RECTANGULAR DIELECTRIC RESONATOR ANTENNAS: THEORETICAL MODELLING AND EXPERIMENTS

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ABSTRACT

A rectangular dielectric resonator antenna (RDRA) is investigated theoretically and experimentally. The Conventional Dielectric Waveguide Model (CDWM) and the Finite Element Method (FEM) are employed to calculate the radiation characteristics of the antenna. The results are presented and compared with those obtained experimentally. It is concluded that the CDWM can be used for a first order estimation of antenna parameters, but more accurate results can be obtained using the FEM for radiation patterns.

INTRODUCTION

Dielectric Resonators (DRs) have been widely used in shielded microwave circuits such as cavity resonator, filters and oscillators. In recent years, application of these components as antennas in microwave and millimetre band has been extensively studied [1-5], as they provide efficient radiation due to extremely low loss in dielectric material. Moreover, small size, large bandwidth and simple coupling structures are the other advantages of the DRA. It has been reported that DRs in cylindrical [1], hemispherical [6], rectangular [7] and other geometries [8-10] located on top of a ground plane could operate as antennas by a proper excitation of the resonator. Compared with other geometries, rectangular resonators are more attractive for their fabrication advantages, and the existence of two independent aspect ratios for a better design flexibility to meet impedance and radiation requirements. More significantly, in RDRAs, mode degeneracy [4] can be avoided by properly choosing the dimensions and hence lower cross polarisation can be obtained.

In this paper a probe-fed rectangular dielectric resonator antenna (RDRA), supported by a ground plane, is studied theoretically and experimentally. Two different modelling techniques, namely the Conventional Dielectric Wave-guide Model (CDWM) and the Finite Element Method (FEM), are utilised to predict the radiation parameters of the antenna including the resonance frequency, radiation patterns, directivity, Q-factor and impedance bandwidth. The theoretical results are verified experimentally revealing the merit of each modelling technique.

THE CONVENTIONAL DIELECTRIC WAVEGUIDE MODEL (CDWM)

Figure 1 shows the RDRA structure under consideration. It has a relative dielectric constant ε_r and dimensions a, b and h along x-, y- and z-direction respectively. The resonator is placed on the top of a circular ground plane with a diameter d. A vertically oriented coaxial probe of height h located at x=a/2 and φ=0° is used to excite the dominant mode TE^y_{111} [6]. For theoretical modelling using the CDWM, the ground plane is considered to be infinitely large as an approximation. Image theory is then applied. The ground plane is removed and replaced by the image of the resonator. The equivalent isolated resonator has twice the height of the original resonator and it is fed by a dipole of twice the length of the probe.

Using the CDWM theory, the isolated resonator is assumed to be the truncation of an infinite rectangular dielectric wave-guide. The fields of the dominant mode inside the resonator are obtained by solving Maxwell's equations with the magnetic wall model (MWM) boundary conditions at x= ±a/2 and z= ±h and continuous tangential fields at y= ±b/2. They are given as:

$$E_x = -(A/\varepsilon_d)k_z \cos(k_x x)\cos(k_y y)\sin(k_z z)$$
$$E_y = 0$$
$$E_z = (A/\varepsilon_d)k_x \sin(k_x x)\cos(k_y y)\cos(k_z z)$$
$$H_x = (A/j\omega\mu_0\varepsilon_d)(k_x k_y)\sin(k_x x)\sin(k_y y)\cos(k_z z)$$
$$H_y = (A/j\omega\mu_0\varepsilon_d)(k_x^2 + k_z^2)\cos(k_x x)\cos(k_y y)\cos(k_z z)$$
$$H_z = (A/j\omega\mu_0\varepsilon_d)(k_y k_z)\cos(k_x x)\sin(k_y y)\sin(k_z z)$$

where $\varepsilon_d=\varepsilon_0\cdot\varepsilon_r$. The characteristic equations for the resonant mode are:

$$k_x=(\pi/a),\quad k_y\tan(k_y b/2)=\sqrt{k_x^2+k_z^2-k_0^2},$$
$$k_z=(\pi/2h)$$

The resonance frequency is the solution of the separation equation given by:

$$k_x^2+k_y^2+k_z^2=\varepsilon_r k_0^2$$

where k_0 is the free space wave number. The radiated fields are considered to be due to the equivalent magnetic currents on the DR surfaces. In far field region, it can be obtained that:

$$E_\theta=-jk_0\frac{e^{-jkr}}{4\pi r}L_\phi,\ E_\phi=jk_0\frac{e^{-jk_0r}}{4\pi r}L_\theta$$

where

$$L_\phi=\left(\frac{2A\pi^2}{\varepsilon_d ah}\right)\cdot\cos\phi\cos(k_0\frac{a}{2}\sin\theta\cos\phi)\cos(k_0h\cos\theta)$$
$$\times\left\{\frac{D_1}{D_2}+\frac{2D_1}{D_3}\right\}+\left(\frac{2Ak_0k_x\pi}{\varepsilon_d h}\right)\cdot\cos(\delta\pi/2)\cdot\sin(\theta)\sin(\phi)$$
$$\times\sin(k_0\frac{b}{2}\sin\theta\sin\phi)\cdot\cos(k_0h\cos\theta)\cdot\cos(k_0\frac{a}{2}\sin\theta\cos\phi)\cdot\frac{1}{D_2\cdot D_3}$$

and

$$L_\theta=\left(\frac{2A\pi^2}{\varepsilon_d ah}\right)\cos\theta\sin\phi\cos(k_0\frac{a}{2}\sin\theta\cos\phi)\cdot\cos(k_0h\cos\theta)\frac{D_1}{D_2}$$
$$+\left(\frac{2A\pi k_0k_x}{\varepsilon_d h}\right)\cos(\delta\pi/2)\sin2\theta\cos^2\phi\cdot\sin(k_0\frac{b}{2}\sin\theta\sin\phi)$$
$$\times\cdot\cos(k_0h\cos\theta)\cos(k_0\frac{a}{2}\sin\theta\cos\phi)\frac{1}{D_2\cdot D_3}$$

with

$$D_1=\left(\frac{\sin(k_0\frac{b}{2}\sin\theta\sin\phi+\delta\pi/2)}{k_0\sin\theta\sin\phi+\delta\pi/b}+\frac{\sin(k_0\frac{b}{2}\sin\theta\sin\phi-\delta\pi/2)}{k_0\sin\theta\sin\phi-\delta\pi/b}\right)$$

$$D_2=(\pi/2h)^2-(k_0\cos\theta)^2$$

$$D_3=(\frac{\pi}{a})^2-(k_0\sin\theta\cos\phi)^2$$

The directivity of the antenna can be calculated using the equation given by:

$$D_{max}=\frac{(E_\theta^2(\theta,\phi)+E_\phi^2(\theta,\phi))_{max}}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}(E_\theta^2(\theta,\phi)+E_\phi^2(\theta,\phi))\sin\theta d\theta d\phi}$$

and the Q-factor of the RDRA is defined as $Q_0\approx Q_r=\omega W/P_r$ where W is the stored energy given by:

$$W=\frac{A^2}{32\varepsilon_d}abh(1+\frac{\sin(k_yb)}{k_yb})(k_x^2+k_z^2)$$

inside the DR and P_r is the total power radiated by the RDRA, which are given respectively by:

$$P_r=\frac{1}{4}\frac{1}{\eta_0}\int_0^{2\pi}\int_0^{2\pi}(|E_\theta|^2+|E_\phi|^2)r^2\sin\theta d\theta d\phi$$

For Q-factor measurement, the Q_0 of the RDRA can be obtained using the one port reflection coefficient measurement discussed in [11] and the bandwidth of the antenna for VSWR $\leq$ 2.5 is approximately related to the Q_0 factor by:

$$BW(\%)\approx(100/Q_0)$$

The Finite Element Model

The RDRA in Figure 1 is simulated using the HP85180A High Frequency Structure Simulator (HFSS) [12]. The HFSS is a software package based on the FEM. In general, in the HFSS, the geometric model is divided into a large number of elements, which are thetrahedra. The value of a vector field quantity such as E- or H-field inside each element is obtained by interpolation from the vertices of the tetrahedron. The antenna structure modelled is surrounded by an absorbing sphere with the second order radiation boundary condition given by [12]:

$$(\nabla\times\overline{E})_{\tan}=jk_0\overline{E}_{\tan}-(j/k_0)\nabla_{\tan}\times(\nabla_{\tan}\times\overline{E}_{\tan})$$
$$+(j/k_0)\nabla_{\tan}(\nabla_{\tan}\cdot\overline{E}_{\tan})$$

where $\overline{E}_{tan}$ is the tangential component of the E-field on the surface. The absorbing sphere is placed at least a quarter of wavelength away from the source of the signal. The HFSS then maps the *E*-field computed in (4) on the absorbing surface and calculates the far-field and radiation patterns using

$$\overline{E}(x,y,z)=\int_s \begin{bmatrix} (j\omega\mu_0 \overline{H}_{\tan})G+(\overline{E}_{\tan}\times\nabla G)+ \\ (\overline{E}_{normal}\times\nabla G) \end{bmatrix} ds$$

where $\overline{E}_{\tan}, \overline{H}_{\tan}$ are the tangential components of electric and magnetic fields respectively and $\overline{E}_{normal}$ is the normal component of the electric field on the radiation surface *s*, and *G* is the free space Green's Function.

Results and Discussion

For a specific RDRA with a=19mmn b=19mm, h=9.5mm and ε_r=38 supported by a ground plane with d=$\propto$ and d=10cm, the results of analysis and simulation are listed in Table 1, together with their corresponding measured values for d=10cm. The radiation patterns for d=$\propto$ and d=10cm are shown in Figures 2 and 3 respectively.

It can be seen that, for d=$\propto$ the predicted radiation patterns using the CDWM and HFSS agree very well. Also the predicted directivity agrees well with an error of 10%. The predicted resonance frequency using the CDWM is less than that of the FEM with only 1.5% difference. The simulated Q-factor, using the HFSS, differed from the CDWM ones by +12% and so, the BW predicted value is lower by the same factor.

In case of finite ground plane, it can be observed that there is only difference in simulated and measured E-Plane radiation patterns compared with the CDWM at small elevation angles, which is believed to be due to the effect of the finite size of the ground plane. As a results the HFSS produce more accurate radiation patterns. The simulated result for the directivity has not such good agreement compare to the experiment where the error can be high as +28.5%. It is said that this error is due to the non-convergence of the numerical method in the allowed run time of the simulation. However, the CDWM has more accurate result for the directivity. The predicted resonance frequency and Q-factor using the HFSS in this case have an error of -5% and +19% respectively in compare to measured ones. These errors are because of the existence of thin air gaps between the RDRA and ground plane and between the RDRA and the feed probes, which are not included in the simulation. The difference between measured and simulated cross-polarisation level is 12.5 dB.

Discussion and Conclusions

Two different modelling methods are used for the modelling of a rectangular DRA. Results indicate that the CDWM predicts a first order estimation of the RDRA radiation parameters and the HFSS can produce more accurate radiation patterns. However, the radiation patterns are affected by the finite size of the ground plane at small angles near to the ground plane. Also there is error in the simulated resonance frequency and Q-factor in compare to the measurement in case of finite ground plane. The effects of finite size of ground plane and air gaps in the antenna structures need to be taken into consideration in the theoretical modelling to produce more accurate prediction of radiation patterns, in which case the CDWM has its limitation.

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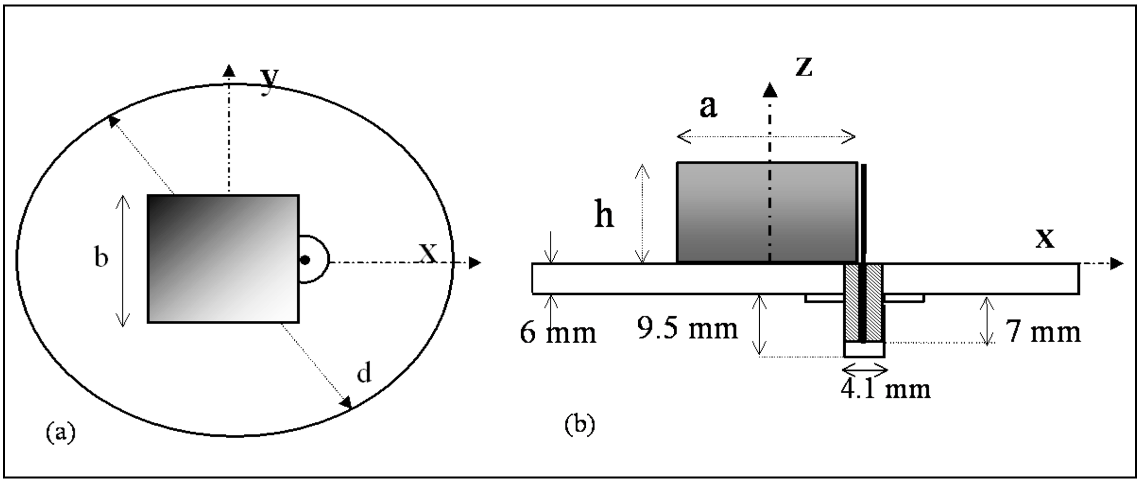

Figure 1: The structure of the RDRA under consideration: a) Top View b) Side view.

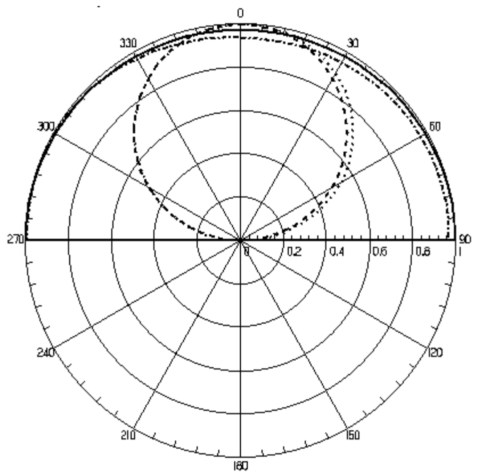

Figure 2: Theoretical co-polarised radiation patterns of the RDRA on an infinite ground plane.
(CDWM: ——— E_θ at $\phi=0°$ - - - - - E_ϕ at $\phi=90°$)
(FEM: - · - · - · - E_θ at $\phi=0°$ .... E_ϕ at $\phi=90°$)

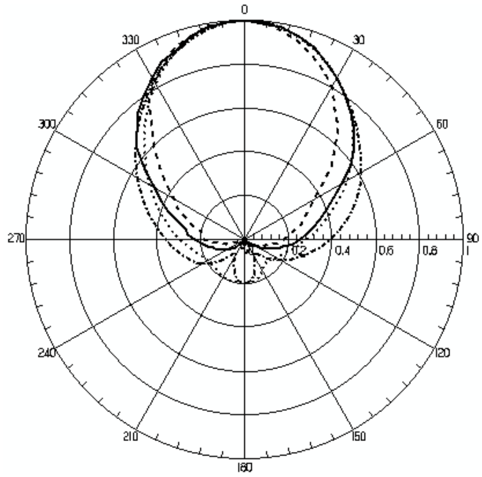

Figure 3: Theoretical and measured co-polarised radiation patterns for the RDRA on a finite ground plane d=10cm.
(Measured: ——— E_θ at $\phi=0°$ .... E_ϕ at $\phi=90°$)
(FEM: - · - · - · - E_θ at $\phi=0°$ - - - - - E_ϕ at $\phi=90°$)

Table 1. Radiation characteristics of the RDRA on a circular ground plane

Parameter	**CDWM d=∝**	**FEM**		**Measured d=10cm**
		d=∝	d=10cm	
Frequency (GHZ)	2.022	2.053	2.078	2.175
Q-Factor	33.088	37.185	36.793	30.906
Bandwidth (VSWR<2.5) (%)	2.850	2.551	2.578	3.075
Directivity or Gain	2.881	3.198	4.629	3.344
Cross-Polarisation level (dB) at θ=0°	_	_	33.959	21.425