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Investigation of Resonant Modes in Rectangular Dielectric Resonator Antennas

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دراسة الأوضاع الرنانة في هوائيات الرنان العازل المستطيلة

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Abstract:
This work presents a comprehensive investigation of the resonant behavior in Rectangular Dielectric Resonator Antennas (RDRAs) using the Dielectric Waveguide Model (DWM). Analytical modeling and MATLAB-based numerical simulations are combined with validation from CST and eigenmode solvers to thoroughly evaluate the influence of geometrical parameters and dielectric permittivity on mode excitation. The study also demonstrates the effectiveness of aperture-coupled feeding techniques in achieving selective mode excitation. These results provide a solid foundation for optimizing RDRA designs aimed at advanced wireless and electromagnetic applications.

Keywords: Dielectric Resonator Antennas, Waveguide Model, Wireless, Eigenmode Solvers.

الملخص
يقدم هذا العمل دراسة شاملة للسلوك الرنيني في هوائيات الرنان العازل المستطيلة (*RDRAs*) باستخدام نموذج الدليل الموجي العازل (*DWM*). يُدمج النمذجة التحليلية والمحاكاة العددية القائمة على *MATLAB* مع التحقق من صحة النتائج باستخدام *CST* ومحللات الوضع الذاتي لتقييم تأثير المعاملات الهندسية والسماحية العازلة على إثارة الوضع بدقة. كما توضح الدراسة فعالية تقنيات التغذية المقترنة بالفتحة في تحقيق إثارة الوضع الانتقائي. توفر هذه النتائج أساسًا متينًا لتحسين تصميمات *RDRA* المخصصة للتطبيقات اللاسلكية والكهرومغناطيسية المتقدمة.

الكلمات المفتاحية: هوائيات الرنان العازل، نموذج الموجه، لاسلكي، مُحلل الوضع الذاتي.

Introduction

The escalating demand for compact, high-performance antennas in modern wireless communication systems has catalyzed extensive research into alternative antenna technologies, among which Dielectric Resonator Antennas (DRAs) have garnered significant attention [1], [2]. In contrast to conventional metallic radiators, DRAs exhibit inherently low dielectric and radiation losses, enabling high efficiency across a broad range of frequencies. This characteristic makes them especially suitable for microwave and millimeter-wave applications, which are critical for the advancement of 5G, satellite communication, and emerging 6G technologies [3].

Among the various geometrical configurations of DRAs, the rectangular dielectric resonator antenna (RDRA) stands out due to its structural simplicity, ease of fabrication, and superior modal control. The rectangular geometry allows selective excitation of specific resonant modes, providing enhanced flexibility in tailoring radiation characteristics such as gain, beamwidth, and polarization. This controllability makes RDRAs particularly attractive for applications requiring directional radiation and frequency agility, including satellite links, radar systems, and next-generation wireless platforms [4], [5].

A comprehensive understanding of the resonant modes within RDRAs is crucial for both theoretical development and practical antenna design. These resonant modes are defined by distinct electromagnetic field distributions that determine the antenna's operating frequencies and radiation performance. The modal behavior is strongly influenced by key physical parameters, most notably, the dielectric constant and the resonator's dimensions. Accurate characterization and control of these parameters enable designers to fine-tune the antenna's frequency response, improve impedance matching, and suppress spurious radiation and unwanted modes [6].

In this context, the present study investigates the modal characteristics of rectangular DRAs using the Dielectric Waveguide Model (DWM) as the primary analytical framework. By integrating theoretical derivations with numerical solutions and validating them through full-wave electromagnetic simulations, this work establishes a detailed correlation between structural design, dielectric properties, and mode excitation. The results offer valuable insights into the design of efficient and high-performance RDRAs tailored to the stringent requirements of modern communication systems.

Dielectric Waveguide Mode

The Dielectric Waveguide Model (DWM) serves as a foundational analytical framework for characterizing electromagnetic wave propagation within dielectric-loaded structures such as dielectric resonator antennas (DRAs). In this model, the rectangular dielectric resonator antenna (RDRA) is approximated as a dielectric waveguide, where the confinement and distribution of electromagnetic modes are primarily governed by the geometry of the resonator and the contrast in dielectric constant between the resonator material and the surrounding medium [7]. This contrast leads to total internal reflection, which facilitates strong field confinement within the resonator.

Electromagnetic modes supported by the waveguide are typically classified into Transverse Electric (TE) and Transverse Magnetic (TM) categories, based on the orientation of their electric and magnetic field components relative to the direction of wave propagation. In TE modes, the electric field is entirely transverse to the propagation direction, with no longitudinal electric component present. Conversely, TM modes exhibit purely transverse magnetic fields while permitting a longitudinal component of the electric field. The behavior and distribution of these modes are determined by solving Maxwell's equations subject to the boundary conditions imposed by the waveguide's geometry and material interfaces [8, 9]. This modal analysis provides essential insight into the resonant characteristics of the RDRA, enabling accurate prediction of mode frequencies, field distributions, and polarization properties. Such understanding is critical in the design and optimization of high-performance dielectric antennas for various wireless and millimeter-wave applications

Supported Modes of a RDRA

In the case of a rectangular Dielectric Resonator Antenna (DRA) mounted on a ground plane, Transverse Magnetic (TM) modes are typically not supported. This limitation arises from the electromagnetic boundary conditions at the interface between the dielectric resonator and the conductive ground plane, specifically at $z = 0$. TM modes inherently require a non-zero electric field component normal to the ground plane, with a maximum occurring at the boundary [10]. However, the presence of the perfect electric conductor enforces a zero tangential electric field at this interface, making the excitation of TM modes physically unfeasible under standard conditions. As a result, Transverse Electric (TE) modes become the dominant resonant modes in such configurations. These TE modes are characterized by having no electric field component in the direction of propagation, and they satisfy the boundary conditions imposed by the ground plane.

The resonance frequencies of these modes are highly dependent on both the physical dimensions (length, width, and height) of the dielectric block and its relative permittivity (εr). Variations in either the size or the dielectric constant directly affect the effective wavelength within the resonator, thereby determining the specific frequencies at which resonance occurs. This relationship highlights the importance of precise geometric and material design in achieving desired resonant characteristics in practical DRA implementations.

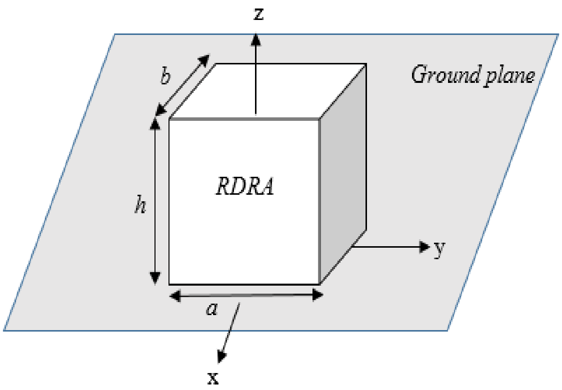


Figure 1. The rectangular DRA placed on the ground plane [11].

Figure 1 depicts a rectangular RDRA on a ground plane. Using DWM, resonance frequencies of the TE_{mnp} TE modes can be analytically estimated, considering the speed of light and the resonator's dimensions a, b, and h [12, 13].

$$k_x = \frac{m\pi}{a} \quad (1)$$

$$k_y = \frac{n\pi}{b} \quad (2)$$

$$k_z \tan\left(\frac{k_z h}{2}\right) = \sqrt{\left((\varepsilon_r - 1)k_0^2 - k_x^2\right)} \quad (3)$$

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \quad (4)$$

$$k_0 = \frac{2\pi}{\lambda_0} = \frac{2\pi f_0}{c} \quad (5)$$

Where c is the speed of the light and λ0 is the wavelength in free space. Hence the resonance frequency modes can be calculated as:

$$f_0 = \frac{c}{2\pi\varepsilon_r}\sqrt{\left(k_x^2 + k_y^2 + k_z^2\right)} \quad (6)$$

The associated magnetic field distributions provide deeper insight into modal behavior as a function of geometry a, b and h as:

$$H_z = \frac{(k_z k_x)}{(jw\mu_0)}\sin(k_x x)\cos(k_y y)\sin(k_z z) \quad (7)$$

$$H_y = \frac{(k_y k_x)}{(jw\mu_0)}\sin(k_x x)\sin(k_y y)\cos(k_z z) \quad (8)$$

$$H_x = \frac{(k_y^2 + k_z^2)}{(jw\mu_0)}\cos(k_x x)\cos(k_y y)\cos(k_z z) \quad (9)$$

$$E_x = 0 \quad (10)$$

$$E_y = k_z\cos(k_x x)\cos(k_y y)\sin(k_z z) \quad (11)$$

$$E_z = -k_y\cos(k_x x)\sin(k_y y)\sin(k_z z) \quad (12)$$

Results and Discussion

The influence of the physical dimensions and dielectric constant εr of the Rectangular Dielectric Resonator Antenna (RDRA) on its resonant frequencies was thoroughly analyzed using a numerical approach based on the solution of the resonance equations (Equation 6) implemented in MATLAB. This analytical model accounts for the geometry and material properties of the resonator to estimate the frequencies at which specific modes are excited. To validate the accuracy of the numerical results, a comparative study was conducted against data obtained from full-wave electromagnetic simulations performed in CST Studio Suite, as well as from the CST eigenmode solver.

The resonance frequencies predicted by the MATLAB model exhibited a strong correlation with those derived from both simulation tools, confirming the reliability of the analytical method. However, slight deviations were observed between the numerical and simulated results. These discrepancies are primarily attributed to the inclusion of the feed network in the simulation models, which alters the electromagnetic field distribution and slightly shifts the resonant frequencies. In contrast, the analytical model assumes an idealized structure without any feeding mechanism, leading to a purer theoretical prediction. Despite these minor differences, the overall agreement across the methods validates the effectiveness of the numerical model in predicting the modal behavior of RDRAs.

Table 1. Dielectric constant and rectangular DRA dimensions' effects on modes.

Parameter	4 × 4 × 5 mm³	5 × 5 × 6 mm³	8 × 5 × 4 mm³
Dielectric constant (εr)	10	12	15
f_0 (GHz) MATLAB	26.6	26.8	34.3
f_0 (GHz) Simulated	27	27	35
f_0 (GHz) Eigenmode Solver	26.63	26.68	34.23
Resonance Mode	TE115	TE117	TE155

The table 1 summarizes the impact of varying dielectric resonator sizes and dielectric constants (εr) on the fundamental resonance frequency *(f_0)* and excited TE modes, based on MATLAB calculations, full-wave simulations, and eigenmode solver results. Three RDRA configurations were analyzed: 4 × 4 × 5 mm³ with ε_r = 10, 5 × 5 × 6 mm³ with ε_r = 12, and 8 × 5 × 4 mm³ with ε_r = 15. The corresponding TE resonance modes were identified as TE_{115}, TE_{117}, and TE_{155}, respectively. The calculated resonance frequencies using MATLAB were 26.6, 26.8, and 34.3 GHz, which closely match the simulated results (27, 27, and 35 GHz) and eigenmode solver outcomes (26.63, 26.68, and 34.23 GHz), confirming the accuracy of the analytical estimations. These results highlight the influence of both geometry and dielectric constant on mode excitation and resonant behavior, where higher εr and shorter height lead to excitation of higher-order TE modes and increased resonance frequency.

As demonstrated in Table 2, excitation of higher-order modes requires larger resonator volumes. For example, the TE_{119} mode requires roughly 7.3 times the volume needed for TE_{113} and 1.8 times that for TE_{117}, assuming a fixed permittivity of 9.9. This volume-dependency informs mode selection strategies in antenna design. while the resonant frequencies remain relatively stable around the 23 GHz band (23.4, 23.3, and 23.6 GHz). This indicates that despite significant increases in resonator volume, the operating frequency is primarily governed by the mode configuration and dielectric loading rather than size alone. The results demonstrate that higher-order modes can be achieved with larger structures while maintaining operation within the desired frequency band, making it possible to tailor DRA performance through geometric and modal control.

Table 2. Rectangular DRAs of various dimensions functioning in the resonance modes of TE_{113}, TE_{117}, and TE_{119}

Parameter	3.5 × 3.5 × 4 mm³	5 × 5 × 8 mm³	6 × 6 × 10 mm³
TE Resonance Mode	TE_{113}	TE_{117}	TE_{119}
Resonance Frequency (GHz)	23.4	23.3	23.6
Volume (mm³)	49	200	360

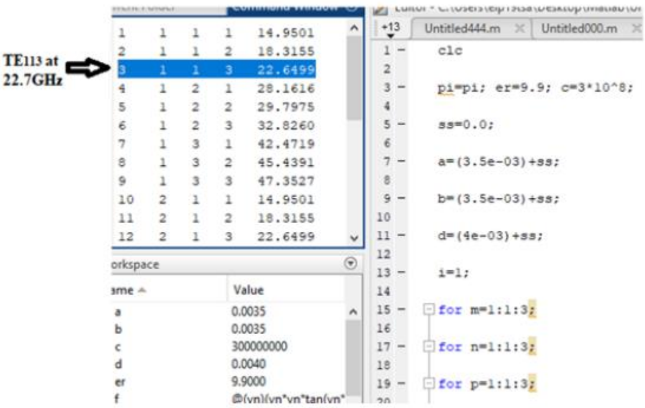
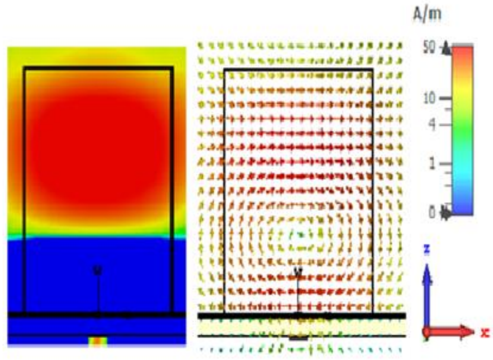
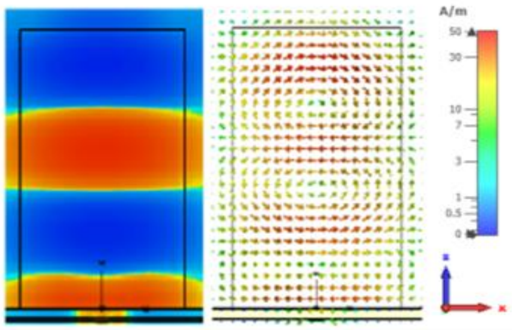


Figure 2. MATLAB script for calculating the TE_{113} mode at 22.7 GHz.

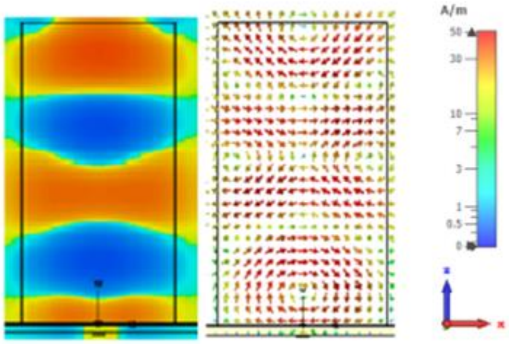
As illustrated in Figure 2, the MATLAB code serves as a practical example demonstrating how the resonant frequency of an excited mode in a Dielectric Resonator Antenna (DRA) can be analytically estimated. This estimation is based on key physical parameters of the DRA, specifically its geometrical dimensions and the relative permittivity *(εr)* of the dielectric material. By incorporating these inputs into the analytical expressions, the MATLAB script provides a straightforward and efficient method for predicting the resonance behavior of the antenna



(a)



(b)



(c)

Figure 3. Magnetic field distribution of the TE_{113} mode at 23.4 GHz, (c) Magnetic field distribution of the TE_{117} mode at 23.3 GHz, and (d) Magnetic field distribution of the TE_{119} mode at 23.6 GHz.

Furthermore, Figures 3(a) through 2(c) depict the magnetic and electric field distributions corresponding to the TE_{113}, TE_{117}, and TE_{119} modes, respectively. These field profiles offer valuable insight into the modal characteristics and energy confinement within the dielectric structure. When comparing the resonant frequencies obtained from the MATLAB calculations with those derived from full-wave electromagnetic simulations, a slight mismatch is observed. As discussed earlier, these discrepancies are primarily attributed to the fact that the simulation models incorporate additional components most notably, the feed network which are not accounted for in the simplified analytical model. The presence of the feed structure in the simulation influences the electromagnetic environment, thereby causing a shift in the resonant frequency. This highlights the importance of considering such practical elements during the design and analysis phases to ensure accurate prediction and performance assessment of DRAs.

Figure 4 presents the simulated reflection coefficient $|S_{11}|$ curves corresponding to the excitation of different resonant modes using a consistent aperture-coupled feeding configuration. The feeding structure consists of a rectangular slot etched in the ground plane, positioned directly above a microstrip transmission line. This arrangement facilitates efficient electromagnetic coupling into the dielectric resonator, enabling the selective excitation of the desired modes. The results demonstrate that the aperture-coupled feed effectively excites the TE_{113}, TE_{117}, and TE_{119} modes, each showing distinct resonant dips in the $|S_{11}|$ response. The observed impedance bandwidths, defined at the -10 dB return loss threshold, were approximately 5.7% for TE_{113}, 2.9% for TE_{117}, and 2.6% for TE_{119}. These variations in bandwidth reflect the modal field distributions and coupling efficiency of each mode. The results confirm the suitability of the aperture-coupled slot technique for mode-selective excitation and provide valuable insights for bandwidth optimization in dielectric resonator antenna (DRA) designs.

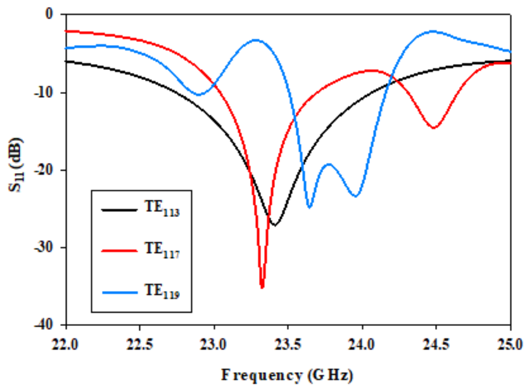


Figure 4. $|S_{11}|$ of rectangular DRAs excited in the TE_{113}, TE_{117} and TE_{119} resonance modes.

Additional simulations, as illustrated in Figure 5, were conducted to investigate the impact of varying the dielectric constant ε_r on the resonant behavior of a rectangular dielectric resonator antenna (RDRA) with fixed dimensions of 3.5 × 3.5 × 4 mm^3. The results clearly indicate that increasing the dielectric constant leads to a downward shift in the resonance frequencies. This behavior is consistent with theoretical expectations, as the resonant frequency is inversely proportional to the square root of the dielectric constant. Consequently, higher ε_r values increase the effective electrical size of the resonator, thereby lowering its natural resonant frequencies. These findings further validate the sensitivity of DRA performance to material properties and align well with previous studies [14].

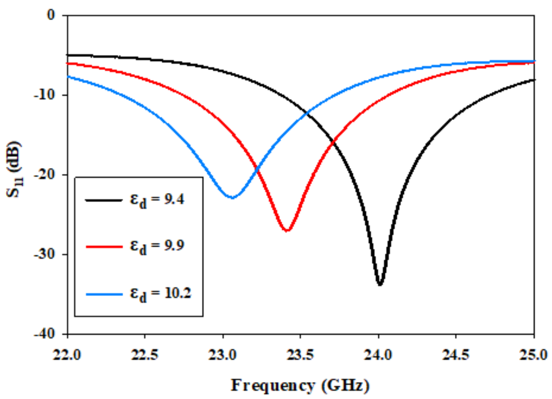


Figure 5. The variation of the return losses as a function of the dielectric constant.

The aperture-coupled feeding approach, with a slot typically around half the wavelength (λ/2) and a length-optimized stub on the microstrip line, enhances impedance matching and enables selective excitation of desired modes. This feed design controls current distribution and coupling, suppressing undesired modes and improving overall antenna efficiency [15,16].

Conclusion

This study has demonstrated the effectiveness and accuracy of the Dielectric Waveguide Model (DWM) in predicting the resonant frequencies and electromagnetic mode characteristics of rectangular dielectric resonator antennas (RDRAs). Supported by thorough numerical analysis and validated through both MATLAB computations and full-wave CST simulations, the findings confirm that the resonator's geometric parameters and dielectric constant are pivotal in determining modal behavior and resonance performance. Even slight variations in these parameters were shown to significantly influence the excitation and distribution of electromagnetic modes. Additionally, the use of aperture-coupled feeding has been validated as an efficient approach for selectively exciting targeted modes while minimizing unwanted coupling and mutual interference.

This technique enhances impedance matching and contributes to improved overall radiation efficiency, making it especially suitable for TE mode excitation in RDRA configurations mounted on ground planes. Overall, the results of this investigation establish a robust framework for the optimized design of RDRAs that meet the rigorous demands of contemporary wireless communication systems, particularly in high-frequency bands such as millimeter-wave and emerging 5G networks. For future work, attention could be directed toward the advancement of feed network architectures, the exploration of tunable and high-performance dielectric materials, and the integration of cutting-edge fabrication technologies. These developments are expected to further elevate the performance, adaptability, and application reach of dielectric resonator antennas in next-generation wireless and sensing platforms.

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