Comparative Analysis of Cylindrical Dielectric Resonator Antenna (CDRA) Design for Biomedical Sensing Applications

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Abstract: Antenna design has been trending as compact, high-performance and low-cost due to next-generation wireless technologies, biomedical sensing requirements. The Dielectric Resonator Antennas (DRAs) have gained an edge over other antennas due to their high radiation efficiency, very low conductor losses and large bandwidth as specially at higher frequencies (above 1GHz) where the majority of traditional microstrip patch antennas suffers. The Cylindrical Dielectric Resonator Antenna (CDRA) is a prominent type which can be easily fabricated, supports various resonant mode excitation and it becomes an appropriate candidate for biological or communication related applications among all other DRAs. In this paper the proposed advanced CDRA for biomedical sensing is compared with state-of-the-art DRA structures available in recent literature. It is a set to underscore the design methodologies, performance metrics as well as application suitability for sub-6GHz biomedical and wireless domain.

Keywords: Dielectric Resonator Antenna; Biomedical; Cylindrical; Bandwidth

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Introduction

Dielectric resonator antennas (DRAs) have become increasingly prominent within modern high-frequency, high-performance wireless communications, serving as a powerful alternative to conventional designs [1]-[3]. The core of a DRA consists of a precisely shaped ceramic or dielectric block; its operation hinges on the abrupt dielectric constant drop across the boundary between the resonator and air. This sharp boundary effectively behaves like a waveguide, securely confining and then radiating electromagnetic energy at microwave and millimeter-wave wavelengths. Because the mechanism relies on the dielectric medium rather than on conductive structures, metal-loss penalties at these elevated frequencies are virtually negligible. As a result, a dielectric resonator antenna achieves superior radiation efficiency and a markedly reduced overall insertion loss, reinforcing its suitability in demanding transmission environments [4], [5].

Key characteristics of DRAs include their tunable bandwidth, flexibility in feeding methods (slots, probes, microstrip, coplanar waveguides), and the ability to miniaturize by leveraging materials with higher relative permittivity. As a result, DRAs are commonly used in phased arrays, mobile wireless devices, military radar equipment, 5G cellular communications, and automotive radar, where compact size, efficiency, and high-frequency performance are paramount. Their design enables operation over a wide frequency range (from approximately 1GHz to above 44GHz) and they have high power handling capacities due to their ceramic material composition. Additionally, DRAs are well-suited for conformal applications that require antennas to be integrated onto curved or complex surfaces. An area where CDRAs are gaining significant traction is in the field of medical applications, particularly in biomedical sensing and non-invasive medical diagnostics. Recent advancements have led to the design of compact, highly sensitive CDRA-based sensors operating within the ISM (Industrial, Scientific, and Medical) frequency bands (2.4–2.5GHz), a range often utilized for wireless medical devices [6], [7], [8].

A notable example is the integration of a CDRA with an artificial magnetic conductor (AMC) for real-time, non-invasive monitoring of blood glucose levels in humans. This approach addresses critical shortcomings of invasive diagnostics, offering a compact, economical, and safe sensing platform. The device achieves high sensitivity and stability by leveraging ceramic materials and advanced electromagnetic design, yielding measurable correlations between CDRA signal variations and changes in blood glucose concentration. The proposed CDRA demonstrates a specific absorption rate (SAR) well within safe limits for human exposure, making it an attractive candidate for wearable medical devices. Moreover, CDRAs have been validated for a variety of biomedical applications such as monitoring physiological parameters, sensing different tissues or liquids, and wireless health telemetry. The structure's compact size, high gain, and stable directivity ensure that these antennas deliver robust performance in embedded medical systems. With radiation and total efficiencies exceeding 80%, CDRAs are set to play an increasingly critical role in future wireless biomedical sensors, smart healthcare devices, and real-time monitoring systems.

Literature Review

Upadhyay et al. introduced a cylindrical dielectric resonator antenna (CDRA) integrated with an artificial magnetic conductor for real-time, non-invasive blood glucose monitoring in humans. Operating in the ISM band (2.4–2.5GHz), the device demonstrated a gain of 3.6–7.7dBi, high sensitivity to glucose variations, and a low specific absorption rate (SAR) well within safety limits, thereby highlighting its suitability for wearable medical sensors [9]. A study by Singh et al. details the design of a CDRA using an Al_2O_3 cylindrical resonator, reporting a resonant frequency of 4.17GHz, high radiation efficiency (>85%), and stable gain/directivity. This compact and efficient antenna is shown to support modern biomedical sensing and wireless health telemetry, making it ideal for next-generation healthcare devices [5]. Singhwal et al. (2024) proposed a DRA for implantable medical devices, resonating at 2.45GHz in biocompatible environments, with simulations in various tissue phantoms. The design achieves low metallic loss, high gain, and safe SAR margins, demonstrating strong potential for implantable telemetry and wireless diagnostics [10].

A report introduced an ultra-compact antenna for wireless body area networks, resonating at 2.45GHz with a 29% bandwidth and a volume of 6.5mm^3. SAR studies showed safety for implantation, and the multi-layer tissue model validated device performance in skin, kidney, muscle, liver, and brain, supporting real-time patient monitoring [11]. A review by Saxena et al. examined multi-geometrical stacked DRAs, identifying advances in stacked and hybrid feeding methods. With improved bandwidth, gain, and adaptability, these DRAs enhance wireless telemetry for healthcare and can be customized for specific diagnostic modalities [12]. Yogev et al. discussed the biomedical applications of implantable DRA-based and other sensors for monitoring temperature, mechanical, optical, and electrophysiological parameters. DRA properties, including biocompatibility and high efficiency, make them promising for long-term physiological monitoring [13]. Sainath et al. explored flexible multi-slotted DRAs for wearable applications in biomedical monitoring. Their findings identify design challenges, including maintaining durability, wideband capability, and conformal integration with the human body, which are actively being addressed in contemporary DRA research [14].

Methodology for Cylindrical Dielectric Resonator Antenna (CDRA) in Medical Applications

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.

The methodology for designing a Cylindrical Dielectric Resonator Antenna (CDRA) for biomedical applications, especially for non-invasive medical sensing such as blood glucose monitoring, involves a systematic approach from material selection to experimental validation. The process aims to create a compact, efficient, safe, and sensitive antenna suitable for real-life medical environments.

1. Application Requirement and Frequency Band Selection

The initial phase defines the target biomedical application and the operating frequency range. Most medical sensing devices use the Industrial, Scientific, and Medical (ISM) band centered at 2.4–2.5 GHz, ensuring minimal interference and regulatory compliance for wireless operation. This frequency also balances penetration depth in biological tissues and antenna size constraints for wearable or implantable usage.

2. Material Selection

The choice of the dielectric resonator material is crucial. High-permittivity ceramics such as alumina (Al_2O_3) with a relative permittivity around 9.9 and very low loss tangent (~0.001) are preferred. These materials enable miniaturization of the antenna while maintaining high radiation efficiency, thus reducing tissue heating and power loss. The substrate for the microstrip feeding network is typically a low-loss microwave laminate (e.g., Rogers RT/duroid 5880) to minimize dielectric losses. A copper ground plane is used beneath the substrate to enhance antenna gain and directivity.

3. Antenna Geometry and Design

The physical dimensions of the CDRA radius and height are calculated using the dielectric waveguide model to resonate at the chosen frequency. Unlike conventional metallic antennas, the CDRA's resonant frequency depends heavily on both the dielectric constant and the dimensions of the cylinder. The geometry is carefully optimized to maximize bandwidth and gain while ensuring a small antenna footprint suitable for biomedical devices.

To enhance antenna performance, the CDRA is backed by an artificial magnetic conductor (AMC) surface, often with a beehive or mushroom-shaped unit cell design. AMC surfaces reflect electromagnetic waves in phase, increasing antenna gain and reducing backward radiation, which is critical to protect healthy tissues from excess exposure.

4. Feeding Technique

The antenna is fed primarily by a microstrip line to excite dominant dielectric resonant modes efficiently. Microstrip feeding offers simplicity, integration ease with RF circuits, and good impedance matching capabilities. The location of the feed probe or microstrip line is optimized by simulation to achieve the best impedance match (return loss below −30 dB).

5. Electromagnetic Simulation and Tissue Modeling

Full-wave electromagnetic simulation tools such as CST Microwave Studio or HFSS are used to model the antenna in a realistic scenario. The antenna is simulated both in free space and in proximity to anatomically accurate bio-phantom models representing human tissues (e.g., the Hugo phantom). This phase verifies antenna performance parameters like gain, bandwidth, radiation pattern, and especially specific absorption rate (SAR) to ensure compliance with safety standards (<1.6 W/kg averaged over 1g of tissue).

6. Performance Optimization and Sensitivity Analysis

Parametric studies are conducted varying antenna dimensions, feeding position, and AMC structure characteristics to optimize gain, efficiency (>85%), and bandwidth. Sensitivity tests involve simulating changes in dielectric properties of tissues that correlate with physiological variations, such as glucose concentration differences. The CDRA's response to these variations is examined to determine detection thresholds and calibration curves for reliable sensing.

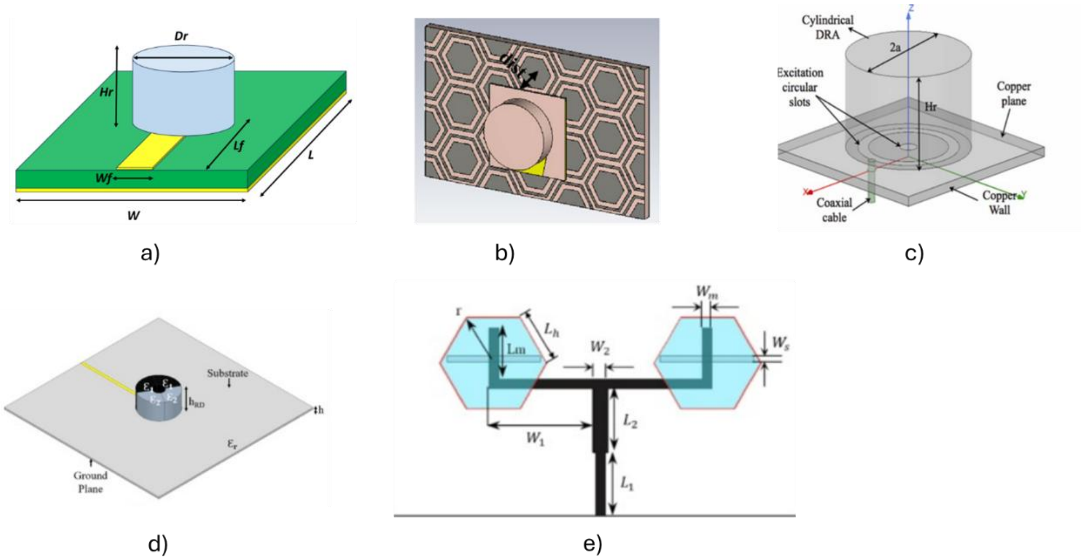
7. Fabrication and Experimental Validation

Following simulations, the antenna prototype is fabricated using precision ceramic machining and printed circuit board (PCB) technology for the feeding network and AMC layer. Experimental setups include connecting the antenna to a vector network analyzer for S-parameter validation and measuring radiation patterns in anechoic chambers.

When feasible, in vitro measurements with tissue-mimicking phantoms or in vivo tests (subject to ethical clearances) validate the antenna's practical performance. Comparisons between simulated and experimental results finalize the design and confirm its usability for medical applications.

8. Integration and Scalability Assessment

Finally, the antenna's integration potential with wearable or implantable medical systems is evaluated. Scalability in mass production, cost-effectiveness, and mechanical robustness are considered for real-world healthcare deployment.



a)

b)

c)

d)

e)

Figure 1. Perspective view of DRA in [5], [9], [15], [16], [17].

Table 1. Comparison of DRA parameters

Feature	CDRA for Biomedical Sensing [5]	AMC-Backed CDRA [9]	Cavity-Backed Slot CDRA [15]	Camembert DRA [16]	MIMO DRA [17]
Resonant Frequency	4.17GHz (sub-6GHz)	2.4–2.52GHz (ISM band)	Up to 9.7GHz	2.3–6.2GHz (wideband)	2.7–5.9GHz (for 5G)
Bandwidth	3.95–4.5GHz	300MHz	Wideband	>4GHz	Dual-band (sub-6GHz)
Peak Gain	7dBi	7.69dBi	Up to 7.13dBi	7.8dBi	5–8dBi (array)
Efficiency	>85% radiation, >80% total	High gain, SAR evaluated	Enhanced via slot feeding	High	High, good isolation (MIMO)
Novelty/Focus	Simple, cost-effective design	AMC integration, SAR reduction	Cavity slot feed, gain, bandwidth	Innovative geometry, multi-band	Circular polarization, array compactness
Biomedical Sensing	Targeted	Non-invasive glucose monitoring	Possible	Sensing, telemetry	Smart medical devices, connectivity
Integration & Miniaturization	Yes	Yes	Yes	Yes	Yes
SAR Considerations	Not analyzed	Analyzed, found safe	Not specified	Not specified	Not specified
Design Complexity	Moderate, uses FR-4, Al_2O_3	Moderate, AMC layer	Increased (slot cavity)	Moderate	High (MIMO layout)

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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