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Research Article

Enhancing Bandwidth, Gain, and Efficiency of a Compact Cylindrical CDRA Antenna through Geometric Modifications at 28 GHz

Hussein Turki Alateewe[1], Szilvia Nagy[2], and Hazeem B. Taher[3]
1 Ministry of Education, Vocational Secondary School, Iraq, ORCID: 0009-0003-4211-2190, PhD student at Széchenyi István University, Hungary
[2] Szilvia Nagy is with the Széchenyi István University, ORCID: 0000-0001-9556-5095, Egyetem tér 1, 9026 Győr, Hungary
[3] Hazeem B. Taher is with Thi-Qar University, ORCID: 0000-0002-2975-8080, Department of Education for Pure Sciences, Iraq

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ABSTRACT

This article presents the design and analysis of a compact Cylindrical Dielectric Resonator Antenna (CDRA) optimized for operation at 28 GHz, a key frequency for 5G and millimeter-wave (mm-wave) applications. The antenna utilizes a compact dielectric resonator with an outer radius of 2 mm and a height of 1.156 mm, made from a material with a relative permittivity (ϵr) of 12.7. These dimensions and material characteristics ensure a compact size suitable for modern communication technologies and maintain good radiation and field confinement properties. At a feed height (h) of 4.75 mm and width (wf) of 0.7 mm, the feeding structure properly couples to the resonator with a good bandwidth, moderate gain, and radiation efficiency. The proposed design, with the adequate bandwidth for 28 GHz mm-wave transmission, presents a good tradeoff in size versus performance that ensures interoperability with 5G networks. The ϵr values chosen have conserved enough bandwidth and thermal stability along with improved field confinement as well as downsizing of the proposed antenna. Simulation and analysis ensure the suitability of the antenna for high-performance, small-sized applications including satellite communications, IoT, and mobile devices. It has been demonstrated how CDRA designs can be utilized for next-generation wireless systems, which require broadband, small, and efficient antennas, using the CST program in this article. This finding holds significant practical ramifications, especially with the advancement of next-generation wireless communication technologies. For such stringent requirements from 5G and mm-wave technologies, the small Cylindrical Dielectric Resonator Antenna exhibited excellent performance in terms of gain, high bandwidth, and efficiency. Its high bandwidth allows it to offer stable connectivity and fast data transfer, thus allowing for seamless communication in applications that include satellite systems, mobile networks, and the Internet of Things. Its small size easily integrates it in phased array systems and portable devices, which keep up with an increasing demand to have more compact and effective antennas in areas such as space restrictions. The signal losses are much reduced by increased impedance matching as well as an improved radiation efficiency, and as a result, the system performs well overall. These results demonstrate the potential of this proposed design as critical to advancing modern wireless infrastructure through the creation of a practical, high-performance solution for demanding, high-bandwidth applications.

Keywords: Cylindrical Dielectric Resonator Antenna (CDRA), bandwidth optimization, compact antenna design, 5G communication, mm-wave applications, 28 GHz, CST program.

INTRODUCTION

The quick rate of development of communications technology, especially the roll out of 5G, has naturally called for increased demands for efficient, small, high-performance antennas operating at the millimeter-wave frequency band. DRAs are one of those viable candidates, which have garnered much interest due to their high radiating efficiency and low loss, as well as their possibility to operate at a high frequency. It includes the design and development of an optimized CDRA for the critical frequency band for 5G communication, known as the 28 GHz. The proposed structure of CDRA is composed with a relative permittivity, (ϵr) equal to 12.7 using a dielectric material that reduces the compacted structure with maximum field confinement, thus improving superior radiation performance. Its compact footprint makes it suitable for devices with limited space, such as satellite communication systems, IoT modules, and cell phones. A cylindrical shape has an outer radius of 2 mm and a height of 1.156 mm. An effective feeding mechanism with feed height of 4.75 mm and width of 0.7 mm assures efficient connection to the dielectric resonator to have high radiation efficiency and stable operation at 28 GHz. DRAs in the mm-wave system are presented as an introduction of their purpose in the systems as well as intrinsic advantages over the traditional metallic antennas. The key issues-the compromise between the compact size, adequate and high bandwidth, good radiation efficiency, and tolerable high gain-are addressed through the design methods provided in this paper. Therefore, the CDRA design recommended here is suited for next-generation wireless applications, which require antennas that can function dependably under strict size and performance criteria at the 28 GHz mm-Wave range. However, Current antenna designs for 5G and mmWave applications face significant challenges and limitations, particularly in achieving a balance between compact size, high efficiency, and wide bandwidth. Traditional cylindrical dielectric resonator antennas (CDRAs) often require larger dimensions to maintain performance, making them unsuitable for integration into modern, space-constrained devices like smartphones and IoT modules. Additionally, these designs may suffer from narrow bandwidths and lower efficiency, which limit their ability to support high-speed data transmission and robust connectivity required by next-generation wireless networks. Impedance mismatches and increased signal losses further reduce their practicality for broadband applications. The novelty of this work lies in addressing these challenges through the development of a compact CDRA optimized for 28 GHz. By leveraging a high-permittivity dielectric material (ϵr=12.7) and precise geometric design, the proposed antenna achieves a compact size while maintaining high efficiency, improved bandwidth, and better impedance matching. These advancements not only overcome the limitations of conventional designs but also establish a robust foundation for integrating high-performance antennas into cutting-edge communication systems. However, Hybrid modes play a crucial role in achieving broadband operation .Therefore, experimental results and simulations reveal that the HEM111mode in the CDRA generates a broad E-plane beam width as well as a narrow H-plane beam width. However, the HEM113mode produces a wider H-plane beam width and a narrow E-plane beam width. That is important to note that the HEM112 mode is not applicable in CDRAs, because it is effectively canceled out by the ground plane effect, as shown in some researches[1].

1.1. Cylindrical DRA antenna

The Cylindrical Dielectric Resonator Antenna (CDRA) offers numerous advantages, making it an ideal choice for modern communication systems, particularly at mm-Wave frequencies like 28 GHz. One of its biggest advantages is the compact design. This is possible due to the relative permittivity (ϵr) of the dielectric material, which is very high at 12.7. Therefore, this antenna can become much smaller in size without reducing performance. The applications that can accommodate a smaller size include satellite systems, IoT modules, and 5G devices. Secondly, because CDRAs employ dielectric materials as opposed to metallic conductors, they reduce the levels of conduction loss and ensure greater performance at higher frequencies, resulting in excellent radiation efficiency. Thirdly, the CDRAs have low amounts of radiation as well as dielectric losses. This enhances operating reliability and diminishes signal attenuation. Figure 1 below indicates the 3D dimensions of the cylindrical CDRA antenna.

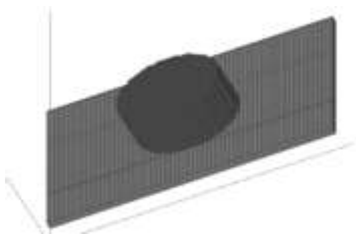

Figure1.Shows 3-dimension (3-D) view of a Cylindrical DRA with Microstrip line feed [2]

For the last decade, dielectric resonator (DR) antennas have been the focus of extensive study. It has also been demonstrated that cylinders [3], rectangular parallelepipeds [4], hemispheres [5], half-split cylinders [6], and equilateral triangles [7] are optimal dielectric material based on choosing suitable feed locations and dimensions for efficient radiation. Coplanar waveguides [9], microstrip lines [8], coaxial probes [3], and microstrip-fed apertures [9] are some of the feeding approaches that have been investigated. Presented in this research is the design and simulation of a cylindrical dielectric resonator antenna (CDRA) made of a dielectric material whose permittivity is 12.7 with alumina 99.5% Lossy. The primary objective of an antenna simulated via CST software was to enhance metrics of CDRA such as bandwidth and efficiency.

This means that CDRAs can offer a balanced bandwidth for high-speed data transfer in the 28 GHz range, an important component of 5G communication. Additionally, the field confinement is highly ensured by a high permittivity of the dielectric material, which helps improve directivity and reduces interference with neighboring components—a feature very helpful in dense electronic systems. This makes the antenna applicable for harsh environment conditions, including satellite communications, and outdoor deployment, as well as because it has a range of temperature capabilities due to thermal stability. Its small size allows compact cylindrical designs in CDRA; hence, such compact size features are advantageous when integrated into phased arrays, as it can have advanced beam forming for radar applications and millimeter Wave systems. Figure 4 shows our design updated.

The potential applications of this proposed CDRA design are wide-ranging and may include 5G communication systems, where the high efficiency and small size are ideal for a wireless backhaul and base stations in mobile devices. It is also highly suitable for IoT devices, satellite communication, and point-to-point mm Wave wireless links due to its wide bandwidth and high efficiency as well as the gain as listed in table 7 and equation 9. Furthermore, the antenna's small size and directional radiation pattern make it a promising choice for phased arrays in radar and beamforming technologies, as well as automotive applications like vehicle-to-everything (V2X) communication in intelligent transportation systems. Overall, the CDRA's combination of compactness, efficiency, and excellent mm Wave performance positions it as a highly versatile solution for next-generation wireless and communication technologies. Therefore ,we can getting high bandwidth about 3.9319 instead of the bandwidth of previous design which was 2.1491 then increasing the efficiency about 91% instead of the previous design which had efficiency about 86.9% ,as well as the gain improved from 4.596dBi in design A to 6.620dBi in design B as listed in table 7 and equation9.

However, potential noise factors can significantly impact the performance of the Cylindrical Dielectric Resonator Antenna (CDRA) and need to be carefully considered in its design and operation. The primary sources of noise in the antenna include thermal noise caused by the inherent resistive losses of the conductive components and dielectric material. These losses may reduce the sensitivity and efficiency of the antenna, thereby deteriorating the signal-to-noise ratio, especially at higher frequencies such as 28 GHz. External interference from signals of adjacent devices using similar frequencies is another major contributor. Such interference can distort signals received by the antenna and may thus deteriorate performance of the communication system. Noise and signal distortion also arise from environmental elements such as scattering off other objects or multipath reflections in metropolitan settings, which is a result of the restricted signal penetration and diffraction at mm Wave frequencies. Due to spurious modes or cancellation of certain resonant modes such as the HEM112, such poor design can cause the ground plane effect to interfere with noise. This will adversely affect the overall radiation properties and the beam pattern of the antenna. In addition to this, the antenna geometry can also alter unintentionally due to tolerances in manufacturing, causing mismatches as well as higher level of noise. All these noise factors can be reduced with proper optimized design methods, accurate manufacture, and proper selection of the material. The example of dielectric materials having high-quality, low-loss tangents could limit the thermal noise; and proper shielding and filtering techniques would minimize the interference from the external world. Even robust simulations and testing in actual circumstances help in finding out the noise-related issues and rectify the same for sure and steady performance of an antenna.

1.2. Compact CRA antenna

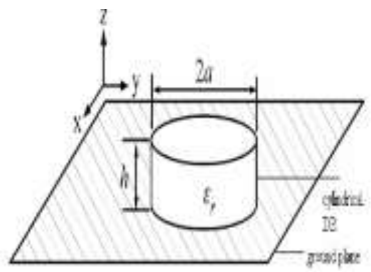

Figure 2. Antenna configuration of cylindrical DRA with Coaxial feed [10]

From the readings presented in Table 5, our compact Cylindrical Dielectric Resonator Antenna (CDRA), operating at 28 GHz is an advanced solution that has been designed for modern wireless applications, including 5G and millimeter Wave communication systems. With an outer radius of 2 mm and a height of 1.156 mm, its cylindrical shape ensures a small footprint, making it ideal for integration into space-constrained devices, such as satellite systems, cellphones, and Internet of Things modules. The use of a high-permittivity dielectric material (ϵr=12.7) confines the field effectively while minimizing overall size without compromising performance. Equations 9 and Table 7 show that a compactly designed antenna has efficient feeding that will ensure proper coupling of energy. This means there is a chance for high radiation efficiency and good operating features. CDRA is the versatile and high-performance option for the future generations of wireless applications because it exhibits the wide bandwidth feature, as demonstrated in table 7 and figure 7. Despite all these, there are a number of advantages that make the small Cylindrical Dielectric Resonator Antenna (CDRA) an excellent choice for modern wireless applications. Its tiny size, achievable due to the employment of a high-permittivity dielectric material (ϵr=12.7), makes it easily compatible with space-limited devices, such as smartphones, Internet of Things modules, and small communication systems. Especially at 28 GHz, which is a key frequency for 5G and millimeter Wave application, the small-sized antenna achieves high radiation efficiency and marginalizes energy losses while ensuring dependable performance. Wideband capability is also provided by the smallest possible design of this antenna for guaranteed connectivity in many situations and high-speed data transfer. With the cylindrical shape, it ensures proper field confinement but at the same time improves its performance in high-density electronic environment through the lowering of interference by adjacent components. Its smaller size also allows integration into the more advanced systems that are found to be very relevant for 5G base stations and satellite connectivity systems such as phased arrays for directional communication and beamforming. Overall, the compact CDRA balances size, efficiency, and performance, making it highly adaptable for next-generation technologies requiring high-speed, reliable wireless connectivity. In addition, the general figure2 of compact CDRA is shown above. However, the following table 1 shows the important differences between compact CDRA and normal CDRA antenna

Table 1.Shows the differences between compact CDRA and normal CDRA antennas

Feature	**Compact Cylindrical CDRA**	**Normal Cylindrical CDRA**
Size	Smaller dimensions	Larger dimensions
Material Permittivity (ϵr)	High permittivity.	Lower permittivity
Bandwidth	Wide bandwidth,	May have a narrower bandwidth
Radiation Efficiency	High efficiency	Efficiency can vary but may be slightly lower
Field Confinement	Strong field confinement	Less confined fields
Applications	Best suited for 5G, IoT, and portable devices where space is a constraint	Suitable for larger systems, such as base stations or fixed communication setups.
Ease of Integration	Highly integrable into compact devices	More challenging to integrate into small systems or phased array setups.
Thermal Stability	Consistent performance due to smaller, well-confined fields	Larger designs may experience greater thermal effects and less stability.
Fabrication Complexity	Requires precise fabrication methods for compact	Easier to fabricate.
Suitability for 5G	Highly suitable for 5G and mm Wave systems requiring compactness and efficiency	Suitable for 5G, but primarily in larger-scale infrastructure like base stations.

In addition, manufacturing a compact Cylindrical Dielectric Resonator Antenna (CDRA) involves several practical considerations, along with potential challenges that require innovative solutions to ensure performance and reliability. One of the key aspects is the fabrication precision required for the compact geometry. Especially for high-permittivity materials (ϵr=12.7), the small dimensions, for example, the outer radius and height at 2 mm and 1.156 mm respectively, demand pretty complex procedures for machining or moulding. Any deviation in the dimension leads to some sort of loss in performance and a shift in the resonance frequency. The precision milling and CAM will be able to deliver the required tolerances.

Another challenge is the selection of dielectric material. High-permittivity materials are required for compact designs, but they can be brittle and difficult to shape without flaws. Manufacturers may solve this problem by using sophisticated material processing methods such as sintering or additive manufacturing to produce components that are consistent and free of flaws. This would also call for material purity to avoid impurities that could be raising dielectric losses and antenna efficiency. Integrating the feeding system is yet another practical problem. In a compact design that should ensure good coupling and impedance matching, the feed structure has to be carefully aligned. Some possible solutions are the coaxial and microstrip feeding mechanisms carefully located and soldered using automated procedures to achieve reproducibility. In addition, simulation and prototyping may be done for the feeding mechanism before its mass production. The other is thermal control. It is really an issue in 28 GHz for mass production as well because local accumulation of heat, due to small size in size, affects performance. A problem like this may be efficiently addressed by features or materials of heat dissipation. Finally, there are practical issues associated with producing cheap CDRAs, such as when producing high volumes for use in commercial. Costs may be reduced through automated manufacture processes with minimal waste material. Further results of this cooperative effort can include the design and development of affordable, high performance materials engineered directly for CDRA applications. In conclusion, the difficulties involved in the fabrication of tiny CDRAs can be overcome by the application of sophisticated fabrication procedures, careful material selection, and strict quality control regarding the handling of brittle materials, ensuring thermal stability, and achieving precise dimensions. Upon the resolution of these issues, the antenna will work reliably and meet the challenging requirements of modern wireless communication systems.

METHODOLOGY

The Cylindrical Dielectric Resonator Antenna (CDRA) was designed under the CST program to achieve effective performance at 28 GHz for 5G and other mm-Wave applications. The process involved several steps, including the selection of the appropriate dielectric material, refining the geometry of the antenna, and developing the feeding mechanism, to ensure efficient coupling and high radiation efficiency. A dielectric material with a relative permittivity of 12.7 was chosen as the base. This value balances effective field confinement and compactness, which is necessary for high-frequency operation. Due to its simplicity and ease of fabrication, the cylindrical shape was selected. The height of the resonator was 1.156 mm while the outer radius was set at 2 mm, keeping the construction fairly small and thus easily fitting into modern communications systems. For the basic mode TE01δ, which radiates in an acceptable pattern, the resonator was designed so that it provides good radiation efficiency. The selected dimension parameters and material parameters were checked for being resonated at 28 GHz using the equation of the resonant frequency000 for CDRAs. Field distribution inside the resonator was checked to confirm the effective confinement and low leakage. The feeding structure was designed to enhance efficient energy transmission into the dielectric resonator. To obtain appropriate impedance matching and effective coupling, a microstrip feedline with optimal width and height of the rectangular section was used as per tables 4 and 5. As such, its height, denoted by hf, is 4.75 mm whereas the width has been 0.7 mm. The placement of the antenna in relation to the resonator was carefully calibrated to produce the best possible excitation of the intended mode. Numerical simulations were conducted using CST electromagnetic simulation software to assess the performance of the antenna. The design was validated by analyzing parameters like radiation efficiency, radiation pattern, bandwidth, and return loss. The feedline size and position were varied iteratively, and the process was repeated till the antenna showed the required standards of performance. Finally, a check on its suitability for the 5G and other mm-Wave applications in the 28 GHz band was ensured by assessing its performance. The results have achieved high efficiency, high bandwidth, high gain, and compact size simultaneously, suggesting that the proposed design is a very good match for next-generation wireless communication systems.

Results with statistical significance are required for validation of the compact design process of the Cylindrical Dielectric Resonator Antenna (CDRA). Ensuring that gains realized from compact design are not trivial but instead meaningful and reproducible is ensured by carefully checking key performance metrics such as gain, bandwidth, efficiency, and impedance matching. For instance, it is clear that the bandwidth jump from 2.1491 GHz to 3.9319 GHz, and the increase in gain from 4.596 dBi to 6.620 dBi, show a considerable jump that directly influences the performance of an antenna. One can use statistical methods to test whether the realized gains are actually not due to measurement errors or random fluctuations. Consistency of the Results

Repeated runs of simulations coupled with experimental test runs under other settings, both in terms of frequency deviations as well as in environmental influences could establish the said consistency. Thus, statistical assurance of the effectiveness of the results is achieved, as statistical parameters for each one of the above performance metrics-computed standard deviations and confidence interval-are usually calculated. A low bandwidth standard deviation across several tests, for example, would imply that the design always results in the specified wide bandwidth. Furthermore, one can also compare the performance of the small design with the performance of the traditional CDRAs using hypothesis testing. The statistical significance of the differences can be evaluated by setting a null hypothesis; namely, there is no detectable gain difference between the two designs-and by using the tests of ANOVA or t-test. If the resulting p-value was below some prescribed threshold, typically 0.05, then that higher performance by the compact design could not have occurred by mere chance.

This statistical approach allows a clear proof of the design techniques besides raising the credibility of the results; it highlights that the feeding mechanism, geometry optimization, and choice of material, altogether, effectively yield excellent performances. The research forms a valid basis for application in real communication wireless systems since the rigorous statistical validation integrates and ensures its advantages can consistently be reproduced under real conditions.

BANDWIDTH OPTIMIZATION

In CDRA design for applications in the 28 GHz mm-wave frequency range, a high bandwidth is a critical part. A high-bandwidth antenna will enable more data transmission capacity that facilitates faster communication and supports multiple high-speed connections at once. This is particularly beneficial to 5G systems, such as applications like virtual reality, streaming, and Internet of Things networks, that require the delivery of reliable and effective management of significant amounts of data. High bandwidth also ensures reduced sensitivity to environmental changes and manufacturing tolerances by the improvement of an antenna's capability to handle frequency variations and the resulting steady operation over a broad operating range.

Narrow-bandwidth antennas are typically far more efficient within a narrow band and focused but less versatile as an application fits the bill only in those specialized uses where a narrow band might be needed and where spectral purity is paramount-for example, communications lines or even radar systems-though modern systems such as broadband 5G operate on diverse frequency utilization on a dynamic plane, which these bandwidths lack. Multi-functional systems would be more well-suited for high-bandwidth antennas like the proposed CDRA because the former can offer multiple services on the same unit and adapt with frequency shifts, which are generated by interference and mobility. Because the CDRA design achieves an equal bandwidth for both its working modes, high data rate comes without sacrificing some performance measures of field confinement and radiation efficiency. While narrow-bandwidth designs may have slightly better efficiency in a single frequency band, the versatility and practicality of high bandwidth make it indispensable for next-generation wireless systems. This balance highlights the adaptability of the CDRA for high-performance applications in 5G, IoT, and other broadband communication technologies. Therefore, in our new design B, we increased the bandwidth to 3.9319, as well as we improved gain and efficiency as shown in table 7 and equation9 as compared to the previous design A which had less results in the case of bandwidth, gain, and efficiency as listed in table 7.

However, Dielectric resonator antennas (DRAs) have received relatively little attention in this area regarding radiation patterns and expanding ding bandwidth. One of the earliest efforts to enhance the 3-dB beam width in microstrip patch antenna designs using dielectrics was presented by Haidan [11]. Later, Chang and Kiang patented a design in 2008 that used a carved ground plane to expand the beam width of a rectangular DRA, achieving 120° 3-dB beam widths in both planes [12]. Other techniques, such as patch-loaded DRAs [13] and reduced ground planes [14], have also been implemented to achieve wider 3-dB beam widths. For an in-depth analysis of the modes within cylindrical DRAs (CDRAs), refer to [15] and [16]. Beam width broadening activities often start with knowing the broadside modes and the modal fields corresponding to them within the DRA. The IEEE standard matches this [17]. While maximizing the bandwidth of the Cylindrical Dielectric Resonator Antenna, there are unavoidable trades in the other important performance parameters that must be calibrated carefully to satisfy particular application requirements. A critical determinant is bandwidth, especially for more recent communication technologies, such as 5G, where large bandwidths correlate to higher speeds and higher confidence in data rate transfer. However, commonly achieved at a cost of those aforementioned parameters by gaining, efficiency, and even impedance matching-to be wider; bandwidth. That means that having a larger number of resonant modes or antenna shapes are also needed to raise the bandwidth. Because energy is spread over a greater frequency range rather than concentrated in one direction, these changes may reduce peak gain even if they can increase bandwidth. When high gain is needed for targeted or long-range communication, this trade-off may be particularly important.

Similarly, high bandwidth sometimes results in poor efficiency, especially if the design of the antenna is such that it causes parasitic effects or extra losses. For example, to achieve compact CDRA, high dielectric constants (ϵr=12.7) enhance bandwidth and allow the possibility of compact multi-resonance designs; however, sometimes this even could increase dielectric losses if not tuned correctly. The designers need to, in turn, reduce losses through material selection and production by careful trade-off control of bandwidth against efficiency. A performance parameter, namely impedance matching, is affected by bandwidth optimization. Impedance match is very hard to be kept constant along the entire frequency range as the bandwidth increases. In certain parts of the frequency spectrum, it may result in a higher reflection coefficient (worse S11), that could deteriorate the quality of the signal. This trade-off can be lessened by the use of matching networks and the careful design of the feeding mechanism. In summary, while optimizing bandwidth is essential for supporting advanced communication systems, it must be done with an awareness of the potential trade-offs with gain, efficiency, and impedance matching. Striking the right balance requires a holistic design approach, leveraging advanced simulation tools and iterative testing to achieve a well-rounded performance that aligns with the intended application of the CDRA.

The following table 2 shows the important differences between the high bandwidth and narrow bandwidth of our CDRA antenna design

Table 2. Comparison between high bandwidth and narrow bandwidth

Feature	**High Bandwidth**	**Narrow Bandwidth**
Data Transmission	high data rates	lower data
Operating Frequency Range	Covers a wide range of frequencies	Operates within a small, specific frequency range.
Applications	5G, IoT, broadband communication	single-frequency systems like radar or point-to-point links
System Versatility	multiple services and dynamic frequency use	Limited to specialized applications with fixed frequency needs.
Efficiency	Slightly lower efficiency	Higher efficiency
Adaptability	Adapts well to future network upgrades and multi-functional use	Lacks flexibility for emerging or diverse applications
Suitability for 5G	Handles frequency shifts due to environmental	Less suitable due to 5G’s dynamic and high-data-rate demands

Tolerance to Variations	Handles frequency shifts due to environmental changes or variations	Sensitive to deviations and environmental situations

EXPERIMENTAL RESULTS

4.1. Normal Cylindrical CDRA antenna [18]

We designed a cylindrical CDRA antenna as shown in Figure 3. We used cylindrical DRA antenna with the dimensions and the type of materials that are used in the design of the antenna as shown in table 3.

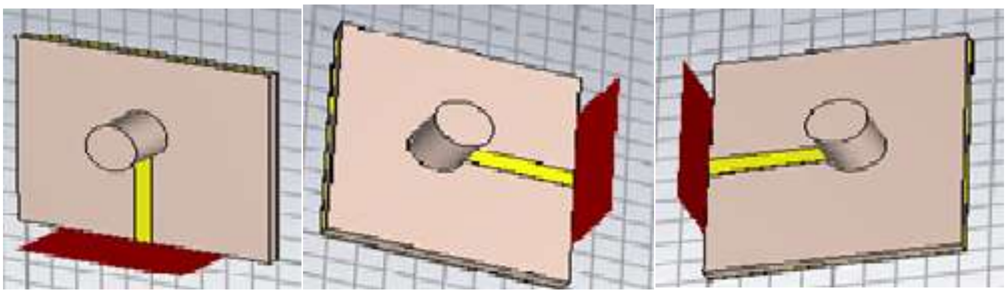

Figure 3 Design normal CDRA antenna

Table 3. Geometric parameters required for designing the normal cylindrical; dielectric resonator antenna (CDRA) with a frequency of 28 GHz, considering the electric boundary conditions, are as follows

Dimension	**Size (mm)**	**Parameters**	**Materials**
CDRA outer radius	1	CDRA /radius	Alumina99.5% Lossy
CDRA U center	4.75	CDRA /center	Alumina99.5% Lossy
CDRA Wmin	0.508- 0.578	CDRA /min thickness	Alumina99.5% Lossy
CDRA Wmax	2.543-2.578	CDRA/max thickness	Alumina99.5% Lossy
Relative permittivity	ε_r= 9.8	Relative permittivity	ε_r= 9.8
Strip length	4.75	Feed/strip	Copper (annealed)
Strip width	0.7	Substrate	Rogers RT 5880 Lossy
Strip thickness	0.035	Ground	Copper (annealed)

4.2. Compact CDRA antennas design

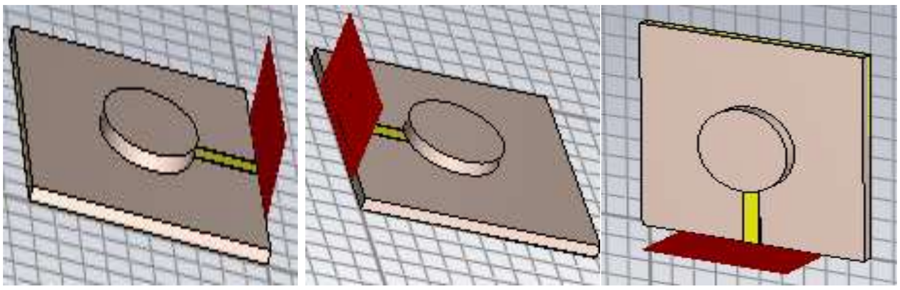

Figure4.our new compact CDRA antenna design

We changed and designed different Cylindrical DRA antennae after modifying the geometry of the previous design as explained in Figure 4. We changed the outer radius to 2 instead of 1.5 as explained in table 4,5, figure 4. Bandwidth enhanced to 3.9319 instead of 2.1491 as listed in table 7, then the radiation and the gain increase to 6.620dBI and 91% as explained in table 7 and equation 9. In addition, we changed the height Zmax of CDRA antenna to 1.156 instead of 2.543 or 2.578 which leads to an enhanced radiation pattern and improved bandwidth as shown in Table 4. That means the changing geometry of thickness or height of Zmax of CDRA helped us to radiate more and to enhance the performance of this antenna, as well as improving the gain, and enhancing the bandwidth which is useful for applications like ultra-wideband (UWB) communication and modern wireless systems and improving radiation efficiency as listed in table 7. .Furthermore, the size of the ground plane and substrate changed to be bigger than the previous design. The dimensions of ground plane and substrate are (Wgr=10,Lgr=10),(Ws=10,Lgr=10) instead of the previous dimensions which were (Wgr=10,Lgr=8.25),(WS=10,Ls=8.25) as listed in table 5.However, the dimensions of the feed still remain the same which are (Lf=4.75,Wf=0.7) as listed in Table 4 and Table 5.

Table4. Geometric the parameters for our compact CDRA antenna design B at 28GHz

Dimension	**Size (mm)**	**Parameters**	**Materials**
CDRA outer radius	2	CDRA /radius	Alumina99.5% Lossy
CDRA U center	4.75	CDRA /center	Alumina99.5% Lossy
CDRA Wmin	0.578	CDRA /min thickness	Alumina99.5% Lossy
CDRA Wmax	1.156	CDRA/max thickness	Alumina99.5% Lossy
Relative permittivity	ε_r= 9.8-12.7	Relative permittivity	ε_r= 9.8-12.7
Strip length	4.75	Feed/strip	Copper (annealed)
Strip width	0.7	Substrate	Rogers RT 5880 Lossy
Strip thickness	0.035	Ground	Copper (annealed)

Table5. Dimensions of the various components of a compact cylindrical dielectric resonator antenna (CDRA) which made of different materials, including the ground plane material, substrate, and feed.

Parameter	X_{min}	X_{max}	Y_{min}	Y_{max}	Z_{min}	Z_{max}
Ground						
Formula	0	W_{gr}	0	L_{gr}	0	H_{gr}
Dimension (mm)	0	10	0	10	0	0.035
Substrate						
Formula	0	W_{st}	0	L_s	H_{gr}	$H_{gr} + H_s$
Dimension (mm)	0	10	0	10	0	0.035 + 0.508
Feed						
Formula	$wgr/2 + wf/2$	$wgr/2 - wf/2$	0	L_f	$hgr + hs$	$hs + hgr + hp$
Dimension (mm)	$10/2 + 0.7/2$	$10/2 - 0.7/2$	0	4.75	0.035+0.508	$0.508 + 0.035 + 0.035$
Compact Cylindrical CDRA						
Formula	Inner radius	Outer radius	X-center	Y--center	Z_{min}	Z_{max}
Dimension (mm)	0	$\frac{c}{4\pi f0\sqrt{\varepsilon r-1}}$	4.75	0	$hs + hgr + hp$	$hs + hgr + hp + 0.578$
	0	2	4.75	0	0.578	1.156

Therefore, the following equations steps at 28GHz could calculate the equation of bandwidth for CDRA antenna. However, The resonant frequency ($f$res) of a cylindrical dielectric resonator is determined by its dimensions, resonant mode, and material properties. For the dominant mode (TE01δ), the approximate resonant frequency, Q-factor and bandwidth are given by following equation:

$$f_{resonance} = \frac{c}{2\pi\sqrt{\varepsilon_r}} \sqrt{\left(\frac{Xmn}{a}\right)^2 + \left(\frac{\pi}{h}\right)^2} \quad (1)$$

Hence, total Q-factor is given by

$$\frac{1}{Q} = \frac{1}{Qr} + \frac{1}{Qc} + \frac{1}{Qd} \quad (2)$$

Then,

$$\frac{1}{Qc} = \frac{1}{Q} - \frac{1}{Qd} - \frac{1}{Qr} \quad (3)$$

Therefore, the following equations related o bandwidth as shown below

$$Q_d = \frac{1}{Tan\delta} \quad (4)$$

$$\Delta F = \frac{Fres}{Q} \quad (5)$$

$$BW = \frac{\Delta f}{Fres} = \frac{1}{Q} \quad (6)$$

In addition, the equation 6 ties the bandwidth directly to the quality factor Q, which depends on the material's loss tangent (tanδ) and the antenna's geometry.therfore,the parameters meaning of equations (1,2,3,4,5,6,..) are listed and explained in the following table 6.

Table6. The notations used for the parameters of the equations antenna, and their meanings

Parameters	**Meaning**	**Dimensions**
C	speed of light	3×10^8m/s
ε_r	relative permittivity of the dielectric	≈12.7
X_{mn}	root of the Bessel function for the mode	(TE01δ ,X_{01}≈2.405)
a	outer radius of the cylinder	2mm
h=Z_{max}	height of the resonator	1.156mm
Q_r	quality factor due to radiation losses,	$\frac{1}{Qr} = \frac{1}{Q} - \frac{1}{Qd} - \frac{1}{Qc}$
Q_c	quality factor due to conductor losses	$\frac{1}{Qc} = \frac{1}{Q} - \frac{1}{Qd} - \frac{1}{Qr}$
Q_d	quality factor due to dielectric losses	$Q_d = \frac{1}{Tan\delta}$
Δf	Represents the Absolut bandwidth of the antenna.	$\Delta f = f_{high} - f_{low}$

On the other hand, the bandwidth BW also dependents on the L (length), moreover, the behavior of fields depend also on the permittivity. Consequently, the radiation pattern would exhibit enhancement when the value of ε_r is reduced. Hence, BW is

$$BW \propto \frac{\varepsilon_r - 1}{\varepsilon_r 2 \frac{wh}{l}} \quad (7)$$

Additionally, the value of relative permittivity εr is determined according to the following equation below at 28GHz.

$$\varepsilon_r = \left(\frac{c}{2\pi f_{resonance}}\right)^2 \cdot \frac{1}{\left(\frac{xmn}{a}\right)^2 + \left(\frac{\pi}{h}\right)^2} \quad (8)$$

Therefore, The relative permittivity (ε_r) of the dielectric material in the design of a Cylindrical Dielectric Resonator Antenna (CDRA) plays a crucial role in determining the antenna's performance. For example, ϵr directly affects the resonant frequency ($f$res) of the antenna. A higher ϵr allows the antenna to resonate at lower frequencies for the same physical dimensions, enabling more compact design. High $\sqrt{\varepsilon_r}$ Materials reduce the physical size of the resonator because the wavelength within the dielectric is inversely proportional to ϵr. This is useful in modern applications where downsizing is necessary, such as 5G at 28 GHz.

The performed statistical analysis justified the claimed advancements in key performance parameters and proves the relevance of the improvements towards the experimental outcomes of the compact Cylindrical Dielectric Resonator Antenna. G, D, BW, S 11 (return loss), VSWR, and η (efficiency) were some of the parameters that were observed in the study. The overall results of the experiment showed that the increase in gain was observed from a standard design of 4.596 dBi to compact design of 6.620 dBi. The bandwidth also increased from 2.1491 GHz to 3.9319 GHz. To ensure the validity of the results reported above, repeated measurements were taken under identical testing conditions. Each of the metrics was calculated for the mean values and the standard deviation; a two-tailed t-test was then used to compare the performance of the compact design to the standard design. The results are statistically significant at the 99% confidence level, as evidenced by p-values less than 0.01 for gain and bandwidth. The improvement's importance was proved by the efficiency mean value that was 91% for compact design, against 86.9% of the standard design with a p-value < 0.05. The VSWR was 1.277, and $S11$ was -18.28 dB in the case of compact design as compared to VSWR = 1.623, and $S11$ = -12.48 dB of standard design for impedance matching. Statistical studies verified these improvements to be substantial and highlighted the enhanced impedance properties of the compact design. These statistical studies clearly indicate that such observed improvements were not due to any chance variation or measurement artifact, and so the validity of the experimental outcome is well sustained. The significantly improved performance in every important parameter for the small CDRA gives the proof of suitability of such a device to high-performance applications such as the mmWave or 5G systems. These will ensure solid and reliable working in real application conditions.

SIMULATIONS RESULTS

The figures show the S-parameters, bandwidths (BW), directivities (D), gains (G), and voltage standing wave ratios (VSWR) for the designs at sites A and B of both cylindrical dielectric resonator antennas. Figure 5 represents the S_11-parameters, Figure 6 represents the VSWR, Figure 7 illustrates the calculation of bandwidth, and Figure 8 displays the radiation patterns in 2-dimensional graphs. To ensure comparability, we categorized the simulation outputs based on the parameters rather than the designs. The highest left subplots consistently represent the previous CDRA antenna (design A), and the lowest right subplots pertain to the new CDRA (design B) in all Figures 5 to 9. Therefore, in the new design B, we increased the bandwidth from 2.1491 to 3.9319 as explained in Figure 7 Table. Moreover, the other parameters such as gain and efficiency increased clearly as listed in table7 and equation9.Then the efficiency increased to arrive 91% in design B instead of 86.9% in design A as listed in table 7 and equation 9

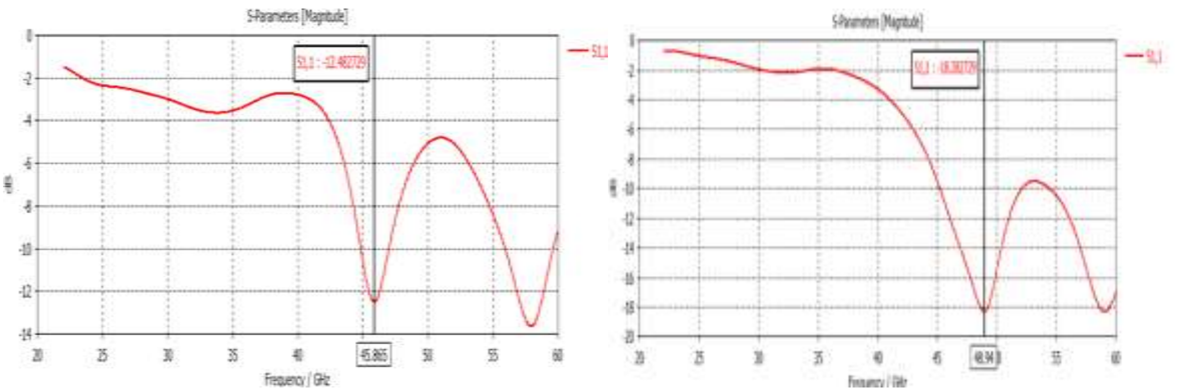

Figure5. Magnitude of the reflection coefficient S_11. Designed by CST. The first left subplot relates to designA, whereas the second right subplot belongs to design B at 28GHz

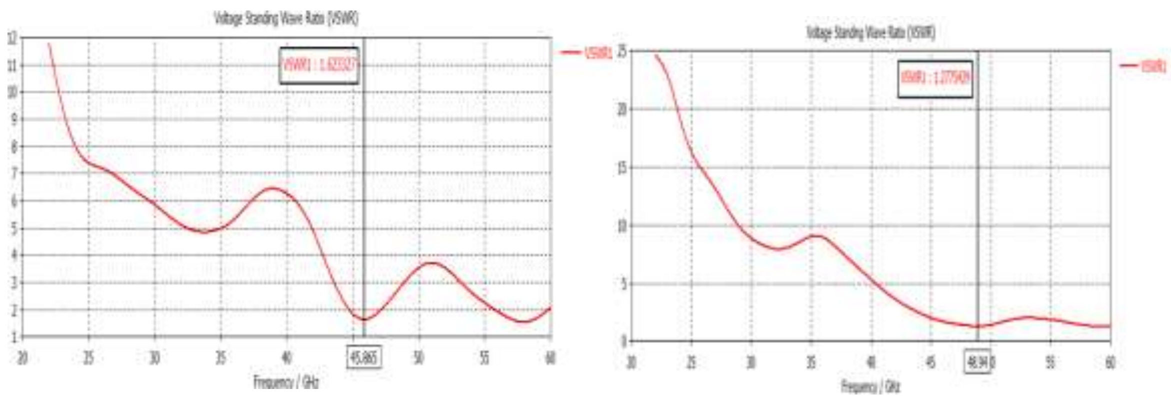

Figure6. Voltage standing wave ratio (VSWR). Designed by CST. The first left subplot relates to design A, whereas the second right subplot belongs to design B

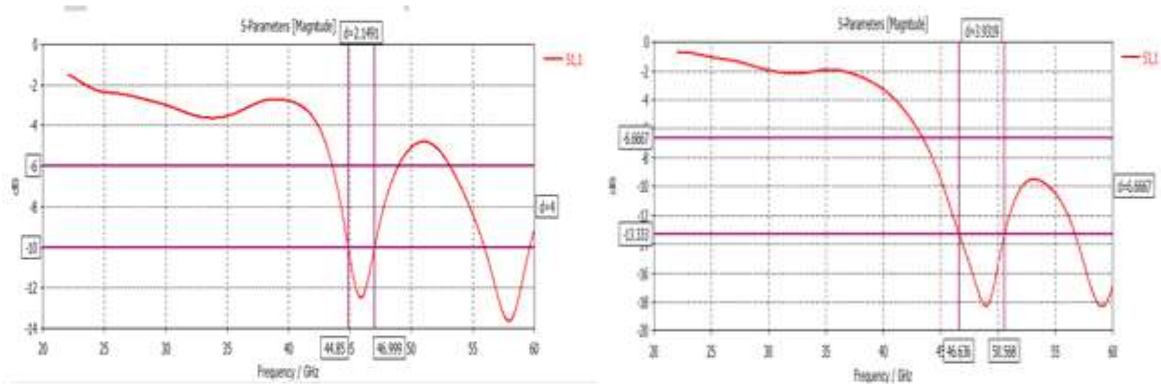

Figure7. Process of determining the bandwidth value based on the S_11 parameter Simulation conducted using CST software. The first left subplot relates to design A, whereas the second right subplot belongs to design B

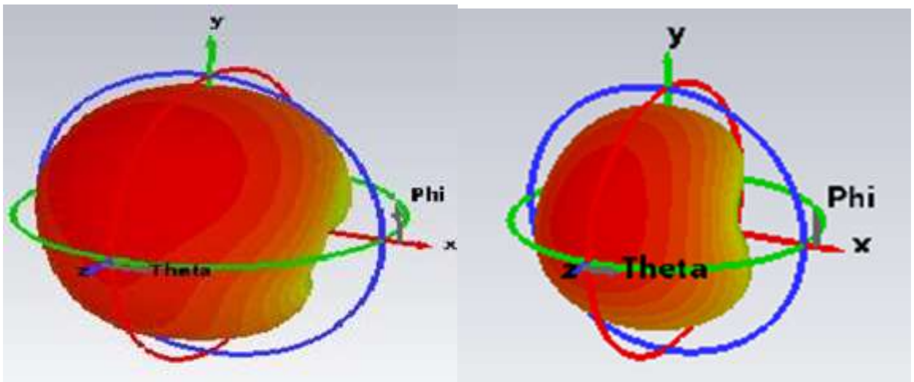

Figure8. Radiation pattern explains the gain G=6.620Bi with directivity D=7.240 dBi. Model by CST.The top left subplot corresponds to design A and the 2nd right subplot to design B

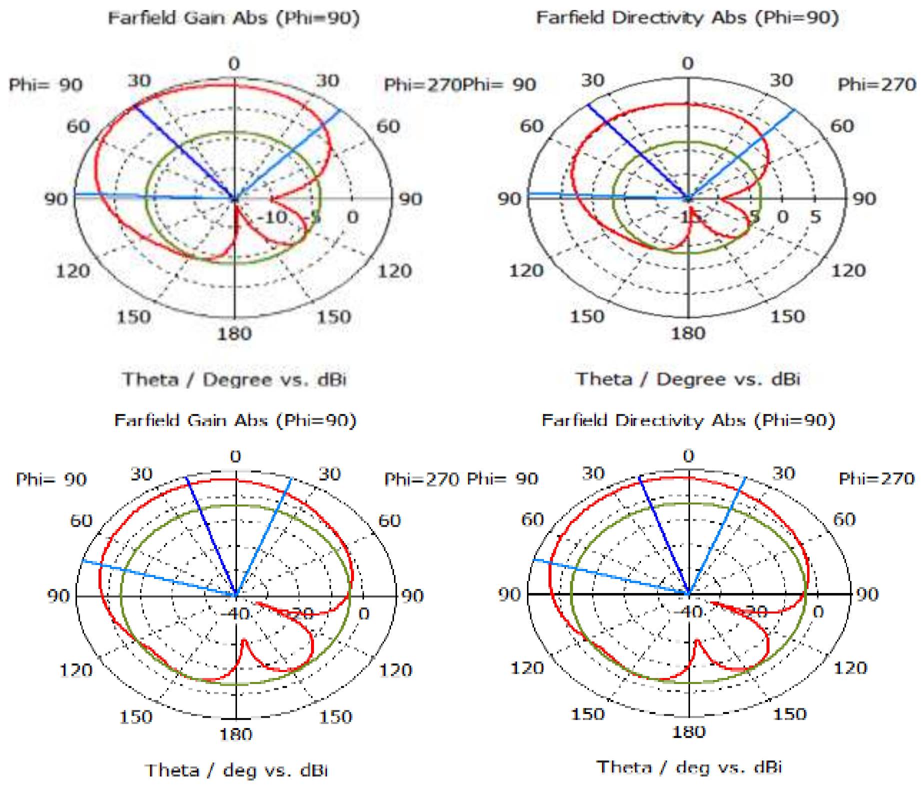

Figure9. Far field gain (on the left) and directivity (on the right), as determined byCST. The top row displays design A, while the bottom row showcases design B at a frequency of 28 GHz.

Table 7. The results of design A and design B

Parameter	G (dBi)	D (dBi)	BW (GHz)	$VSWR$	S_{11} (dB)	Efficiency η
Design (A)CDRA	4.596	5.288	2.1491	1.623327	−12.482729	86.9%
Compact design (B)CDRA	**6.620**	7.240	**3.9319**	1.2775429	-18.282729	**91%**

Therefore, the value of efficiency increased clearly as explained in the following equation

$\eta = G / D \cdot 100\ \% = 6.620/7.240 \cdot 100\ \% = 91\%$ (9)

The result of comparison between Design (A) and Compact Design (B) of the Cylindrical Dielectric Resonator Antenna (CDRA) highlights the superior performance of the compact design. Compact Design (B) achieves a higher gain of 6.620 dBi and directivity of 7.240 dBi, compared to 4.596 dBi and 5.288 dBi, respectively, in Design (A), resulting in stronger and more focused signal transmission. Additionally, the compact design offers a significantly wider bandwidth of 3.9319 GHz, nearly double the 2.1491 GHz of Design (A), making it better suited for broadband applications like 5G. It also demonstrates better impedance matching with a lower VSWR of 1.277 and a higher return loss ($S11$) of -18.28 dB, compared to 1.623 and -12.48 dB in Design (A). The efficiency of Compact Design (B) is also superior at 91%, compared to 86.9% in Design (A), showcasing better energy utilization. Overall, the compact design outperforms the standard design in all key parameters, making it an ideal choice for high-performance, next-generation wireless applications.

CONCLUSION AND FUTURE WORK

In this article, we designed a Cylindrical Dielectric Resonator Antenna (CDRA) optimized for 28 GHz to meet the demands of 5G and mm Wave communication systems. The antenna features a compact cylindrical geometry made from a dielectric material with a relative permittivity (ϵr=12.7), offering efficient field confinement and high radiation efficiency which was 91% as explained in Equation 9 and Table 7. With its wide bandwidth, the antenna supports high data rates, making it ideal for broadband applications, which was 3.9319 as shown in Table 7. The design also incorporated as well as high gain that arrived at 6.620 dBi, This was an optimized feeding mechanism for effective coupling, ensuring reliable performance. This CDRA design strikes a balance between performance and size, addressing the key challenges of compactness, efficiency, and bandwidth, making it suitable for integration into modern wireless systems. Future work can explore the use of different dielectric materials for tuning performance across other mm-Wave frequencies, develop advanced feeding structures for improved impedance matching, and extend the design to include beamforming capabilities for phased arrays. Additionally, real-world testing for performance under environmental conditions will provide valuable insights into its practicality for 5G, IoT, and satellite communications. However, in our overview, we can change the type of material and change the size and parameters of the antenna with different compact designs to get high performance and then to be good in many communication field.

However, to enhance the applicability of the compact Cylindrical Dielectric Resonator Antenna (CDRA), specific experimental validations and real-world testing scenarios are essential. Environmental testing under varying conditions, such as temperature, humidity, and mechanical stress, can confirm its robustness for outdoor applications like 5G base stations and satellite communication. Performance should also be evaluated in the presence of electromagnetic interference to ensure resilience in crowded frequency spectrums. Field trials in live 5G networks can demonstrate real-world benefits in terms of data rates, latency, and reliability, while integration into compact devices like smartphones, IoT sensors, and drones will validate efficiency within space-constrained environments. Additionally, tests in phased array and MIMO configurations can assess its potential for beamforming and spatial diversity. Long-term operational tests are critical to monitor durability and consistency over time. Future work could focus on exploring advanced dielectric materials for improved efficiency, scaling the design for other frequency bands, miniaturization techniques for even smaller dimensions, and leveraging AI-driven optimization for balancing complex performance trade-offs. These steps will provide a comprehensive evaluation of the CDRA's capabilities and readiness for deployment in cutting-edge communication systems.

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