured gain is above 5 dBi over the frequency range of interest, is shown in Figure 8.

Table 4 compares the measured performances of these antennas. From the Table 4, it is noticed that by adding the metal plate on top surface of conventional RDRA, 61% reduction is observed in the resonant frequency. Based on simulation studies, it has been found that to resonate at 2.4 GHz, physical dimensions of a conventional rectangular DRA should be $w = 40\,\mathrm{mm}$, $d = 26\,\mathrm{mm}$, $h = 18\,\mathrm{mm}$. Hence, the proposed compact RDRA yields volume reduction about 87% as compared to conventional RDRA.

Several similar antennas are reported in the literature with compact and low profile cylindrical DRA (CDRA) and RDRA [10, 15–20]. A comparison of these is provided in Table 5 in terms of their volume, dielectric constant, and resonant frequency. A figure of merit β which is the measured resonant frequency multiplied with the DRA

Table 4. Comparison for compact & conventional RDRA.

Particulars	Conventional RDRA	Compact RDRA
Resonant Frequency (GHz)	6.1	2.375
Return loss (dB)	−21.00	−34.00
Bandwidth (MHz)	809	65
% Bandwidth	13.3	2.74
Gain (dBi)	4.33	5.75
Reduction in Fr.	—	61%
Reduction in BW	—	92%

volume [GHz. mm^3] can be used for an effective comparison of these antennas. The smaller the value of β is, the compact the DRA is. From the Table 5, it is noticed that proposed antenna has the smallest figure of merit among these.

Table 5. A comparison of proposed antenna with other published compact DRAs.

Type of DRA	Volume (mm^3)	ε_r	Resonant Frequency (GHz)	β (GHz. mm^3)	Ref.
RDRA	4097	9.2	2.076	8505	10
Half -CDRA	276721	12	1.06	293325	15
RDRA	38720	12	0.918	35545	15
Half -CDRA	36625	12	2.39	87533	16
RDRA	2420	10.2	6.0	14520	17
RDRA	11935	10	2.413	28799	18
CDRA	2331	27	4.797	11181	19
Half -CDRA	12735	69	2.455	31266	20
Proposed Antenna	1800	10.3	2.375	4275	–

5. CONCLUSION

In this paper, a compact rectangular DRA has been designed for 2.4 GHz operation with a simple microstrip line feeding mechanism. This design makes use of a metal layer on the top of a typical rectangular DRA. It has been noticed that there is a significant reduction of resonant frequency and volume at the expense of impedance bandwidth as compared to a conventional rectangular DRA when metal plate is added. Experimental results demonstrates that covering the top surface of DRA with a metal layer results in 62% reduction of resonant frequency as compared to a conventional DRA configuration. The resulting antenna meets typical requirements for wireless applications at this band.

REFERENCES

1. Long, S. A., M. W. McAllister, and L. C. Shen, "Rectangular dielectric resonator antenna," *IEEE Electronics Letters*, Vol. 19, 218–219, Mar. 1983.
2. Petosa, A., *Dielectric Resonator Antenna Handbook*, Artech House, 2007.

3. Kranenburg, R. A. and S. A. Long, "Microstrip transmission line excitation of dielectric resonator antennas," *IEEE Electronics Letters*, Vol. 24, No. 18, 1156–1157, Sep. 1988.
4. Makwana, G. D. and K. J. Vinoy, "A microstrip line fed rectangular dielectric resonator antenna for WLAN application," *Proceeding of IEEE International Symposium on Microwave*, 299–303, Dec. 2008.
5. Martin, J. T. H. ST. and Y. M. M. Antar, "Dielectric resonator antenna using aperture coupling," *IEEE Electronics Letters*, Vol. 26, No. 24, 2015–2016, Nov. 1990.
6. Kranenburg, R. A., S. A. Long, and J. T. Williams, "Coplanar waveguide excitation of dielectric resonator antenna," *IEEE Transaction on Antennas and Propagation*, Vol. 39, 119–122, Jan. 1991.
7. Ittipiboon, A. and R. K. Mongia, "Theoretical and experimental investigation on rectangular dielectric resonator antenna," *IEEE Transaction on Antennas and Propagation*, Vol. 45, No. 9, 1348–1356, Sep. 1997.
8. Sreekantan, S., Y. K. Ling, Z. A. Ahmad, M. F. Ain, M. B. Othman, and S. I. S. Hassan, "Simulation and excremental investigators on rectangular, circular, and cylindrical dielectric resonator antenna," *Progress In Electromagnetics Research C*, Vol. 7, 151–166, 2009.
9. Ain, M. F., S. I. S. Hassan, J. S. Mandeep, M. A. Othman, and B. M. Nawang, "2.5 GHz $BaTiO_3$ dielectric resonator antenna," *Progress In Electromagnetics Research*, PIER 76, 201–210, 2007.
10. Mongia, R. K., "Reduced size metallized dielectric resonator antennas," *IEEE Antennas and Propagation International Symposium Digest*, Vol. 4, 2202–2205, Canada, Jul. 1997.
11. Lee, M. T., K. K. Luk, K. W. Leung, and M. K. Leung, "A small dielectric resonator antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 50, 1485–1487, Oct. 2002.
12. Saed, M. A. and R. Yadla, "Microstrip-fed low profile and compact dielectric resonator antennas," *Progress In Electromagnetics Research*, PIER 56, 151–162, 2006.
13. Nasimuddin and K. P. Esselle, "A low-profile compact microwave antenna with high gain and wide bandwidth," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 6, 1880–1883, Jun. 2007.
14. Nasimuddin and K. P. Esselle, "Antennas with dielectric resonators and surface mounted short horn for high gain and wide

bandwidth," *IET Microwaves, Antennas and Propagation*, Vol. 1, No. 3, 723–728, Jun. 2007.

15. Tam, M. T. K. and R. D. Murch, "Half volume dielectric resonator antenna designs," *IEEE Electronics Letters*, Vol. 33, No. 23, 1914–1916, Nov. 1997.
16. Tam, M. T. K. and R. D. Murch, "Compact cylindrical sector dielectric resonator antennas," *IEEE Antennas and Propagation Society International Symposium, 1998 Digest*, Vol. 4, 1958–1961, 1998.
17. Gao, Y., B. L. Ooi, W. B. Ewe, and A. P. Popov, "A compact wideband hybrid dielectric resonator antenna," *IEEE Microwave and Wireless Components Letters*, Vol. 16, No. 4, 227–229, Apr. 2006.
18. Lim, E. H. and K. W. Leung, "Compact wideband circularly polarized dielectric resonator antenna with an underlaid hybrid coupler," *2008 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting*, Jul. 5–12, 2008.
19. Chen, H. M., Y. F. Lin, C. H. Lin, and S. C. Lin, "Compact dual band hybrid dielectric resonator antenna," *TENCON-2007, IEEE Region 10 Conference*, 214–216, 2007.
20. Praveen Kumar, A. V., V. Hamsakutty, J. Yohannan, and K. T. Mathew, "Half split cylindrical dielectric resonator antenna for 2.4 GHz WLAN operation," *2006 IEEE Antennas and Propagation Society International Symposium*, 997–1000, 2006.