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EFFECTIVE WAVE GUIDE MODEL (EWGM) FOR RESONANT FREQUENCY COMPUTATION OF RECTANGULAR DIELECTRIC RESONATOR ANTENNAS

S. Maity and B. Gupta

Department of Electronics and Tele-Communication Engineering
Jadavpur University
Kolkata-700 032, India

Abstract—A new model (EWGM) is presented to predict the resonant frequency of Rectangular Dielectric Resonator Antenna (RDRA) more accurately. Correction factors are introduced to calculate the effective dimensions by considering the effect of relative permittivity and aspect ratios (length/height and width/height) of RDRA. Results obtained from EWGM are compared with previous studies and experimental data to show its accuracy and effectiveness.

1. INTRODUCTION

Dielectric Resonators (DRs) have been widely used in shielded microwave circuits such as cavity resonators, filters and oscillators. As the frequency range goes upward gradually to millimeter and sub-millimeter region (100 GHz–300 GHz), conductor loss limits the use of metallic antennas. On the other hand, Dielectric Resonator Antenna (DRA) made up of low loss dielectric material is a potential candidate for high frequency application. In recent years, application of DRAs in microwave and millimeter band has been extensively studied [1–5], as they provide efficient radiation due to extremely low loss in the dielectric material. Its inherent wide band nature, compactness in size, light weight, low cost, ease of fabrication etc. make DRA very attractive. Theoretical and experimental investigations have been reported on cylindrical, spherical, rectangular, triangular, hexagonal and/or trapezoidal DRAs in literature.

Closed cavity model with Perfect Magnetic Conductor (PMC) walls, Boundary Element Method (BEM), Method of Moment (MoM),

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Corresponding author: S. Maity (sdpt123_maity@yahoo.co.in).

Spectral Domain Method (SDM), Transmission Line Matrix (TLM) method, Finite Difference Time Domain (FDTD) method, Finite Element Method (FEM), Null Field Method (NFM) etc. are used to predict its resonant frequency.

Mainly two techniques, Magnetic Wall Model (MWM) with first and/or second order approximation [7] and Dielectric Waveguide Model (DWM) are widely used to analyze the rectangular DRA (RDRA). Marcatili's model [8], Knox and Toulios's model or Effective Dielectric Constant (EDC) method [9] and Rectangular Shaped Resonator (RSR) model [10] are used to approximate the DWM. To analyze it, first the RDRA, placed on ground plane is excited by dielectric image guide, microstrip slot, coplanar waveguide, aperture (slot) or probe. Due to presence of ground plane, image theory is then applied equivalently to replace the resonator by an isolated DR and hence the effect and/or dimensions of feed mechanism are ignored. According to the Conventional Wave Guide Model (CWGM) [4], resonant frequency (f_r) of RDRA ($a \times b \times c$) is a function of two aspect ratios: length/height (a/c) and width/height (b/c) and the relative permittivity (ε_r). The expression of resonant frequency (f_r) does not include feed mechanism. Further, we usually get a wide difference between theoretical and experimental resonant frequencies as predicted by any of these models.

The concept of effective dimensions of RDRA has been first reported by Antar et al. for RDRA by introducing Modified Wave Guide Model (MWGM) [11] in 1998 which gives better results for medium values of relative permittivity around $\varepsilon_r = 37.84$. According to MWGM, each dimension of RDRA ($a \times b \times c$) is expressed as

$$p = p\left(1 - \varepsilon_r^{-1}\right); \quad p = a, b, c \tag{1}$$

A fitted closed form formula has also been reported using CWGM for prediction of resonant frequency of rectangular DR for antenna application by Neshati et al. in 2001 [12]. According to them, the resonant frequency of RDRA ($a \times b \times c$) can be obtained as:

$$f_r = \frac{c}{2a\sqrt{\varepsilon_r}}\sqrt{1 + q^{-2} + p^{-2}\delta_{CDWM}^2} \tag{2}$$

where

$$\begin{aligned} \delta_{CDWM} &= \left(0.35 + 0.38p - 0.078p^2\right) + (0.41 - 0.11p) \\ &\quad \times\exp\left(-\frac{q - 0.09 - 0.01p}{0.31 + 0.26p - 0.06p^2}\right) \end{aligned} \tag{3}$$

$q = 2c/a$; $p = b/a$ and c is the velocity of light in free space. But this is valid only for

$$0.5 < p < 2.0; \quad 0.2 < q < 2.0 \quad \text{and} \quad 30 < \varepsilon_r \leq 100.$$

Equation (3) does not include the effect of relative permittivity (ε_r). This technique fails to predict the resonant frequency of RDRA beyond $0.5 < p < 2.0$ and/or $0.2 < q < 2$.

Efficient Dielectric Waveguide Model (EDWM) [13] has been reported on the basis of curve fitting technique by Gurel et al. in 2009. They expressed the resonant frequency (f_r) as:

$$f_r = (1 + 0.001333\varepsilon_r)\frac{c}{2\pi}k_o \tag{4}$$

where k_o is free space wave number. MWGM and EDWM both introduce a correction factor by considering the effect of relative permittivity (ε_r). But Van Blade1 showed that the modes of a rectangular DR do not satisfy the magnetic wall condition even when the dielectric constant of the resonator tends to infinity [14].

Losses increase proportionally with volume of the DRA and/or also for very low ε_r. Particularly when width (w) is less than height (h) of RDRA, there is a wide variation between measured resonant frequency and theoretical resonant frequency. The resonant frequency of a rectangular DRA for TE^Y_{111} mode is given by [6]

$$f_r = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{(\pi/w)^2 + (\pi/d)^2 + (\pi/2h)^2} \tag{5}$$

where c is the velocity of light in free space. For low profile DRA, w, $d \gg h$, neglecting the effect of $(1/w)^2$ and $(1/d)^2$, the above equation can be written as $f_r = \frac{c}{4h\sqrt{\varepsilon_r}}$. But for the other cases where the aspect ratios, w/h and d/h are low or in the middle range of values we have to consider correction factors for w, d and h also.

Both Equations (1) and (4) given above deal with relative permittivity of RDRA alone. On the other hand, Equations (2) and (3) deal with dimensions of RDRA only without considering the effect of relative permittivity. There is no standard relation or empirical formula which considers the effect of both relative permittivity and dimensions of RDRA for predicting the resonant frequency. Therefore, in this section accurate correction factors for effective dimensions are reported on the basis of relative permittivity and dimensions of RDRA, noting that Electro-Magnetic (EM) energy confined within the DRA is related to permittivity and its dimensions [14]. The model developed is compared to predict the resonant frequency with CWGM, MWGM and EDWM for a wide range of values of ε_r starting from very low to very high values (9.8–100). It is found that our model gives better results than CWGM, MWGM and EDWM. In our model, the physical dimensions of the DR are replaced by its effective dimensions obtained using the correction factors. This procedure is carried out in all dimensions to replace the original DR by an effective waveguide cavity.

Fields within the cavity are analyzed to get the resonant frequency and the model developed is named EWGM (Effective Wave Guide Model).

2. EFFECTIVE DIMENSIONS AND EIGEN VALUE EQUATION OF RECTANGULAR DRA

The rectangular DRA as shown in Figure 1, placed on a finite ground plane has length $= d$, width $= w$, height $= h$ and relative permittivity $= \varepsilon_r$. For the aperture-coupled structure where the slot is along the y-axis or the probe is placed along x axis, the field for the fundamental mode of concern is $TE^Y_{11\delta}$. In the conventional waveguide model, the calculation of resonant frequency is based on a waveguide structure with a Perfect Electric Conductor (PEC) plane at $z = 0$, and Perfect Magnetic Conductor (PMC) walls at the $|x| = d/2$ and $z = h$ planes, respectively. But Marcatili's Dielectric Waveguide Model (DWM) [8] or Mixed Magnetic Wall model (MMW) [7] doesn't give perfect solution for RDRAs. Governing equations for k_x, k_y and k_z also take another form in the presence of any extra magnetic wall as in the case of Trapped Rectangular DRA (TRDRA). For that reason we do get remarkable difference between theoretical and experimental data.

However, we know that the Electro-Magnetic (EM) energy confined within the DRA is related to permittivity and its dimensions [14]. Electric fields get confined if the relative permittivity ofDRAs increases. The concept of effective dimension(s) for a radiating element is related to E field. For very high value of relative permittivity of DRAs, maximum amount of E-field remains confined. The effective distance between the E-field and the center of DRA reduces. Hence electrical dimension reduces for high values of permittivity.

To analyze the rectangular DRAs, we apply PEC at $z = 0$ and magnetic wall at all other remaining sides of DRA. But these magnetic walls are not perfect. E-fields go outside the DRAs due to fringing for low values of permittivity of DRA. Thus the effective distance between the E-field and the center of DRA increases. Hence electrical dimensions increase for low values of permittivity.

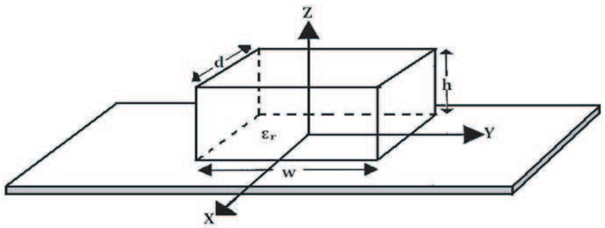

Figure 1. Geometry of RDRA on finite ground plane.

Changes in electrical dimensions along the length and the width are much more than those along the height of DRAs. Considering length extension/decrement along all dimensions, the effective dimensions of RDRA (in cm) are

$$d_e = d\left[1 - g - k\varepsilon_r^{-(a+p)}\right] \tag{6}$$

$$w_e = w\left[1 - k\varepsilon_r^{-(b+p)}\right] \tag{7}$$

$$h_e = h\left[1 - \varepsilon_r^{-1}\right] \tag{8}$$

where

$$k = \begin{cases} +1, & \varepsilon_r \geq 15 \\ -1, & \varepsilon_r < 15 \end{cases} \tag{9}$$

and the values of other parameters a, b, p, g are as given below.

$$a = \begin{cases} 0.6 - 0.3\,(\alpha - 40)/60, & for \quad \varepsilon_r \geq 35 \\ 2.85 - 2.25\,(\alpha - 25)\,/15, & for \quad 25 \leq \varepsilon_r < 35 \\ 2.85 - 0.05(\alpha - 20)/5, & for \quad 20 < \varepsilon_r < 25 \\ 2.8, & for \quad \varepsilon_r = 20 \\ 2.8 - 1.8\,(\alpha - 10)\,, & for \quad 10 < \varepsilon_r < 20 \\ 1, & for \quad \varepsilon_r \leq 10 \end{cases} \tag{10}$$

where α is nearest rounded value of ε_r and is a multiple of 10.

$$p = \begin{cases} 11\,\mathrm{m}, & for \quad dwh \leq 1; \quad d/h \leq 1; \quad w/h < 1 \\ 0.09, & for \quad dwh < 1; \quad 1 \leq (d/h = w/h) \leq 2 \\ 0.2, & for \quad 1 < dwh < 3; \quad (d/h = w/h) > 2 \\ -0.2, & for \quad dwh > 3; \quad (d/h = w/h) > 2 \\ 0, & \quad \text{elsewhere} \end{cases} \tag{11}$$

where $m = 0.1(\alpha - \varepsilon_r)/20$,

$$b = \begin{cases} 1 - 0.7(\varepsilon_r - 40)/60, & for \quad \varepsilon_r \geq 35 \\ 1, & \quad \text{otherwise} \end{cases} \tag{12}$$

and

$$g = \begin{cases} 0.2, & for \quad dwh > 0.9; \quad d \neq w \neq h; \quad 10 \leq \varepsilon_r \leq 20 \\ -0.15, & for \quad dwh \leq 0.9; \quad d \neq w \neq h; \quad 10 \leq \varepsilon_r \leq 20 \\ -0.4, & for \quad d/h > 2; \quad w/h > 2; \quad 20 < \varepsilon_r < 37.5 \\ 0.11, & for \quad d/h \leq 2; \quad w/h \leq 2; \quad 20 < \varepsilon_r < 37.5 \\ 0.065, & for \quad 70 < \varepsilon_r < 80; \quad \begin{cases} d/h < 1; \quad w/h < 1 & or \\ d/h > 4 & or \\ w/h > 4 \end{cases} \\ 0, & \quad \text{otherwise} \end{cases} \tag{13}$$

The parameters in Equations (9)–(13) are obtained by curve fitting technique using the full-wave analysis data.

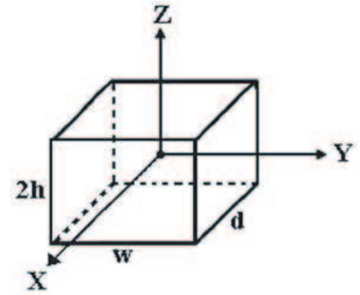

Figure 2. Isolated DR.

Assuming the ground plane is infinitely large, image theory can be applied to replace the resonator by an isolated DR along with its image as shown in Figure 2. The equivalent resonator has twice the height of the original resonator.

The field components of the $TE_{11\delta}^{Y}$ mode inside the resonator can be written as [4, 15]:

$$\begin{aligned}
H_x &= \frac{Ak_x k_y}{j\omega\mu_o\varepsilon_d}\sin(k_x x)\sin(k_y y)\cos(k_z z)\\
H_y &= \frac{A(k_x^2+k_z^2)}{j\omega\mu_o\varepsilon_d}\cos(k_x x)\cos(k_y y)\cos(k_z z)\\
H_z &= \frac{Ak_y k_z}{j\omega\mu_o\varepsilon_d}\cos(k_x x)\sin(k_y y)\sin(k_z z)\\
E_x &= -(A/\varepsilon_d)k_z\cos(k_x x)\cos(k_y y)\sin(k_z z)\\
E_y &= 0\\
E_z &= (A/\varepsilon_d)k_x\sin(k_x x)\cos(k_y y)\cos(k_z z)
\end{aligned} \tag{14}$$

where $\varepsilon_d = \varepsilon_o\varepsilon_r$ is the permittivity of resonator and k_x, k_y and k_z are the wave numbers in x, y and z directions respectively which can be determined from the boundary conditions. Considering Perfect Electric Conductor (PEC) at $z = 0$ and Perfect Magnetic Conductor (PMC) at $z = h_e$ and $|x| = d_e/2$ and field continuity at $|y| = w_e/2$ planes for $TE_{11\delta}^{Y}$ mode, we get

$$k_y\tan\left(\frac{k_y d_e}{2}\right) = \sqrt{(\varepsilon_r - 1)\,k_o^2 - k_y^2} \tag{15}$$

where

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_o^2 \tag{16}$$

$$k_x = \pi/d_e \tag{17}$$

$$k_z = \pi/(2h_e) \tag{18}$$

and k_o is free space wave number corresponding to resonant frequency (f_r).

Table 1. Comparison of measured and predicted resonant frequency for various models.

Sl No	Ref	ε_r	d (mm)	w (mm)	h (mm)	Fm (GHz)	CWGM (GHz)	MWGM (GHz)	EDWM (GHz)	EWGM (GHz)
1	[16]	9.8	9	6	7.6	7.43	7.6757	8.5479	7.7760	7.3094
2	[17]	9.8	14.3	25.4	26.1	3.5	3.7430	4.1683	3.7919	3.4496
3	[18]	10	14	8	8	5.5	5.6117	6.2352	5.6865	5.5033
4	[19]	10	14.3	25.4	26.1	3.92	3.7055	4.1172	3.7549	4.0397
5	[20]	10.8	15.2	7	2.6	11.6	10.3179	11.3707	10.4664	10.9086
6	[21]	10.8	15	3	7.5	6.88	7.0937	7.8176	7.1958	6.8583
7	[4]	10.8	15.24	3.1	7.62	6.21	6.9440	7.6525	7.0439	6.7140
8	[4]	20	10.16	10.16	7.11	4.71	4.6215	4.8647	4.7447	4.7218
9	[4]	20	10.16	7.11	10.16	4.55	4.5914	4.8330	4.7138	4.3236
10	[22]	20	10.2	10.2	7.89	4.635	4.4833	4.7193	4.6028	4.5725
11	[23]	25	18.66	18.66	5	3.612	3.6206	3.7715	3.7413	3.5563
12	[24]	36	18.66	18.66	6	2.532	2.6715	2.7479	2.7997	2.5661
13	[24]	36	18.66	6	18.66	2.835	2.3381	2.4049	2.4503	2.7305
14	[25]	37	18	18	9	2.45	2.1617	2.2217	2.2683	2.4768
15	[4]	37.84	15.24	7.62	7.62	3.06	2.8931	2.9716	3.0390	3.0812
16	[4]	37.84	7.62	7.62	15.24	4.08	3.8810	3.9864	4.0768	4.1320
17	[4]	37.84	8.77	8.77	3.51	5.34*, 5.19#	4.8816	5.0141	5.1278	5.1843
18	[4]	37.84	9.31	9.31	4.6	4.59*, 4.50#	4.1540	4.2668	4.3635	4.4458
19	[4]	37.84	8.6	2.58	8.6	5.34	5.0688	5.2064	5.3245	5.3250
20	[4]	37.84	8.77	3.51	8.77	4.79*, 4.76#	4.5209	4.6436	4.7490	4.7575
21	[4]	37.84	9.31	4.6	9.31	4.11*, 4.25#	3.9991	4.1077	4.2008	4.2143
22	[26]	37.84	9.31	4.6	9.31	4.38	3.9991	4.1077	4.2008	4.2143
23	[26]	37.84	8.97	8.97	8.97	3.78	3.5226	3.6182	3.7002	3.7555
24	[26]	37.84	9.31	9.31	4.6	4.47	4.1540	4.2668	4.3635	4.4458
25	[26]	37.84	8.96	7.61	12.69	3.76	3.4896	3.5843	3.6656	3.7035
26	[27]	38	19	19	9.5	2.147	2.0208	2.0754	2.1232	2.1633
27	[28]	38	19	19	9.5	2.206	2.0208	2.0754	2.1232	2.1633
28	[13]	71	9.8	5.3	19.08	3.22	2.5588	2.5953	2.8009	3.2011
29	[29]	79	28.2	28.2	4.9	2.09	1.8882	1.9124	2.0870	2.1825
30	[4]	79.46	12.7	2.54	2.54	5.43	4.9200	4.9827	5.4411	5.2759
31	[4]	79.46	12.7	6.35	6.35	2.64	2.3996	2.4302	2.6538	2.6706
32	[4]	79.46	7.7	7.7	7.7	3.17	2.8339	2.8700	3.1340	3.1236
33	[30]	90	10	10	5	2.73	2.4962	2.5242	2.7956	2.7259
34	[30]	90	15	15	5	2.13	2.0560	2.0791	2.3026	2.1384
35	[31]	100	10	10	2	4.57	4.2158	4.2584	4.7778	4.5557
36	[31]	100	10	10	1	7.97	7.7587	7.8370	8.7929	8.0183
37	[31]	100	12.7	12.7	1	7.72	7.6628	7.7402	8.6843	7.8579
38	[31]	100	5	10	1	8.85	8.1828	8.2655	9.2736	8.7398
39	[31]	100	10	5	1	8.5	8.0147	8.0956	9.0830	8.4043

* and # denote microstrip slot and probe coupling fed mechanism respectively

3. VERIFICATION OF MODEL

We have investigated RDRAs to predict the resonance frequency over a wide range of permittivity ($9.8 \leq \varepsilon_r \leq 100$) by using our proposed correction factors. For validation, we use data as given in [4, 11, 13, 16–31]. Due to conductor losses, surface wave propagation, large volume

Table 2. Comparison of error for various models.

Sl No	Ref	ε_r	d (mm)	w (mm)	h (mm)	Fm (GHz)	Error (%) CWGM	MWGM	EDWM	EWGM
1	[16]	9.8	9	6	7.6	7.43	3.3067	15.0461	4.6563	–1.6225
2	[17]	9.8	14.3	25.4	26.1	3.5	6.9416	19.0940	8.3386	–1.4407
3	[18]	10	14	8	8	5.5	2.0302	13.3669	3.3902	0.0592
4	[19]	10	14.3	25.4	26.1	3.92	–5.4719	5.0312	–4.2119	3.0529
5	[20]	10.8	15.2	7	2.6	11.6	–11.0526	–1.9763	–9.7721	–5.9603
6	[21]	10.8	15	3	7.5	6.88	3.1064	13.6275	4.5908	–0.3157
7	[4]	10.8	15.24	3.1	7.62	6.21	11.8193	23.2294	13.4291	8.1159
8	[4]	20	10.16	10.16	7.11	4.71	–1.8797	3.2845	0.7362	0.2507
9	[4]	20	10.16	7.11	10.16	4.55	0.9088	6.2198	3.5990	–4.9765
10	[22]	20	10.2	10.2	7.89	4.635	–3.2729	1.8180	–0.6941	–1.3476
11	[23]	25	18.66	18.66	5	3.612	0.2389	4.4155	3.5793	–1.5416
12	[24]	36	18.66	18.66	6	2.532	5.5107	8.5253	10.5739	1.3481
13	[24]	36	18.66	6	18.66	2.835	–17.5285	–15.1722	–13.5709	–3.6872
14	[25]	37	18	18	9	2.45	–11.7687	–9.3178	–7.4170	1.0920
15	[4]	37.84	15.24	7.62	7.62	3.06	–5.4555	–2.8892	–0.6866	0.6922
16	[4]	37.84	7.62	7.62	15.24	4.08	–4.8762	–2.2942	–0.0781	1.2756
17	[4]	37.84	8.77	8.77	3.51	5.34*, 5.19#	–7.2825	–4.7658	–2.6058	–1.5336
18	[4]	37.84	9.31	9.31	4.6	4.59*, 4.50#	–8.6026	–6.1217	–3.9925	–2.1823
19	[4]	37.84	8.6	2.58	8.6	5.34	–5.0785	–2.5019	–0.2906	–0.2809
20	[4]	37.84	8.77	3.51	8.77	4.79*, 4.76#	–5.3209	–2.7509	–0.5452	–0.3671
21	[4]	37.84	9.31	4.6	9.31	4.11*, 4.25#	–4.3278	–1.7308	0.4980	0.8213
22	[26]	37.84	9.31	4.6	9.31	4.38	–8.6964	–6.2180	–4.0910	–3.7825
23	[26]	37.84	8.97	8.97	8.97	3.78	–6.8108	–4.2813	–2.1103	–0.6477
24	[26]	37.84	9.31	9.31	4.6	4.47	–7.0691	–4.5465	–2.3816	–0.5411
25	[26]	37.84	8.96	7.61	12.69	3.76	–7.1927	–4.6735	–2.5115	–1.5021
26	[27]	38	19	19	9.5	2.147	–5.8771	–3.3332	–1.1094	0.7594
27	[28]	38	19	19	9.5	2.206	–8.3944	–5.9186	–3.7542	–1.9354
28	[13]	71	9.8	5.3	19.08	3.22	–20.5353	–19.4001	–13.0146	–0.5859
29	[29]	79	28.2	28.2	4.9	2.09	–9.6562	–8.4980	–0.1424	4.4253
30	[4]	79.46	12.7	2.54	2.54	5.43	–9.3932	–8.2384	0.2039	–2.8381
31	[4]	79.46	12.7	6.35	6.35	2.64	–9.1053	–7.9468	0.5223	1.1604
32	[4]	79.46	7.7	7.7	7.7	3.17	–10.6037	–9.4643	–1.1349	–1.4638
33	[30]	90	10	10	5	2.73	–8.5652	–7.5378	2.4042	–0.1515
34	[30]	90	15	15	5	2.13	–3.4745	–2.3900	8.1056	0.3956
35	[31]	100	10	10	2	4.57	–7.7502	–6.8184	4.5467	–0.3122
36	[31]	100	10	10	1	7.97	–2.6517	–1.6684	10.3248	0.6057
37	[31]	100	12.7	12.7	1	7.72	–0.7406	0.2620	12.4907	1.7859
38	[31]	100	5	10	1	8.85	–7.5390	–6.6050	4.7861	–1.2451
39	[31]	100	10	5	1	8.5	–5.7099	–4.7574	6.8590	–1.1264
Mean Square Error (MSE)							0.1432	0.1929	0.1320	0.0248
Root Mean Square Error (RMSE)							0.3784	0.4392	0.3633	0.1576

* and # denote microstrip slot and probe coupling fed mechanism respectively

and effect of finite ground plane there is observable difference between theoretical resonance frequency and experimental resonance frequency as reported by all earlier workers. Our proposed model, EWGM however, gives much better results while comparing with [11, 13].

To justify the superiority of our proposed correction factors, in Table 1 and Table 2 thirty nine examples are reported. The Root Mean Square Errors (RMSE) for CDWM, MDWM and EDWM are 0.3784, 0.4392 and 0.3633 respectively which are very high compared to our proposed model, EWGM (0.1576) as shown in Table 2.

4. CONCLUSIONS

Resonant frequency depends not only the dimensions of DRA and relative permittivity of DRA but also on the coupling mechanism, size of ground plane and relative permittivity of glue to fix the DRA on ground plane. Confinement of electromagnetic energy is related to the amount of E-field inside the DRA which in turn depends on the coupling mechanism. For the case of probe feed, we have to consider the dimensions and position of probe. Similarly for CoPlanar Waveguide (CPW) coupling dimensions of slot play a vital role. Our proposed EWGM model deals with effective distance between the centre of RDRA and E-field lines which makes it independent of feed mechanism. Correction factors developed for EWGM give very good agreement between measured and predicted resonance frequencies with a RMSE of 0.1576 (or MSE of 0.0248) which is much better than the RMSE (or MSE) obtained using CWGM, MWGM and EDWM as shown in Table 2.

Hence it is concluded that EWGM gives much better result for a wide range of values of aspect ratio ($0.5 \leq d/h \leq 12.7$; $0.2778 \leq w/h \leq 12.7$) and/or relative permittivity of DRA (within the range of $\varepsilon_r = 9.8 - 100$) and indicates its superiority over CWGM, MWGM and EDWM methods already presented in literature as the most general and accurate model reported so far.

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