Analysis of the Impact of an Increase in Permittivity of Material on Cylindrical Dielectric Resonator Antenna Compactness and Performance

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Abstract
Cylindrical dielectric resonator antennas (CDRAs) are well-known for their high efficiency, gain, and wideband features, making them useful for various high-performance applications. However, their use in wearable devices is not as widespread due to the challenges associated with size and compactness. This paper investigates the impact of increasing the permittivity of materials on the size of CDRAs, aiming to address these challenges. Since the size of a DRA is inversely proportional to the square root of the material's permittivity, increasing permittivity leads to a significant reduction in antenna size. This study investigates materials with permittivity values ranging from 5.5 to 20 to observe their effects on antenna miniaturization. The findings show that the DRA size is substantially reduced with higher permittivity materials and delivers a gain of > 6.8dB, for industrial, scientific, and Medical (ISM) band, which makes it a more practical choice for small, high-gain antenna designs in wearable technology and other space-constrained applications.

Keywords— Cylindrical Dielectric Resonator Antenna (CDRA), High Permittivity, Miniaturization, Wearable devices, Wireless Communication, Industrial, scientific, and Medical (ISM) band

I. Introduction

Wearable wireless devices have emerged as a critical breakthrough in the rapid evolution of the Internet of Things (IoT), allowing for seamless connectivity and real-time data transmission and processing. Wearables have become a vital part of our daily lives. They are not only restricted to smartwatches, fitness trackers, and augmented reality (AR) glasses, but they also play an important role in medical and health applications.

Wearable devices are expected to grow to 578 million in 2019, a fivefold increase from 2014 [1], and the number of linked devices will reach 30.9 billion by 2025[2][3]. Wearable devices are those that humans can wear and use to communicate [4] either explicitly or through integrated cellular communication. They communicate with other devices using integrated wireless modules, which interface with other components, including batteries, sensors, and antennas. The wearable antenna plays a crucial role in the functionality of these devices [5]. Wearable antennas must be lightweight, flexible, maintenance-free, and require no installation to function well in varied situations while maintaining optimal performance [6][7]. Planar patch antennas (PPAs) are frequently used antennas in wearable wireless communication systems because of their lightweight, compact size, low cost, ease of fabrication, and planar geometry [8][12]. However, they can exhibit limited radiation efficiency at higher frequencies because of metallic losses. These issues have prompted researchers to develop alternative antennas with increased bandwidth and performance while keeping the physical size of the antenna compact. Dielectric resonator antennas (DRAs) are now attracting a lot of attention due to their attractive properties, such as versatility in design, like rectangular DRA, cylindrical DRA, compact size, low metallic losses, high gain, ease of excitation, and reasonably wide impedance bandwidth [9][11]. The size of a DRA is inversely proportional to the permittivity of the material, which means an increase in permittivity means a reduction in the form factor and size of the DRA, making it appropriate for body-centric applications [10]. Here, they introduced a small triple-band CDRA for GPS, Wi-Fi, and WLAN applications. The CDRA is fabricated using Alumina ceramic, with a dielectric constant of 9.8 and a loss tangent of 0.0001 on FR4 substrate. The radius and height of the 1×3 CDRA array are 4mm x 16mm. An unequal microstrip line power divider excitation technique is introduced to achieve an acceptable bandwidth. The antenna resonates at 1.5 GHz, 2.4 GHz, and 5.8 GHz frequencies, with gain values of 2.8dBi, 3.4dBi, and 5.8dBi, respectively. The Defected Ground Structure (DGS) improves antenna efficiency beyond 75%.

In [13], a novel feeding approach for rectangular DRA miniaturization in wearable applications was presented. A unique capital F-shaped conformal copper strip energizes this single-point-fed antenna. The dimensions of the DRA (height, length, and width) are fixed at 15mm,12mm, and 8mm. The simulated axial ratio bandwidth is ~23.85%, with an impedance bandwidth of ~16.066%.

For the first time, we will discuss in this study how an increase in permittivity affects the overall performance and miniaturization of CDRA for wearable applications. The CDRA is designed using different permittivity materials of 5.5,9.9,11.9, and 20, respectively fed by a microstrip line. We also observed antenna performance such as return loss (RL), impedance bandwidth, gain, and overall size reduction. The rest of the paper is organized as follows. Section II defines the design of CDRA. Simulation results are discussed in Section III. The discussion is concluded in Section IV.

II. Antenna Design

The section explores the basic structure and design of CDRA for the industrial, scientific and medical (ISM) band. The frequency range shown was selected based on the intended application range for wearable IoT devices, typically operating in the ISM band. The antenna design is depicted in Fig.1. It consists of two parts. The first part is a Roger RT/ Duroid 5880 substrate with a dielectric constant of (ε_r=2.2) and loss tangent of (tanα=0.0009). The substrate has a full metallic ground plane. The second part is a cylindrical dielectric resonator, fed with a metallic microstrip line, and which consists of a material where the dielectric constant can be varied across the range: 5.5,9.9,11.9 and 20. The design for each value of the dielectric constant is optimized using the Ansys HFSS software.

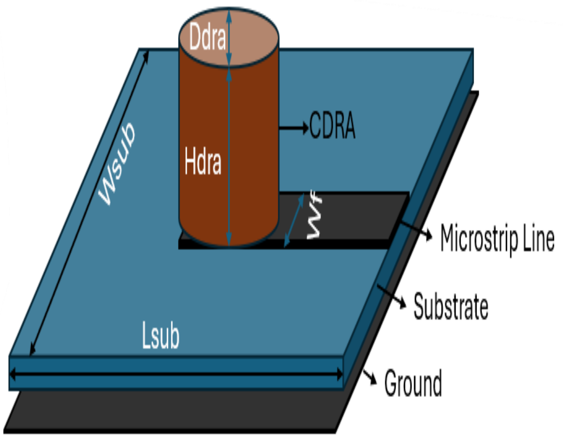


Figure 1: Antenna layout and Dimensions

Table I: Antenna Dimensions

Antenna Parameter	Values (mm)
W_{sub}	45
L_{sub}	45
H_{sub}	0.787
W_f	2.42

For the dielectric constant of 5.5, the dimensions of CDRA, radius, and height are 12mm and 35mm, at a resonance frequency of 5.8 GHz. By increasing the dielectric constant to 9.9, we see a significant reduction in the dimensions, with radius and height now being 9mm and 9mm, respectively, at an operating frequency of 4.8 GHz. With a further increase in dielectric constant to 11.9, there is a further reduction in radius and height to 7mm and 7mm, respectively, at a corresponding resonant frequency of 5.5 GHz. With the final value of the dielectric constant set to 20, the values for radius and height are 6mm and 9mm, respectively, at a resonance of 4.3 GHz. To obtain the optimal values of gain and return loss at the ISM band, the parametric sweep in Ansys HFSS is used to optimize the CDRA's radius (Rdra) and height (Hdra), which are listed in Table II for each case.

Table II: Dimensions of DRA for different dielectric constants material

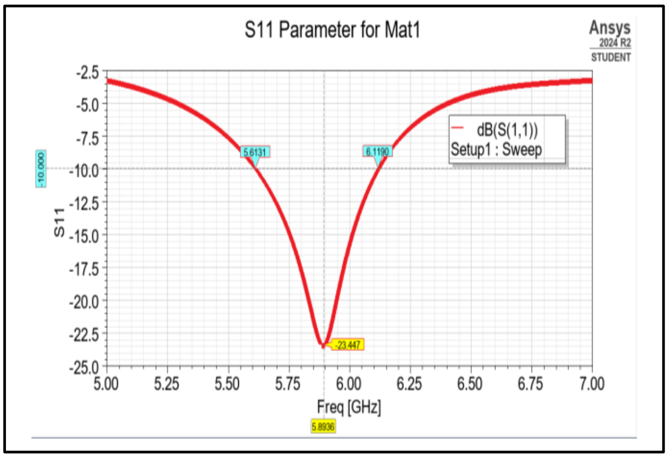
Material	Dielectric Constant (ε_r)	Resonance Frequency (GHz)	R_{dra} (mm)	H_{dra} (mm)
Mat1	5.5	5.8	12	35
Mat2	9.9	4.8	9	9
Mat3	11.9	5.5	7	7
Mat4	20	4.3	6	9

Table II shows that the radius of CDRA significantly decreases as permittivity increases. For Mat1, the value of R_{dra} is around 12 mm, while for Mat4, which is the highest permittivity material, the value of R_{dra} is approximately 6 mm, which is half of the value for Mat1. Similarly, the DRA's height is 35 mm for the material with the lowest permittivity and drastically drops to 9 mm for the material with the highest permittivity. However, there is a shift in the resonance frequency.

From this section, we observe that there is a considerable reduction in both radii and height of CDRA for an increase in permittivity of the material without any significant alterations in RL or gain as discussed in section III, making it suited for on-body and wearable applications.

III. Results and Discussion

To analyze antenna performance for each material, we simulated the CDRA designed for the ISM band in Ansys HFSS software. In this section, we will discuss the impact of permittivity on gain, reflection coefficient (S_{11}), and impedance bandwidth of Mat1, Mat2, Mat3, and Mat4.



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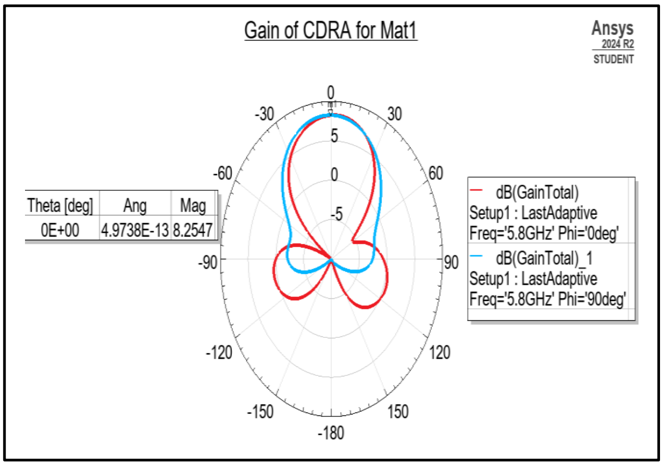
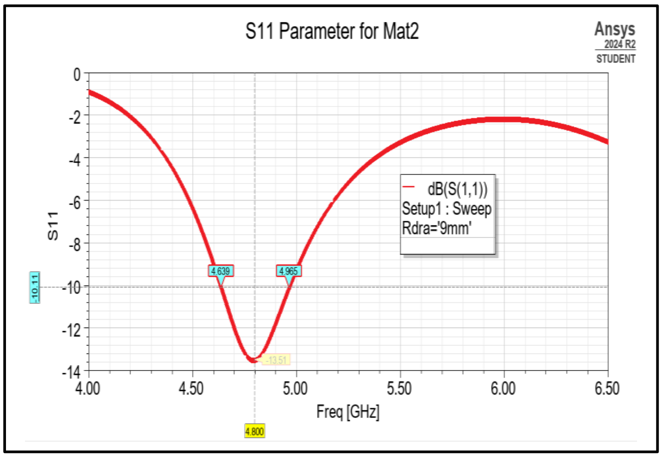


(b)

Figure 2: CDRA performance analysis of Mat1(ε_r=5.5, R_{dra}=12mm, H_{dra}=35mm), (a) Reflection coefficient(S_{11}), (b) Gain along E plane (red curve) and H plane (blue curve)

From Fig.2(a), we can observe the results for Mat1 (ε_r =5.5), the antenna has a return value of -23.4dB for the resonance frequency of 5.89 GHz. The impedance bandwidth of CDRA is 8.7%, and the gain is 8.2 dB. The radiation pattern in both the E-plane and H-plane demonstrates a highly directive behavior with minimal back lobe radiation, as shown in Fig. 2(b). This is particularly important for wearable applications, where it is critical to concentrate signal transmission away from the body. The reduced back lobe helps to minimize user exposure and interference. The antenna achieves a Front-to-Back Ratio (FBR) of approximately 18 dB and a Side Lobe Level (SLL) of around 8.5 dB, indicating strong forward radiation and effective suppression of undesired lobes to avoid exposure and interference. The results for the Mat2 (ε_r =9.9) are presented in Fig.3.



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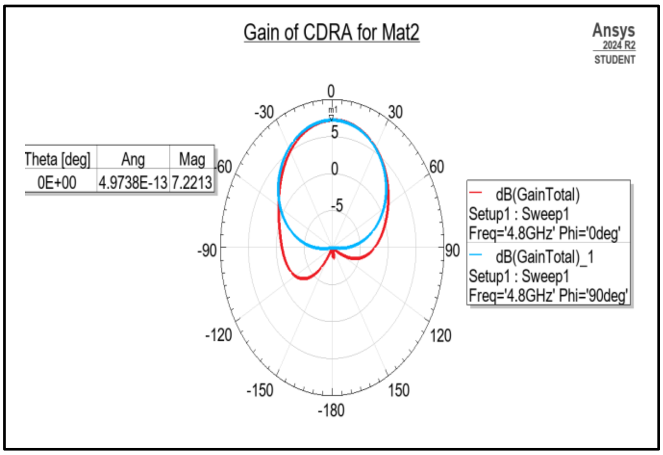
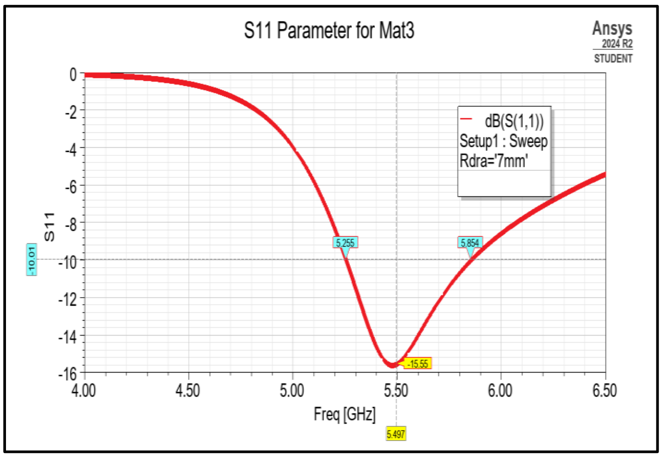


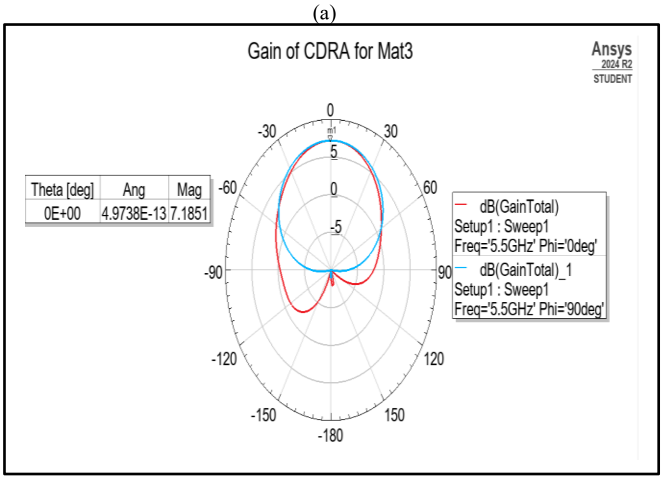
(b)

Figure 3: CDRA performance analysis of Mat2(ε_r=9.9, R_{dra}=9mm, H_{dra}=9mm), (a) Reflection coefficient(S_{11}), (b) Gain along E plane (red curve) and H plane (blue curve)

For Mat2, we have a resonance frequency lower than Mat1, that is around 4.8 GHz with a return loss of around -13.51 dB. The bandwidth is also reduced slightly. The impedance bandwidth is around 7.7%. shown in Fig.3(a). The antenna gain is significantly high; the value of gain is around 7.22 dB. Similarly, for the Mat2, the radiation pattern for both the E plane (phi=0) and H plane (Phi =90) is directive, with FBR and SLL values are around 17 dB and 9.5 dB respectively, as can be seen in Fig.3(b).



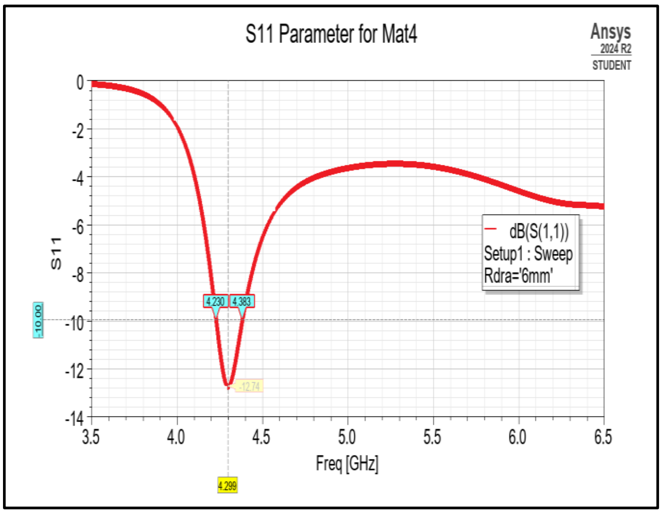
(a)



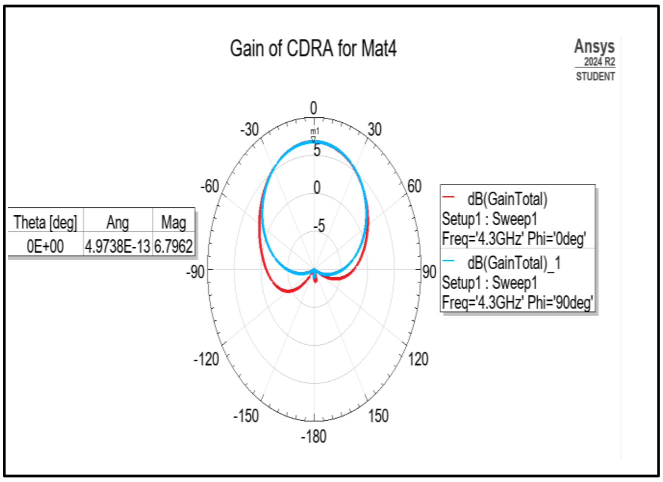
(b)

Figure 4: CDRA performance analysis of Mat3(ε_r=11.9, Rdra=7mm, H_{dra}=7mm), (a) Reflection coefficient (S_{11}), (b) Gain along E plane (red curve) and H plane (blue curve)

Fig.4(a) depicts good reflection coefficient values at 5.5 GHz with an impedance bandwidth of 11%. The high gain can be observed in Fig.4(b), at 7.2dB along the E and H planes for the resonance frequency of 5.5 GHz. Mat 3 has the directive radiation pattern, with the FBR around 15.2 dB, and SLL is around 9.3 dB.



(a)



(b)

Figure 5: CDRA performance analysis of Mat4 (ε_r=20, R_{dra}=6mm, H_{dra}=9mm), (a) Reflection coefficient (S_{11}), (b) Gain along E plane (red curve) and H plane (blue curve)

The reflection coefficient value is less than -12.74 for the Mat4 with the resonance frequency shifted down to 4.3 GHz. The 10dB bandwidth is around 4.3%. The gain of the antenna is 6.79dB, at 4.3 GHz for the E and H planes as shown in Fig.5(b). The radiation pattern is similar to the one for Mat2 and Mat3, with lower side lobe levels. The FBR and SLL levels are 16dB and 11.3dB, respectively.

Table III: CDRA performance analysis for varying dielectric constant

Dielectric Constant (ε_r)	**Resonance Frequency (GHz)**	**S_{11} (dB)**	**Impedance bandwidth (%)**	**Gain (dB)**	**Side Lobe Level (dB)**
5.5	5.8	-23.4	8.7	8.2	8.5
9.9	4.8	-13.51	7.7	7.22	9.5
11.9	5.5	-15.55	11	7.1	9.3
20	4.3	-12.74	4.3	6.8	11.3

From Table III, we can observe that as the value of ε_r increases, there is a downward shift in resonance frequency, as well as a reduction in return loss values, which are still lower than the desired industry standard value < -10 dB. The bandwidth of CDRA is significantly reduced for the high values of ε_r, the antenna has a gain of >6.8dB for each material, but it is reduced as increase in the permittivity of the material increases. And as there is an increase in the Side Lobe Level (SLL) ratio as the permittivity of materials increase to suppress the unnecessary interference of the signal.

Table IV: Comparative analysis of DRA miniaturization

Ref.	**Operati-ng Freque-ncy (GHz)**	**Antenna typology**	**Permitti-vity of materials**	**Antenna Size (mm)**	**Gain (dB)**
[10]	1.5 ,2.4, 5.8	CDRA array	9.8	(R_{dra},H_{dra}) (4,16)	>2.8
[13]	7.2	RDRA	10	Hdra,Ldra, Wdra) (15, 12,8)	-
This Stud-y	5.8	CDRA	5.5	(R_{dra},H_{dra}) (12,35)	>6.8
	4.8		9.9	(9,9)	
	5.5		11.9	(7,7)	
	4.3		20	(6,9)	

We can observe from Table IV that this study explores a detailed analysis of the impact of permittivity on antenna performance and miniaturization compared to previous studies. This makes it useful for the size constraint wearable application like smart watches, fitness tracking, and other IoT devices. We also observed that it not only impacts the performance of the antenna, but there is a tradeoff between the cost and permittivity of the material. Higher permittivity materials are more costly compared to lower permittivity, so we must consider this while working on low-cost, high-performance antennae. Although specific prices vary by supplier and batch size, high-permittivity materials like Alumina Ceramic are generally 3–5 times more expensive than standard and widely available substrates like FR4.

To optimize the resonance of the antenna, we can modify the shape of CDRA as well as modify the dimensions of the antenna. The position and type of feed, such as coaxial or aperture coupling, also play a critical role in achieving efficient resonance. Using simulation tools (Ansys HFSS, CST) and experimenting with multi-resonator designs can further enhance performance, ensuring the CDRA operates at its desired frequency with optimal bandwidth and efficiency. To improve the bandwidth and gain of the antenna, we can further introduce metamaterials and metasurfaces like electromagnetic band gap (EBG), frequency selective surface (FSS), and artificial magnetic conductors (AMC) to the structure of the antenna.

IV. Conclusion

From this discussion, we can conclude that by increasing the permittivity of the CDRA material, there is a significant reduction of CDRA size, with the maintenance of a high gain. That makes it suitable for high-performance and size-constrained applications like smartwatches, smartphones, and many other wearable applications. The only drawback to the increase in permittivity is a reduction in the bandwidth and resonance frequency. For future work, we will explore the techniques for improving bandwidth and operating frequency using the techniques stated in section III. We will also perform experimental testing of the antenna on the body and observe the performance of the antenna on a flexible substrate necessary for some wearable applications.

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