Design and Analysis of Cylindrical Dielectric Resonator Antenna (CDRA) for Biomedical Sensing Application

Rahul Krishnan[1]*, Inam Ullah Khan*[2]*, Sai Kiran Oruganti*[3]
[1] [2] Lincoln University College, Malaysia; [3] Multimedia University, Cyberjaya, Malaysia
pdf.rahul@lincoln.edu.my

Abstract: This study delineates the design and performance evaluation of a Cylindrical Dielectric Resonator Antenna (CDRA) appropriate for biomedical and wireless applications. The proposed CDRA is constructed using an FR-4 substrate (ε_r=4.3 and tan δ=0.02) with a copper ground plane and microstrip feed, and employs an Al_2O_3 cylindrical resonator (ε_r=9.8 and tan δ = 0.0001) to ensure high radiation efficiency. Simulated results reveal that the antenna resonates at 4.17 GHz with a return loss of −40 dB and a minimum VSWR of 1.02, indicating excellent impedance matching. The radiation and total efficiencies exceed 85% and 80%, respectively, at resonance. Furthermore, the antenna achieves a peak gain of 7 dBi and maintains stable directivity across the band. These results demonstrate that the proposed CDRA design is compact, efficient, and well-suited for modern communication systems such as biomedical, WLAN, 5G, and C-band applications. The structure offers a cost-effective and high-performance solution for embedded antenna systems.

Keywords: Microwave; Dielectric Resonator Antenna; Biomedical; Cylindrical; Bandwidth

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Introduction

Dielectric Resonator Antennas (DRAs) have garnered significant interest in contemporary wireless communication technologies owing to their beneficial characteristics, such as elevated radiation efficiency, compact dimensions, low profile, and wide bandwidth. These characteristics make DRAs a compelling choice for applications that demand high-frequency performance and compact antenna solutions. The development of DRAs began in the 1980s with the work of Professor S.A. Long and colleagues, who demonstrated that dielectric resonators could operate effectively as radiators with minimal metallic loss and high efficiency [1]. Over the years, DRAs have evolved to support a variety of resonant modes, enabling their use in advanced communication systems such as MIMO (Multiple Input, Multiple Output) and phased array systems [2].

One of the primary advantages of DRAs is their low conductor loss, which allows for high radiation efficiency, particularly at frequencies above 1 GHz [3]. Traditional antennas, such as microstrip patch antennas, suffer from significant conductor losses at these high frequencies, limiting their effectiveness. In contrast, DRAs, which operate based on dielectric materials with low conductivity, exhibit negligible metallic losses, making them ideal for millimeter-wave applications used in satellite communication, radar, and next-generation wireless networks [4].

The shape, size, and material properties of a dielectric resonator largely ascertain the resonance frequency of a DRA. The ability to modify the geometry and material permittivity of DRAs provides significant design flexibility. Various shapes, such as hemispherical, cylindrical, and rectangular DRAs, have been studied for their unique advantages in different applications. For example, hemispherical DRAs offer large impedance bandwidths, while cylindrical and rectangular DRAs are favored for their ease of fabrication and the ability to excite multiple modes [5].

One of the key advantages of DRAs is their suitability for high-frequency applications. Due to the absence of conductive materials in DRAs, they perform well in the millimeter-wave frequency range, where conventional antennas struggle with increased losses. DRAs operate with high radiation efficiency, making them ideal for applications in high-speed communication, such as 5G and potentially 6G systems. As these technologies demand higher data rates and faster communication, the use of DRAs is expected to expand, particularly in systems that require compact and efficient antenna solutions [6].

In addition to their superior performance at high frequencies, DRAs are also gaining traction in applications that require compact antenna systems, such as MIMO and phased array systems. MIMO systems, which rely on multiple antennas for increased channel capacity, can benefit from the low mutual coupling and high isolation offered by DRAs. This characteristic is critical for maintaining the efficiency of MIMO systems without compromising the size or performance of individual antenna elements. Moreover, DRAs can be effectively used in phased arrays, where beam steering and high gain are required [7].

Feeding techniques for DRAs play a crucial role in their performance. The most common feeding methods include coaxial probes, microstrip feeds, and aperture coupling. Coaxial probe feeding is a widely used technique due to its simplicity and high coupling efficiency, which ensures efficient power transfer to the DRA. Microstrip feeding, on the other hand, is advantageous for integrating DRAs with microwave integrated circuits (MICs), providing a compact solution for real-world applications. Additionally, aperture-coupling techniques, which use slots or cross-slots to feed the DRA, are beneficial for generating circular polarization and enhancing the radiation pattern [8].

Despite their many advantages, DRAs face several challenges. The fabrication process for DRAs can be time-consuming and expensive, particularly when high precision is required to manufacture the dielectric resonator. The cost of materials and the complexity of modifying resonator shapes for specific applications are other barriers to widespread adoption [9]. Furthermore, the numerical methods used to analyze DRA performance, particularly for rectangular DRAs, are still developing. Advanced mathematical modeling techniques are necessary to fully optimize the design of DRAs for various applications [10],[11],[12].

In conclusion, Dielectric Resonator Antennas (DRAs) represent a significant advancement in antenna technology. They offer numerous advantages over traditional antenna types, such as microstrip patch antennas, particularly in high-frequency applications. The ability to achieve low conductor losses, wide bandwidths, and high radiation efficiency makes DRAs an attractive solution for next-generation wireless technologies. As research progresses in the areas of feeding techniques, mode control, and numerical modeling, DRAs are anticipated to be pivotal in the advancement of compact, high-performance antenna systems for 5G, 6G, and beyond [13],[14],[15],[16],[17].

Antenna Design - Cylindrical DRA

The design of a CDRA is predicated on the resonant frequency of the structure, which is contingent upon the cylinder's dimensions, the material's dielectric constant, and the operational mode. The following is a general approach for calculating the resonant frequency of a CDRA:

The resonant frequency for a CDRA can be approximated by the following equation, which takes into account the dielectric constant (ε_r) of the material, the radius of the cylinder (r), and the height of the cylinder (h):

$$f_{TE}(n,p,m) = \frac{c}{2\pi}\sqrt{\frac{\varepsilon_r}{\mu_r}}\sqrt{\left(\frac{X_{np}}{r}\right)^2 + \left(\frac{2m+1}{h}\right)^2}$$

Where:

- $f_{TE}(n,p,m)$ is the resonant frequency of the cylindrical dielectric resonator antenna for the TE mode.
- c is the speed of light in free space (approximately 3×10^8 m/s).
- ε_r is the relative permittivity (dielectric constant) of the dielectric material.
- μ_r is the relative permeability of the dielectric material (usually $\mu_r \approx 1$ for non-magnetic materials).
- X_{np} is the root of the Bessel function of the first kind (for TE modes), corresponding to the specific mode and radial order.
- r is the radius of the cylindrical dielectric resonator.
- m is the axial mode number.
- h is the height of the cylindrical dielectric resonator.

The modes of operation in a CDRA include TE (Transverse Electric), TM (Transverse Magnetic), and hybrid modes. For TE modes, the resonant frequency depends on the radial roots of the Bessel function (X_{np}), which vary depending on the mode (n) and the number of radial lobes (p). The fundamental mode is the one with the lowest resonant frequency, and higher-order modes are excited based on the geometry of the DRA and the feeding mechanism.

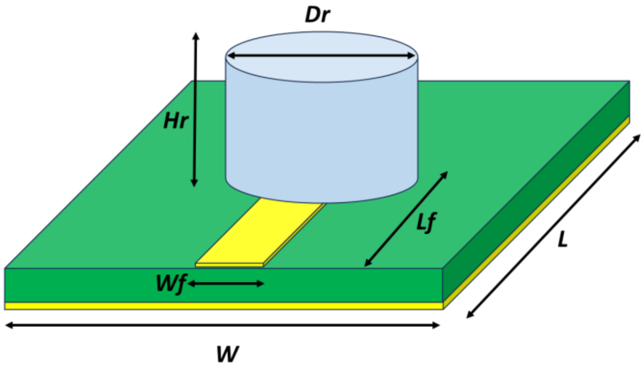

Figure 1. Perspective view of Cylindrical DRA

The proposed CDRA design utilizes an FR-4 substrate with the following specifications: (ε_r=4.3, tan δ=0.02) and a substrate thickness of 1.6 mm as shown in Figure 1. The dimensions of the substrate are 60 mm by 60 mm. A copper ground plane, measuring 60x60 mm and 0.035 mm thick, is placed at the bottom of the substrate. The feed, also with a thickness of 0.035 mm, has an overall length of 40 mm and a width of 4.65 mm as depicted in Table 1. The resonator itself is made from Al_2O_3 (aluminum oxide) with a relative permittivity of ε_r=9.8 and a very low dielectric loss tangent of tan δ=0.0001.

Table 1. Dimensions of proposed CDRA

Sl.no	Parameters	Dimensions (mm)
1	*W*	60
2	*L*	60
3	*Hr*	10
4	*Dr*	20
5	*Lf*	40
6	*Wf*	4.65

Results and Discussion

The proposed CDRA was simulated with CST Microwave Studio. Upon confirming the accuracy of the parameters, the values for resonant frequency, gain, directivity, efficiency, and VSWR were graphically represented and meticulously examined.

Return Loss (S_{11}) Analysis

The simulated return loss ($|S_{11}|$) of the proposed CDRA structure over the frequency range from 3 GHz to 6 GHz is depicted in Figure 2. The parameter $|S_{11}|$ represents the reflection coefficient at port 1, and it is a key indicator of how effectively the antenna is matched to the transmission line. A value below −10 dB is typically considered acceptable for impedance matching, indicating that more than 90% of the power is radiated or absorbed, with less than 10% reflected. As shown in Figure 2, the antenna exhibits a pronounced resonance at approximately 4.2 GHz, where $|S_{11}|$ reaches a minimum of nearly −40 dB, indicating excellent impedance matching at this frequency. This sharp dip confirms the antenna's optimal performance at the resonant frequency. The bandwidth, defined as the frequency range over which $|S_{11}|$ remains below −10 dB, extends approximately from 3.95 GHz to 4.5 GHz, suggesting a fractional bandwidth suitable for applications in the sub-6 GHz band, such as portions of the C-band or 5G communications.

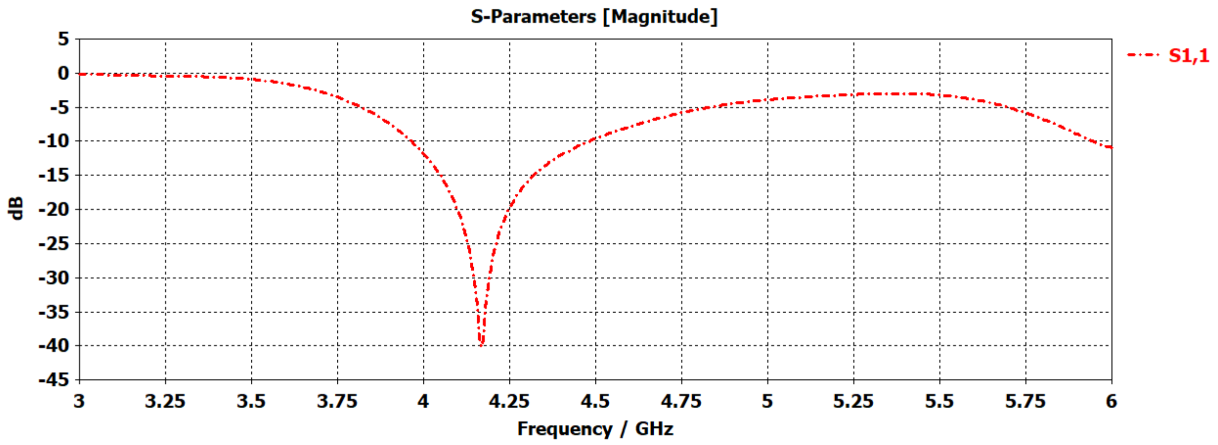

Figure 2. S11 vs Frequency of Cylindrical DRA

Voltage Standing Wave Ratio (VSWR)

Figure 3 shows the simulated VSWR of the antenna across the frequency range of 3–6 GHz. At the resonant frequency of 4.17 GHz, the VSWR reaches a minimum value of 1.02, indicating excellent impedance matching and minimal power reflection. A VSWR below 2 is typically acceptable in antenna design, and the proposed antenna maintains this standard within the operating band of approximately 3.95 GHz to 4.5 GHz. This result confirms that the antenna is well-matched to a 50-ohm system and efficiently radiates energy at the intended frequency.

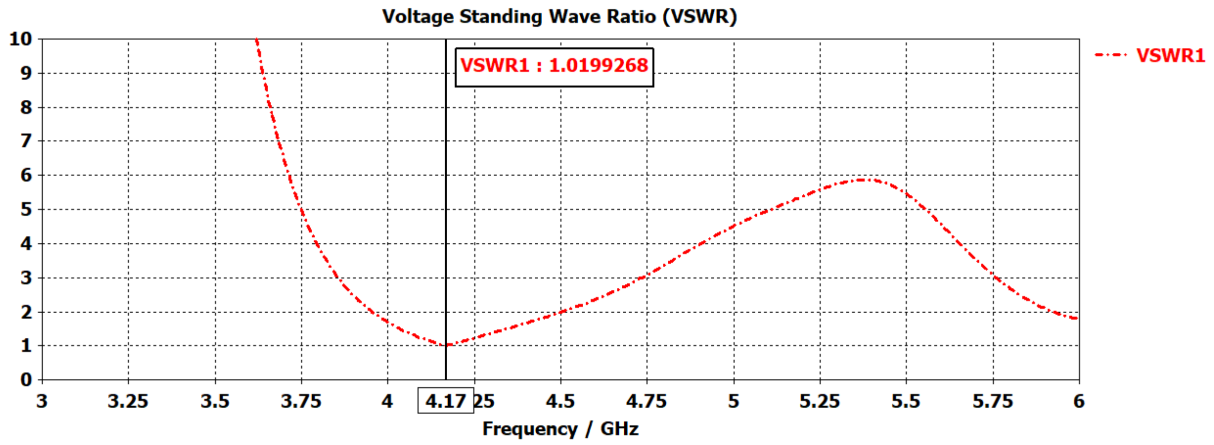

Figure 3. VSWR of Cylindrical DRA

Radiation and Total Efficiency

Figure 4 presents the simulated radiation efficiency and total efficiency of the antenna across the 3–6 GHz frequency range. The radiation efficiency (in red) remains consistently high, above 85%, across the entire band, peaking near 4.25 GHz, which highlights the antenna's ability to effectively radiate power.

The total efficiency (in green), which accounts for both radiation and mismatch losses, reaches its maximum of approximately 88% around 4.25 GHz, aligning with the resonant frequency identified in the S_{11} and VSWR results.

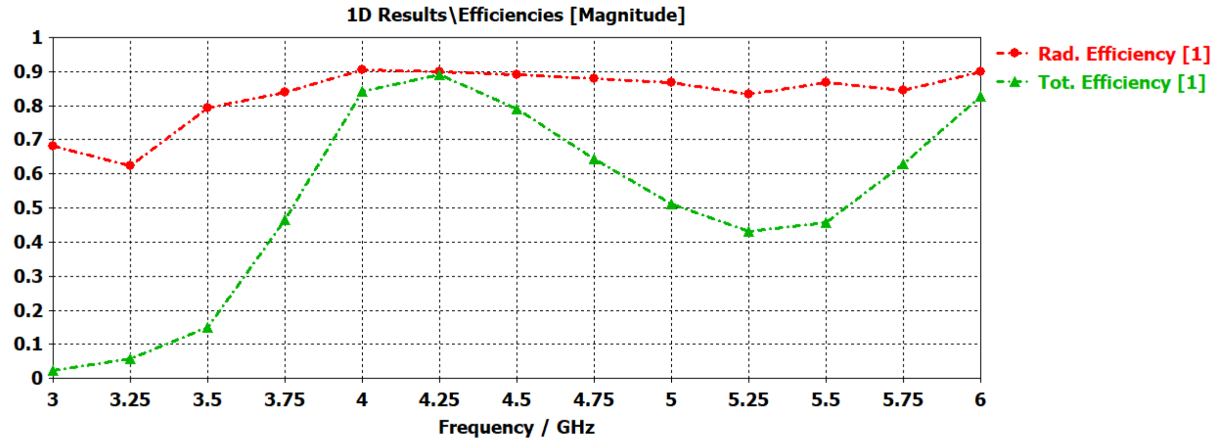

Figure 4. Efficiencies of Cylindrical DRA

Directivity and Gain

The directivity increases with frequency and peaks at approximately 7.5 dBi around 4.75 GHz, indicating strong directional radiation in the main beam direction as shown in Figure 5. This characteristic is desirable for applications requiring focused energy transmission.

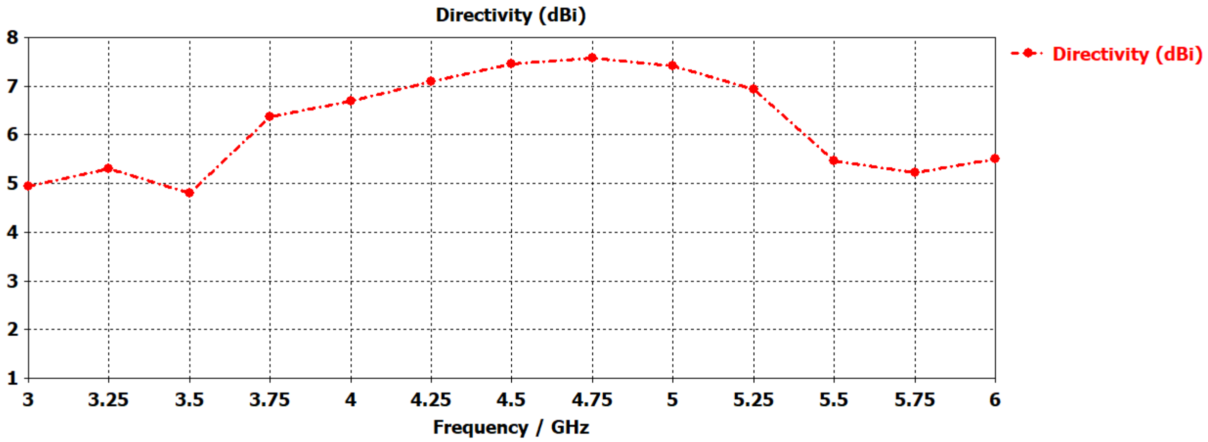

Figure 5. Directivity of Cylindrical DRA

The gain plot follows a similar trend, peaking at around 7 dBi near 4.75 GHz, which aligns with the antenna's high radiation efficiency in this band as shown in Figure 6. The gain remains above 5 dBi across a wide portion of the band, demonstrating stable and efficient performance.

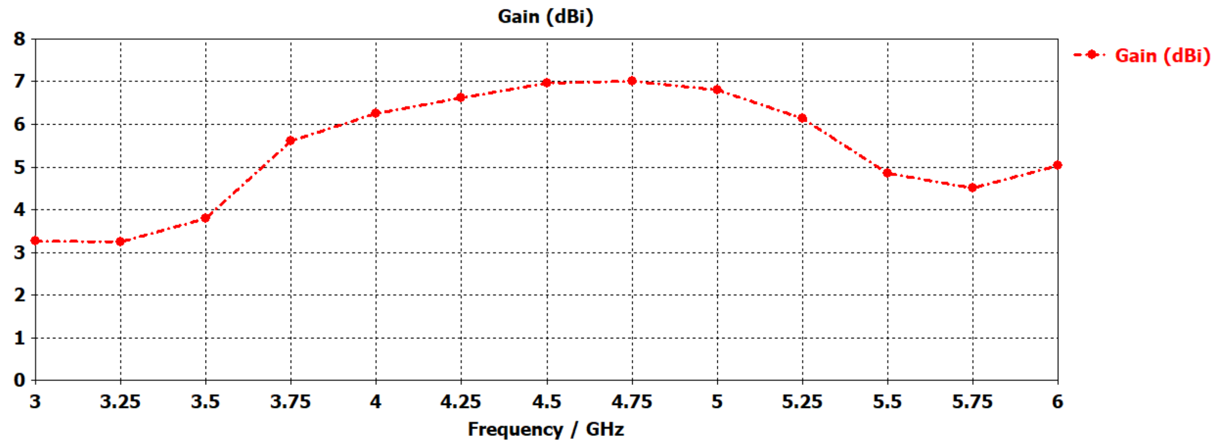

Figure 5. Gain of Cylindrical DRA

Conclusions

A Cylindrical Dielectric Resonator Antenna (CDRA) has been successfully designed and analyzed using an FR-4 substrate and an Al_2O_3 dielectric resonator. The proposed antenna demonstrates excellent performance in the targeted frequency band, exhibiting a return loss of −40 dB at 4.17 GHz, a minimum VSWR of 1.02, and a high radiation efficiency exceeding 85%. The antenna achieves a peak gain of 7 dBi and maintains stable directivity across the operating range. These results confirm the suitability of the design for high-performance wireless applications in the sub-6 GHz spectrum, such as biomedical applications, 5G, WLAN, or C-band communication. The combination of cost-effective materials and compact dimensions makes this antenna a strong candidate for integration into modern wireless systems.

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