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Theory and experiments on horizontally inhomogeneous Rectangular Dielectric Resonator Antenna

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ABSTRACT

A theoretical investigation on horizontally inhomogeneous Rectangular Dielectric Resonator Antenna (RDRA) is presented here using the mode matching technique. The inhomogeneous permittivity is introduced by placing two RDRA segments of different materials horizontally side by side. The fundamental TE^y_{111} mode is investigated here. Eigenfunction, eigenvalue, resonant frequency and far-field radiation patterns are presented. A closed form analytical expression is given here to predict the resonant frequency. Four antenna prototypes are fabricated and tested for experimental validation. It is found that our theoretical results are in good agreement with experimental data, published data as found in the open literature and data obtained using the 3D EM simulator. It is also found that Horizontally Inhomogeneous RDRA (HIRDRA) produces a peak in the broadside direction at fundamental TE^y_{111} mode. It is found that our theory gives results order faster (approx. 400–600 times) than commercially available 3D numerical EM simulator HFSS. The inhomogeneity introduces additional two degrees of freedom (width and permittivity of the additional dielectric segment) which give more flexibility to the antenna design, leading to wider tuning range over conventional RDRA. Advantages of this novel antenna structure are discussed in detail. This theory can easily be extended to investigate fractal shaped RDRAs, log-periodic antenna using RDRAs.

1. Introduction

Dielectric Resonator Antenna (DRA) has got various advantages like small size, low loss, inherent wideband nature and high radiation efficiency. Homogeneous hemispherical, cylindrical and rectangular shaped DRAs have been analyzed widely [1,2]. For a fixed relative permittivity of dielectric (ε_r), Rectangular DRA (RDRA) having dimensions $a \times b \times d$ shows greater flexibility in terms of resonant frequency selection over cylindrical and spherical DRAs due to its two aspect ratios (a/d and b/d).

To enhance the impedance matching and gain, two or more high permittivity dielectric segments have been inserted between the excitation (microstrip line coupling) and RDRA [3–5]. CAD model had been reported therein for efficient calculation of effective permittivity and effective height of vertically stacked RDRA (VSRDRA). This theory is valid when

- the thickness of inserted segment must be sufficiently small than the height of original RDRA
- the permittivity of inserted segment must be high than the ε_r of original RDRA

Such type of stacking configuration on Cylindrical DRA (CDRA) [6–9] and half-split CDRA [10] have also been investigated using 3D EM simulator HFSS [11] to increase the bandwidth. Multi-segment CDRAs with permittivity variation along the azimuth [12] and radial [13–14] direction has been investigated using HFSS in 2015 for dual or triple band application where each band is corresponding to one dielectric segment. No theoretical explanation has been given therein [6–10,12–14] to explain the working principle of multi-segment (inhomogeneous) CDRA.

In the case of Hemispherical DRA (HDRA), the evaluation of exact Green's functions of HDRA using mode-matching technique [15–16] has been extended in [17–19] to investigate multi-layered inhomogeneous HDRA where multiple layers have been introduced to enhance its mode selectivity. In [17–19], Method of Moment (MoM) based complex mode matching process have been used to investigate multi-layered HDRA for different excitation techniques including coaxial-probe [17–18], waveguide slot aperture [19] etc.

Literature survey shows that conventional RDRA (single layer) having inhomogeneous permittivity has also been investigated

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by Yaduvanshi et al. in 2016 [20] where the inhomogeneous permittivity of RDRA has been expressed as a function of space coordinates. Instead of applying imperfect wall at the dielectric interface (between RDRA and air media) to solve the boundary value problem of RDRA, Perfect Electric Conductors (PEC) and/or Perfect Magnetic Conductors (PMC) have been applied therein. Theoretical validation has not been provided therein. But the analysis will be helpful to solve the RDRA problem using perturbation techniques.

In this work, theoretical investigation on inhomogeneous RDRA is presented. Inhomogeneous permittivity is introduced by adding two RDRA segments horizontally (along the *y*-direction) as shown in Fig. 1. These two segments have an identical cross-section along the *x*-*z* direction ($a \times d$) but the different width (b_1, b_2) along the *y*-direction and have different relative permittivity (ε_{r1}, ε_{r2}). Simple boundary conditions are applied as available for conventional RDRA [21]. The fundamental TE^y_{111} mode is investigated using the mode matching technique. A closed form simple transcendental equation is given here for computing the wave-numbers along the *y*-direction inside the two parallel segments of RDRA. Theoretical resonant frequencies are verified with a 3D EM simulator for a wide range of dimensions and relative permittivity. This is shown in the Results section. Four Horizontally Inhomogeneous RDRA (HIRDRA) prototypes are fabricated for experimental validation. It is found that our theoretical results are in close agreement with measured data obtained by the authors, numerically calculated data as published in [22] and data obtained using the 3D EM simulator HFSS [11]. It is found that Horizontally Inhomogeneous RDRA (HIRDRA) gives broadside radiation patterns for TE^y_{111} mode and the patterns are almost symmetric. Theoretical far-field patterns are in good agreement with experimental data. Further, it is also found that our theory gives results order faster (approx. 400–600 times) than 3D EM simulator HFSS as shown in the Result section. Advantages of this novel RDRA structure are addressed in detail in the Discussions section.

2. Theory

Two RDRA segments, RDRA1 and RDRA2 having dimensions $a \times b_1 \times d$ and $a \times b_2 \times d$ and relative permittivity ε_{r1} and ε_{r2} respectively are stacked horizontally along the y-direction and placed over a common ground plane as shown in Fig. 1. The *x*-axis is placed along the interface between these two RDRAs and

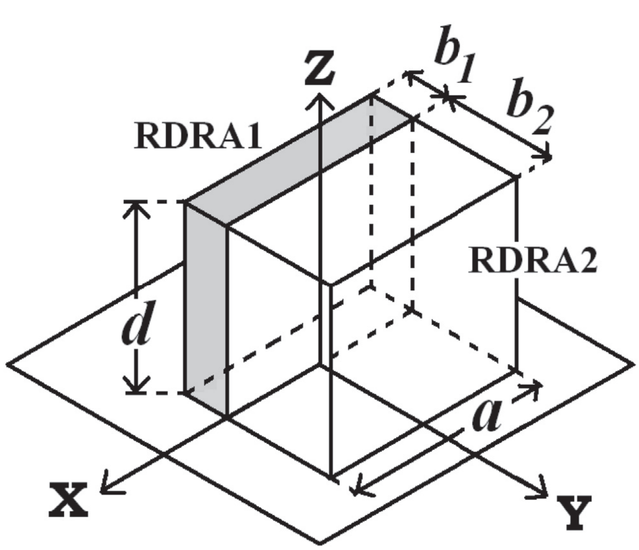

Fig. 1. Geometry of the antenna.

the origin is placed at the center of its length *a* for theoretical simplicity. For the theoretical investigation, the ground plane is removed first by applying the image theory and this process results in an isolated similar structure having dimensions $a \times b \times h$ where $h = 2d$ and $b = b_1 + b_2$. Perfect Magnetic Conductors (PMC) are considered at $x = \pm a/2$ and $z = \pm h/2$ and imperfect magnetic conductors are considered at $y = -b_1$ and $y = b_2$ [21].

The structure of isolated horizontally inhomogeneous RDRA has a dielectric discontinuity along the *y*-direction only. A suitable choice of wave variation along *x* and *z*-directions inside the two RDRA segments for pure TE^y_{111} mode can be expressed as:

$$f(x,z) = \cos(\pi x/a)\cos(\pi z/h) \tag{1}$$

Due to the existence of imperfect magnetic conductors, fields are exponentially decaying outside the resonator along the *y*-direction. Thus, following [23], the eigenfunction inside the two RDRA segments can be expressed as:

$$\psi = f(x,z) \times \begin{cases} A_3 e^{\gamma_y (y+b_1)}, & y \leqslant -b_1 \\ [A_1\cos(k_{y1}y) + B_1\sin(k_{y1}y)], & -b_1 \leqslant y \leqslant 0 \\ [A_2\cos(k_{y2}y) + B_2\sin(k_{y2}y)], & 0 \leqslant y \leqslant b_2 \\ A_4 e^{-\gamma_y (y-b_2)}, & y \geqslant b_2 \end{cases} \tag{2}$$

where

$$k_{x1}^2 + k_{y1}^2 + k_{z1}^2 = \varepsilon_{r1} k_0^2 \tag{3}$$

$$k_{x2}^2 + k_{y2}^2 + k_{z2}^2 = \varepsilon_{r2} k_0^2 \tag{4}$$

$$k_{x1}^2 - \gamma_y^2 + k_{z1}^2 = k_0^2 \tag{5.a}$$

$$k_{x2}^2 - \gamma_y^2 + k_{z2}^2 = k_0^2 \tag{5.b}$$

Here, k_0 is the free-space wave number,

$$k_{x1} = k_{x2} = k_x = \pi/a \tag{6}$$

$$k_{z1} = k_{z2} = k_z = \pi/h \tag{7}$$

and other terms are carrying usual meaning. Tangential components of both electric and magnetic fields are matched at $y = -b_1$, 0 and b_2, leading to:

$$k_{y2}(\gamma_y \tan(k_{y1}b_1) + k_{y1})(k_{y2}\tan(k_{y2}b_2) - \gamma_y) + k_{y1}(\gamma_y \tan(k_{y2}b_2) + k_{y2})(k_{y1}\tan(k_{y1}b_1) - \gamma_y) = 0 \tag{8}$$

It is worth mentioning that γ_y can be expressed from Eqs. (3)–(5) as:

$$\gamma_y^2 = (\varepsilon_{r1} - 1)k_0^2 - k_{y1}^2 \tag{9.a}$$

$$\gamma_y^2 = (\varepsilon_{r2} - 1)k_0^2 - k_{y2}^2 \tag{9.b}$$

After solving the transcendental Eq. (8), we can easily predict the resonant frequency of the structure for pure TE^y_{111} mode.

After determining the constants $A_1 - A_4$ and $B_1 - B_2$, the eigenfunction for the two RDRA segments can be expressed as:

$$\psi = D \times \cos(k_x x)\cos(k_z z) \times \begin{cases} A \times \sin(k_{y1}y + \alpha), & in\ \text{RDRA1} \\ B \times \sin(k_{y2}y + \beta), & in\ \text{RDRA2} \end{cases} \tag{10}$$

where

$$A = T_3\sqrt{(T_1)^2 + 1};\ B = \sqrt{(T_2)^2 + 1};\ \alpha = \tan^{-1}(T_1);\ \beta = \tan^{-1}(T_2) \tag{11}$$