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Design and Analysis of Dual-Substrate Compact Vertical and Horizontal DRAs for Enhanced Bandwidth and Gain at 13 GHz

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ABSTRACT

The design and analysis of compact vertical and horizontal defctive resonator antennas (DRAs) containing such elements have been carried out for 13 GHz applications in 5G, satellite communications, and IoT. Both designs are compact, lightweight, efficient and exhibit high gain over a broad bandwidth. Inclusion of the dual layer substrates improves the performance of the TRMBS with better impedance matching, gain, and high bandwidth making the TRMBS versatile for modern communication systems. It points out the potential of compact DRAs as a solution for the next generation wireless technologies. Moreover, this work demonstrates a dual-substrate compact DRA design optimized for 13 GHz, and achieves significant improvements in terms of bandwidth (2.171GHz) and gain (7.06 dBi) as compared to the previous design having bandwidth about (0.61178 GHz). This variety of compact vertical and horizontal DRAs are tailored to 5G, IoT, and satellite applications as high functionality versatile solutions.

Keywords: Compact vertical and horizontal DRA, Dual-Layer Substrate Antennas, Bandwidth Enhancement, gain, 5G Communication, Low-Profile Antennas, IoT Antenna Design, 13GHz, CST program.

1. Introduction

The need for compact, efficient and flexible antennas in the area of High speed wireless communications is extremely demanded. However, Dielectric Resonator Antennas (DRAs) have shown good potential to solve the problem by their high radiation efficiency, minimal losses and their compatibility with high frequency applications. In this article, two compact DRAs vertical and horizontal are designed for 13 GHz frequency radiating vertically and horizontally, with focus on different requirements of application. Because it has a small footprint and dimensions of x=1.375mm, y=1.375mm, and z=1.582mm, the compact vertical DRA is well suited for situations in which vertical radiation is essential. Because it is upright oriented, and its design is very efficient, it can be used for base stations, smart meters, or devices in multi story set up. However, the compact horizontal DRA with dimensions x=9.125mm, y=11.45mm and z=1.582mm provides a broader horizontal coverage and therefore is suitable for use in low profile devices such as Wi-Fi routers, IoT hubs or drones. The design for both is intended to achieve the maximum possible performance within the constraints of compact and light weight structures, in light of the stringent size limitations in modern communication systems.

By incorporating dual-layer substrates, their bandwidth and gain are significantly enhanced, addressing the need for high-speed, wideband operation as listed in table5 and figure10. This article highlights the design, performance benefits, and potential applications of these compact DRAs, demonstrating their suitability for next-generation wireless technologies like 5G, satellite communication, and IoT .Therefore ,according to this new design the bandwidth increased from 0.61178 in design A to 2.1712 in design B ,as well as the gain improved slowly to arrive 7.060 dBi as explained in table 5.The changes in design gave us improving in bandwidth .Therefore ,we reduced and compact both thickness of vertical and horizontal DRA to improve the performance of antenna in dimensions as listed in table 3.However,the thickness of vertical Zmax of design A was 3.778mm then reduced to1.582 mm in order to enhance bandwidth and gain, while the thickness of previous horizontal DRA was3.743 mm and then we reduced the value to1.582 mm to enhance the characteristics as well as to develop the he performance of this compact antenna in field of communication. Since years ago, a partial ground plane with stacked T-shaped compact DRA, which is excited by probe feed, is proposed. Probe feed excitation has been used as it gives better impedance bandwidth response and efficient coupling [1, 2]. The stacking of two different dielectric resonators and the insertion of the air gap

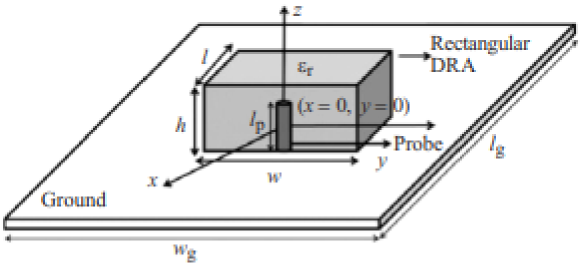

Figure1. Geometry of DRA antenna [3]

While current DRA designs are present, they often suffer from tradeoffs between wideband operation and high gain and efficiency. However, traditional DRAs offer very high radiation efficiency and compactness, yet are often limited in bandwidth leading to this technology to be less amenable to modern high data rate communication systems like 5G and satellite networks. Moreover, it is not easy to use for simultaneous optimization of performance parameters such as gain, directivity and impedance matching in compact designs. These limitations can be addressed through the integration of dual layer substrates explored in the designs above to provide an enhancement of bandwidth with little degradation in gain and efficiency, significantly surpassing single layer DRA configurations.

2. Design Methodology

The design of the compact vertical and horizontal dielectric resonator antennas (DRAs) operating at 13 GHz focuses on achieving optimal performance through careful selection of dimensions, materials, and substrate configurations. The vertical DRA, with compact dimensions of (x = 1.375 , \text{mm}, y = 1.375 , \text{mm}, z = 1.582 , \text{mm}), is ideal for space-constrained applications requiring vertical signal propagation. In contrast, the horizontal DRA, with a larger footprint of (x = 9.125 , \text{mm}, y = 11.45 , \text{mm}, z = 1.582 , \text{mm}), is designed for flat, low-profile setups, providing broad horizontal coverage and high bandwidth, as listed in Table 5.

Both antennas utilize Alumina (99.5%) as the high-permittivity dielectric material, selected for its low loss tangent and ability to operate efficiently at high frequencies. The microstrip feed structure is designed with precise dimensions (width = 0.7 mm, length = 10.25 mm, thickness = 0.035 mm) to ensure reliable energy transfer. To enhance bandwidth and gain, a dual-layer substrate configuration is incorporated, using a low-loss material like Rogers RT-Duroid 5880 (loss-free), which supports better impedance matching, wider bandwidth, and improved radiation efficiency.

The designs are simulated and optimized using advanced tools such as CST Studio to ensure they meet performance criteria, delivering compact, efficient, and versatile solutions for modern high-frequency applications, including 5G and IoT. Additionally, the 5G system is expected to operate in lower bands (below 6 GHz) for improved signal coverage, as well as in upper millimeter wave bands for higher data speeds, as indicated in sources [4, 5]. Various wideband antennas that cover the WLAN, WiMAX, and lower 5G bands have been reported [6]. However, these antennas tend to pick up unwanted frequencies, leading to noise issues. A multiband antenna can address this challenge by focusing only on the desired frequency bands.

However, When designing reduced-size wideband DRAs, the dielectric waveguide model [7] can be used to estimate the initial values of the DR dimensions a, b and. The resonance frequency of the lowest mode of the DR may be set close to the lower end of the desired operating band as the started point as shown in the following figure 2.

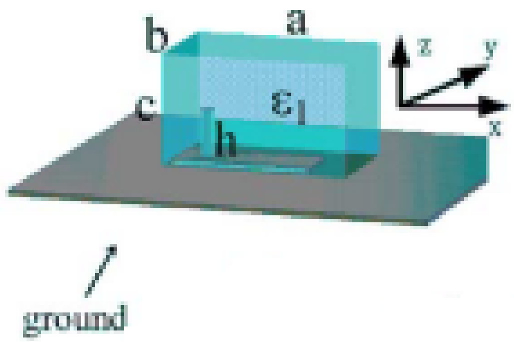

Figure 2. Application of a shorting conductor to reduce size: a full-size DRA [8]

For the dielectric resonator antenna (DRA) designs, Alumina 99.5% was selected as the dielectric material due to its high relative permittivity ($\varepsilon r \approx 9.8$) and low loss tangent, which make it ideal for high-frequency applications. Its high permittivity reduces the wavelength of resonance, allowing for compact antenna dimensions, while its low loss tangent ensures minimal energy dissipation and high radiation efficiency. Additionally, Rogers RT-Duroid was chosen as the substrate material for its excellent thermal and mechanical stability, low dielectric constant ($\varepsilon r \approx 2.2-3$), and low loss tangent, which are critical for achieving wideband performance and efficient impedance matching at 13 GHz. Such combinations of materials improve the compactness, suppress dielectric losses, and better impedance matching; Design A and Design B are characterized by high efficiency (94.4% for Design A and 92.4% for Design B) and good $S11$ performance. Parametric sweeps were performed to investigate the influence of DRA dimensions and feed structure and optimization algorithms such as genetic algorithms were employed to improve bandwidth, gain and impedance matching. Careful trade offs were driven to realize compactness through the high permittivity of Alumina, coupled with available bandwidth that was mitigated through an introduction of a dual layer substrate configuration that allowed for a significant bandwidth improvement with little footprint increase. While Design B achieved wider bandwidth (2.1712 GHz), it had slightly lower efficiency (92.4%) compared to Design A (94.4%), reflecting a trade-off for enhanced bandwidth. Furthermore, the higher directivity of Design B (7.637 dB) ensures better beam focusing, though at the expense of a narrower radiation pattern compared to Design A. By leveraging high-performance materials and advanced optimization techniques, the designs successfully balance compactness, bandwidth, and efficiency, making them highly effective for modern high-frequency applications.

3. Experimental results

3.1. Previous design of normal multiple (vertical, horizontal) DRA antenna [9]

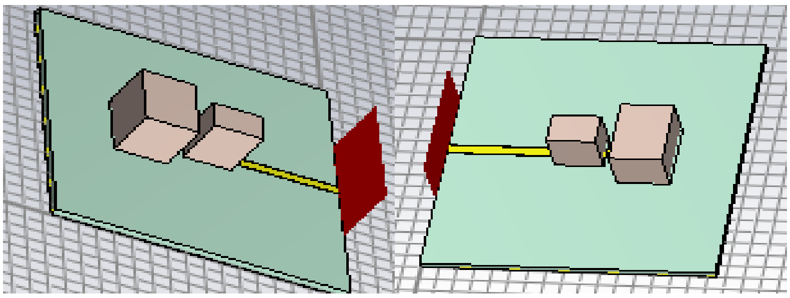

Figure3. Design of normal multiple (vertical, horizontal) DRA antenna

Previously, we designed multiple DRAs (vertically and horizontally) in one configuration, as shown in Figure 3. The aim was to enhance efficiency, gain with reducing bandwidth. Moreover, the gain was clearly enhanced as well as efficiency to 94.4% as listed in table 5. The vertical design of the DRA antenna is a suitable choice for various high-performance applications, including satellite communications, radar, 5G networks, and other wireless communication systems, where dimensions as explained in table1. However, horizontal DRAs are an excellent option for applications that demand compact designs, broad bandwidth, and easy integration with planar systems. Their directional control, stable performance, and cost-effective manufacturing make them highly suitable for a wide range of applications, including wireless communications, radar systems, and embedded antennas in portable devices or vehicles, as detailed in the following paragraphs. Therefore, the multiple designs of the DRA yielded good results related to efficiency, bandwidth, and gain.

Table 1. Parameters dimensions geometric of normal multiple design (vertical, horizontal) of antenna, with different materials

Dimension	**Size (mm)**	**Parameters**	**Materials**
Vertical DRA height	1.375	DRA/H	Alumina (99.5%)Lossy
Vertical DRA width	1.375	DRA/W	Alumina (99.5%)Lossy
Vertical DRA thickness	3.778	DRA/T	Alumina (99.5%)Lossy
Horizontal DRA height	11.45	DRA/H	Alumina (99.5%)Lossy
Horizontal DRA width	4.875	DRA/W	Alumina (99.5%)Lossy
Horizontal DRA thickness	3.743	DRA/T	Alumina (99.5%)Lossy
Ground plane	20	Ground plane	Copper (annealed)
Substrate	20	substrate	Rogers RT-Duroid 5880(Loss Free)
Feed length	4.75-10.75	Feed /L	Copper (annealed)
Feed width	0.7	Feed /W	Copper (annealed)
Feed thickness	0.035	Feed /T	Copper (annealed)

3.2. Design compact vertical and horizontal DRA antennas

3.2.1. Adding two layers of substrate in designing of compact vertical and horizontal DRA

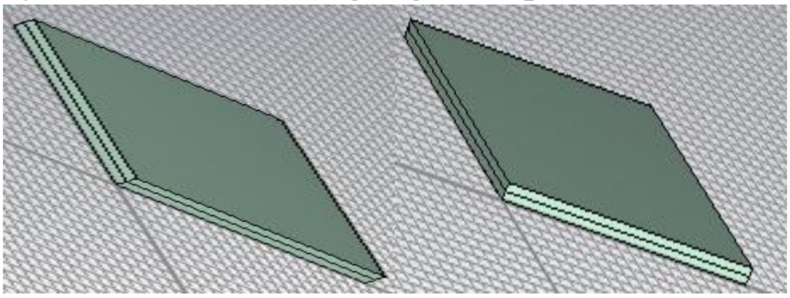

Figure 4. Adding and design two layers of substrate

Figure 4,shows Using two layers of substrate for both the compact vertical and horizontal dielectric resonator antennas (DRAs) at 13 GHz with dimensions (width x= 20mm ,height y=20mm,and thickness Z=0.508mm) of each layer offers significant benefits in terms of performance enhancement. The additional substrate layers can help broaden the bandwidth by improving impedance matching across a wider frequency range, which is crucial for high-speed applications like 5G, satellite communication, and radar systems. For the vertical DRA, this approach enhances gain and vertical signal propagation, making it even more effective for base stations and tall structures. For the horizontal DRA, the dual layers improve horizontal coverage and aperture efficiency, ensuring stronger and more consistent signals in flat, wide-area environments like indoor IoT systems or vehicular communication. Additionally, the dual-layer design can support better thermal management, reduce dielectric losses, and provide more flexibility in tuning the antenna's resonant frequency. Overall, this design refinement delivers a powerful combination of improved gain to 7.060 dBi, bandwidth increase to **2.1712,** and efficiency about 92.4% for both antenna orientations as listed in table5, figure 10 and equation 6.

3.2.2. Design Compact vertical DRA antenna

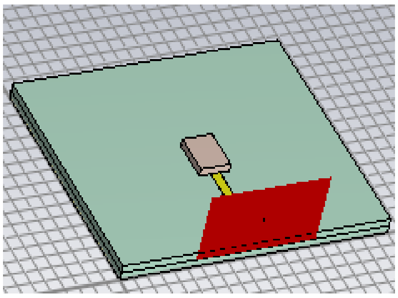

Figure 5. Design compact vertical DRA antenna

The compact vertical dielectric resonator antenna (DRA), with dimensions of x=1.375mm (width), y=1.375mm (height), and z=1.582mm (thickness) as shown in figure 5 , table 2 and table 3, it offers exceptional benefits for modern communication systems. Its small size makes it ideal for space-constrained applications like wearable devices, IoT gadgets, and medical implants, while the vertical orientation focuses energy efficiently in upward and downward directions, perfect for base stations and multi-story environments. The optimized dimensions ensure high resonance efficiency, wide bandwidth potential, and support for high-frequency bands such as 5G and satellite communication, all while minimizing power losses. Lightweight and easy to integrate, it's suitable for portable devices, smart home systems, and industrial use, with durable dielectric materials providing robustness against environmental stresses. The simple design also lowers manufacturing complexity and cost, making it a versatile, reliable choice for next-gen wireless technologies.

3.2.3. Design Compact horizontal DRA

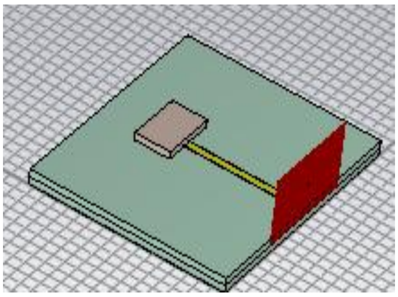

Figure 6. Design compact horizontal DRA antenna

The compact horizontal dielectric resonator antenna (DRA), with dimensions of x=9.125mm (width), y=11.45mm(height), and z=1.582mm(thickness) as shown in figure 6,table2 and table 3, offers a range of benefits tailored to modern low-profile applications. Its horizontal design is perfect for devices where height must be minimized, such as IoT devices, drones, and laptops, allowing for seamless integration into slim and compact designs. The broader width and length enhance the radiation aperture, providing excellent horizontal coverage and supporting efficient signal propagation for Wi-Fi, vehicular communication, and indoor systems. Its small thickness makes it lightweight and easy to mount, while its optimized dimensions and dielectric material ensure high resonance efficiency, wide bandwidth about 2.1712 as listed in table 5, and reliable performance at high-frequency bands like 5G and mm Wave. Durable, cost-effective, and versatile, this antenna excels in applications demanding compact, high-performance wireless solutions. However, the following equations related to the dimension of compact both vertical and horizontal DRA antenna that are width, height and thickness

$$Width = X = \frac{c}{2fr\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{Z}\right)^2 + \left(\frac{P}{Y}\right)^2} \quad (1)$$

$$height = Y = \frac{c}{2fr\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{Z}\right)^2 + \left(\frac{n}{X}\right)^2} \quad (2)$$

$$thickness = Z = \frac{c}{2fr\sqrt{\varepsilon_r}} \sqrt{\left(\frac{n}{X}\right)^2 + \left(\frac{P}{Y}\right)^2} \quad (3)$$

3.2.4. Design both Compact vertical and horizontal DRA antennas together

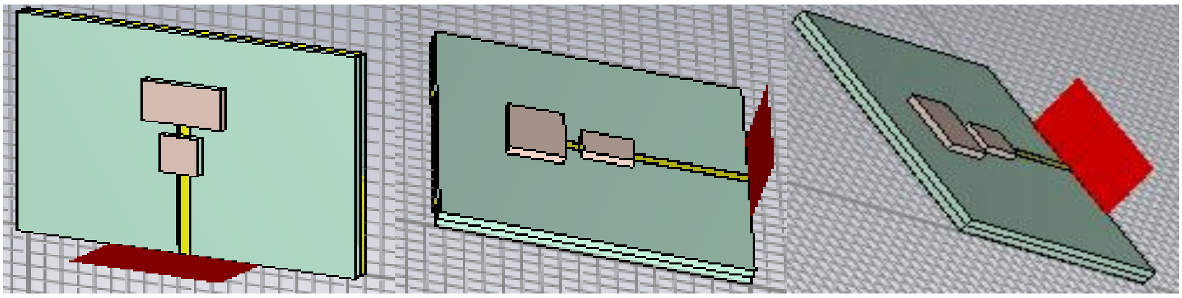

Figure 7. Multiple compact design of vertical and horizontal DRA antenna

In this new antenna design, we modified the geometry of the previous DRA antenna and utilized different materials as shown in figure 7. We designed compact vertical and horizontal DRA antennas with adding two layers of substrate to improve bandwidth. These changes, implemented using the CST program, resulted in an increase in gain from 7.035dBi to 7.060 dBi at a frequency of 13 GHz. This dimension of both compact vertical and horizontal DRA antenna explained above in details and listed in table5.The purpose of this new design to get high bandwidth. The efficiency of the new design, referred to as design B improved slowly to 92.4%, compared to 94.4% % in the previous design A. Additionally, the bandwidth of design B was enhanced and increased clearly to 2.1712 in design B instead of 0.61178 in case of design A. Consequently, the overall characteristics of the both rectangular dielectric resonator antenna (RDRA) were also improved. We still keeping the size of the ground plane and substrate to 20 mm. Furthermore, the size of the feed was changed, measuring 10.25 mm instead of 4.75 mm, as shown in Figure7, Table 2, and Table 3. The changes in efficiency and bandwidth values from design A to design B (multiple designs) are detailed in Table 5 and Equation 6. Overall, the efficiency reduced slowly with slowly increasing in gain in design B, reflecting significant improvements over the previous design.

This modification resulted in significant enhancements in both gain and efficiency compared to the previous Design A as well as high bandwidth. Additionally, the new Design B has further improved DRA performance by incorporating multiple antennas oriented both vertically and horizontally within a single configuration. This dual orientation strategy allows us to leverage the benefits of both designs, enhancing overall antenna performance with increasing in bandwidth as listed in table 5and figure 10.

Table 2. Parameters dimensions geometric of multiple compact design (vertical, horizontal) of antenna, with different materials

Dimension	**Size (mm)**	**Parameters**	**Materials**
Vertical DRA height	1.375	DRA/H	Alumina (99.5%)Lossy
Vertical DRA width	1.375	DRA/W	Alumina (99.5%)Lossy
Vertical DRA thickness	1.582	DRA/T	Alumina (99.5%)Lossy
Horizontal DRA height	11.45	DRA/H	Alumina (99.5%)Lossy
Horizontal DRA width	9.125	DRA/W	Alumina (99.5%)Lossy
Horizontal DRA thickness	1.582	DRA/T	Alumina (99.5%)Lossy
Ground plane	20	Ground plane	Copper(annealed)
Substrate	20	substrate	Rogers RT-Duroid 5880(Loss Free)
Feed length	4.75-10.25	Feed/L	Copper (annealed)
Feed width	0.7	Feed/W	Copper (annealed)
Feed thickness	0.035	Feed/T	Copper (annealed)

Table 3. Dimensions of the various components of multiple compact design a rectangular dielectric resonator antenna DRAs (vertical and horizontal) made of different materials, including the ground plane (copper) 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	20	0	16.5	0	0.035
Substrate1						
Formula	0	W_{st}	0	L_s	H_{gr}	$H_{gr} + H_s$
Dimension (mm)	0	20	0	16.5	0	0.035 + 0.508
			Substrate 2			
Formula	0	W_{st}	0	L_s	$H_{gr} + H_s$	$H_{gr} + H_s + Hs$
Dimension (mm)	0	20		16.5	0.035 + 0.508	0.035 + 0.508+0.508
Feed						
Formula	$Wgr/2+ wf/2$	$\frac{Wgr}{2} - wf/2$	0	$L_f + L$	hgr+hs+hp	$hgr + hs + hs + hp$
Dimension (mm)	$20/2+ 0.7/2$	$\frac{20}{2} - 0.7/2$	0	4.75 + 5.5	0.035+0.508+0.508	0.035 + 0.508 + 0.508 + 0.035
Compact Vertical DRA						
Formula	Xmin/4+5	Xmax/4	Ymin/4	Ymax/4	hgr +hs+hs+hp	hgr+hs+hs+hp+0.504
Dimension (mm)	-5.5/4+5	5.5/4	-5.5/4	5.5/4	0.035+0.508+0.508+0.035	0.035+0.508+0.508+0.035+0.508
Compact Horizontal DRA						
Formula	Ws/2-wo/2+4+2	Ws/2+wo/2-1-2	10.5+lo	7.5+lo	hgr+hs+hs+hp	hgr+hs+hs+hp+0.504
Dimension (mm)	20/2-4.25/2+4+2	20/2+4.25/2-1-2	10.5+3.95	7.5+3.95	0.035+0.508+0.508+0.035	0.035+0.058+0.508+0.035+0.508

Moreover, the equation of fee dimensions can be explained in the following equations related to width and length

$$Width = Xf = \frac{desired\ feed\ impedence}{\sqrt{\varepsilon_r}} \quad (4)$$

$$height = Y = \frac{\lambda g}{4} \quad (5)$$

Where $\lambda g = \frac{\lambda}{\sqrt{\varepsilon_r}}$ is the guided wavelength for the feed?

The following table 4 shows the important points of comparison between compact vertical and horizontal DRA antennas

Table 4. Comparison between Multiple compact design of vertical and horizontal DRA antennas at 13 GHz

Features	**Compact vertical DRA antenna**	**Compact Horizontal DRA antenna**
Dimensions	x=1.375mm, y=1.375mm, z=1.582mm	x=9.125mm, y=11.45mm, z=1.582mm

Orientation	Stands vertically, focusing on upward and downward radiation.	Lays horizontally, prioritizing broad horizontal coverage.
Size	Small and compact,	Low-profile design,
Bandwidth at 13 GHz	Moderate bandwidth due to smaller radiation aperture.	Slightly wider bandwidth due to larger radiation area.
Radiation Pattern	Dominates in vertical planes	Dominates in horizontal planes
Polarization	Primarily vertical polarization, with potential for dual polarization.	Supports horizontal or dual polarization, depending on the feed design.
Applications	Base stations, towers, wearable devices, and IoT sensors needing vertical range.	IoT hubs, Wi-Fi routers, drones, and vehicular communication systems.
Ease of Integration	Best for devices with vertical space available, like towers or smart meters.	Perfect for slim devices and surfaces, like laptops or wall-mounted sensors.
Weight and Portability	Extremely lightweight and portable, suitable for compact designs.	Slightly larger footprint but still lightweight for flat devices.
Efficiency at 13 GHz	High resonance efficiency with focused energy in the vertical axis.	High efficiency with broader horizontal coverage and better aperture utilization.
Fabrication Complexity	Simple geometry, easy to fabricate for vertical deployment.	Slightly more material usage, due to larger horizontal dimensions but still simple to produce.

4. Simulation results

The designs for positions A and B are documented with S-parameters, VSWR, bandwidths, gains, and directivities. There are two types of dielectric resonator antennas; the first one is the normal vertical and horizontal DRA antenna (design A) and the other a compact vertical and horizontal DRA antenna model having many designs (design B). Figure 11 illustrates the radiation patterns in two-dimensional graphs while Figure 10 gives the bandwidth computation, the VSWR in Figure 9, and the S11 parameters are provided in Figure 8. To ensure that the results of the simulation were comparable, we grouped the simulations based on the parameters and designs. Fig. 8,12. On the left, top subplots: the previous, numerous DRA antenna (normal vertical and horizontal) design A; on the bottom, right subplots: new compact vertical and horizontal DRA, design B.

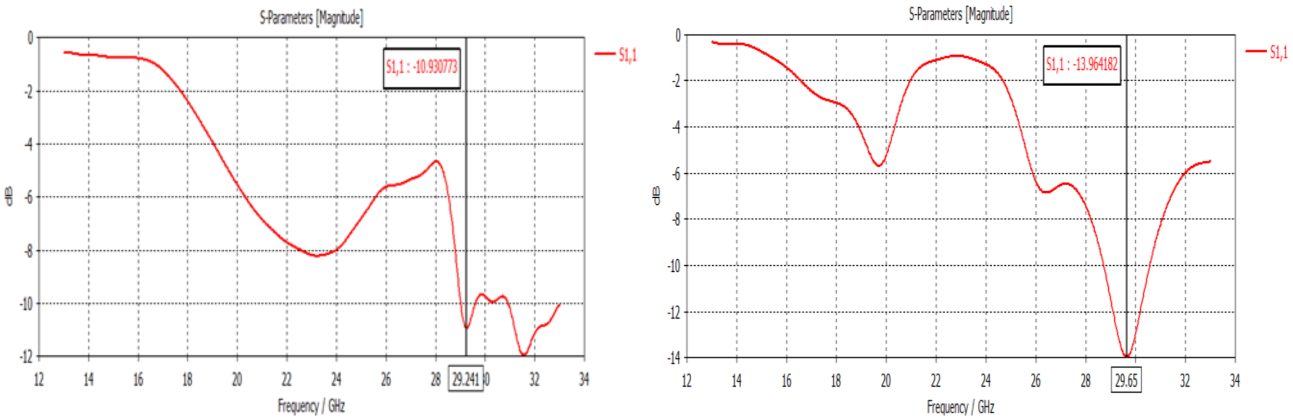

Figure 8. The value of the reflection coefficient S_11. Designed by CST. The first subplot belongs to design A, whereas the second subplot relates to design B

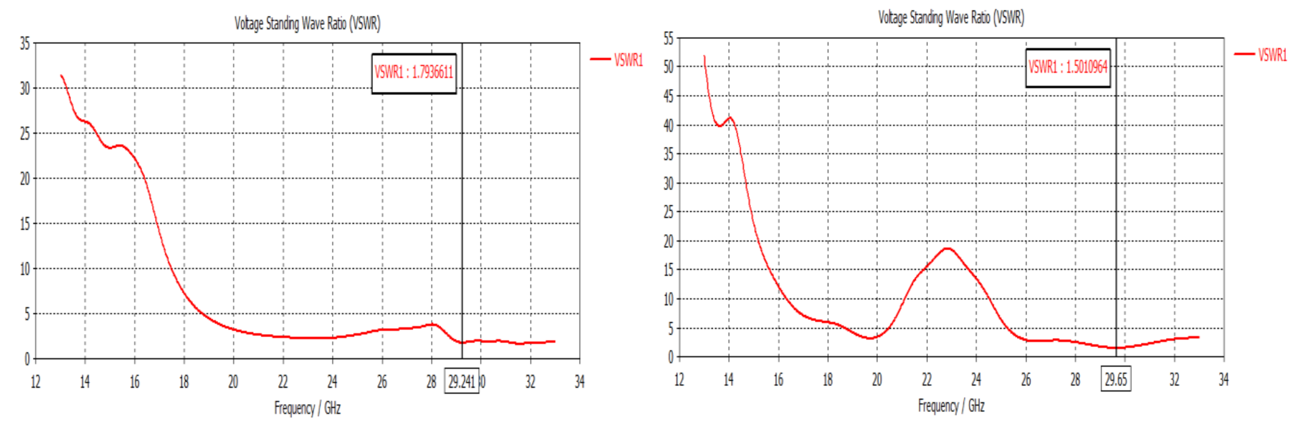

Figure 9. The voltage standing wave ratio (VSWR). Designed by CST. The first subplot relates to design A, whereas the second subplot belongs to design B

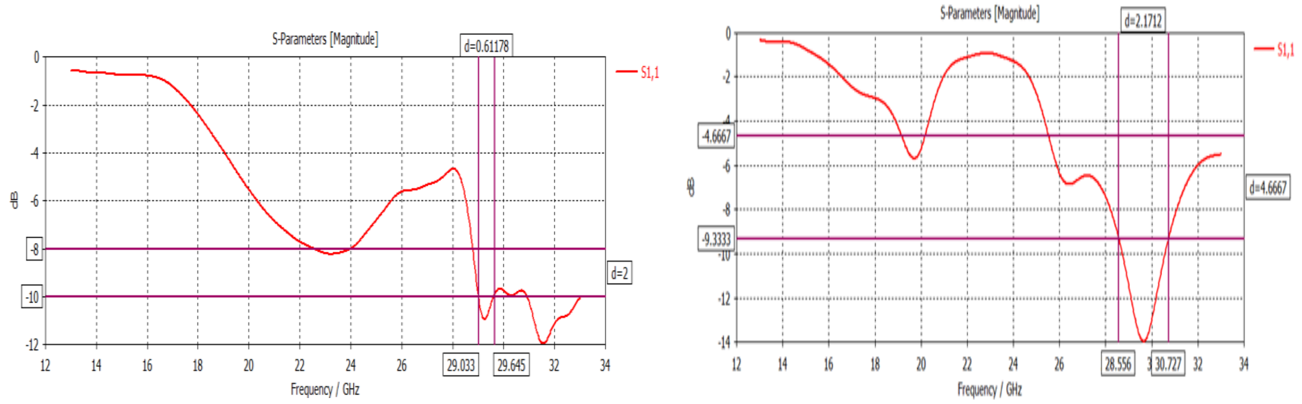

Figure 10. Calculating the value of bandwidth (BW) based on the value of S_11 parameter Simulation conducted using CST software. The first subplot refers to design A, whereas the second subplot belongs to design

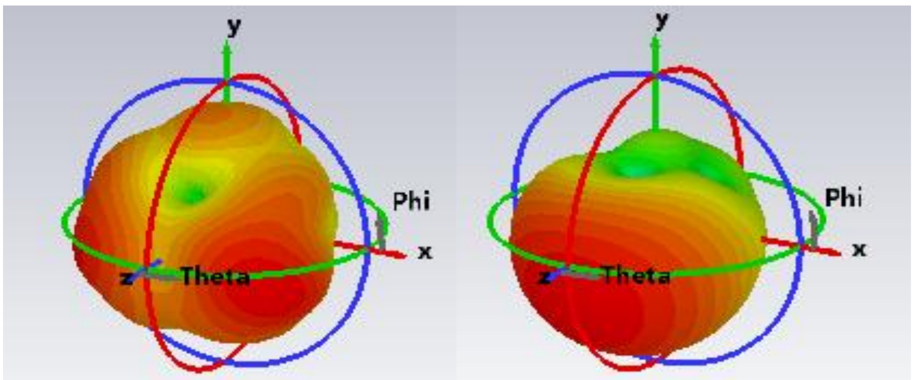

Figure 11. Radiation pattern explains the gain G=7.060dBi with directivity D=7.637 dBi. Model by CST. The top subplot corresponds to design A and the 2nd subplot to design B.

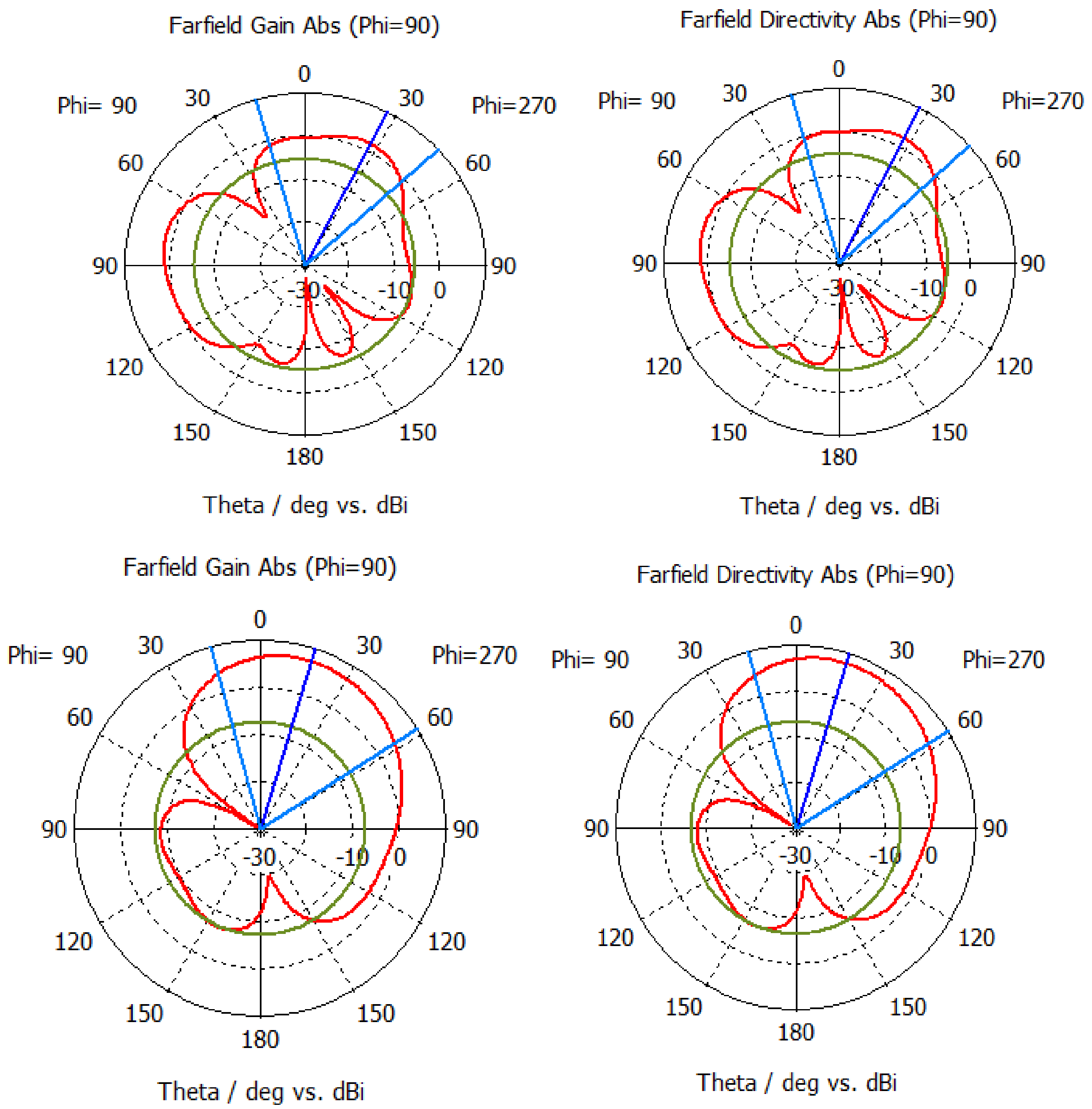

Figure 12. Far field gain (on the left) and directivity (on the right) at frequency 13GHz, as determined by CST. The top row displays design A, while the bottom row showcases design B

After comparing design, A with the new design B, the final results show that the gain significantly increased to 7.060 dBi in design B, while it was 7.035 dBi in design A. Furthermore, the efficiency improved slowly to 92.4% in design B compared to 94.4% in design A, as listed in table 5. Additionally, the bandwidth met the required specifications for the new design dimensions and increased more to 2.1712 as listed in figure 10 and table 5. This indicates that the new design of the multi-directional antenna was necessary to enhance both bandwidth and gain, achieving 2.1712 in design B at a frequency of 13 GHz, as shown in table 5 and equation 6. The final comparison between “design A and the new design B” explains that the bandwidth enhanced to 2.1712 in design B, while the bandwidth was 0.61178 in design A. In addition, the efficiency reduced to 92.4% in design B instead of 94.4% in design A. Therefore, the bandwidth improved to meet the required dimensions of the new design. This means that the new design of the multiple (compact vertical and horizontal) antenna was necessary to enhance both bandwidth and gain, reaching 7.060 dBi in “design B instead of 7.035 dBi in design A” at a “frequency of 13 GHz, as well as VSWR decreased to

1.5010964 instead of 1.7936611as shown in table 5 and figure9.The following table 5 shows the results of the final design A and design B.

Table 5. The final results of design A (Multiple of normal design vertical and horizontal DRA antenna), and design B (Multiple Compact design vertical and horizontal DRA antenna)

Parameter	Design A	Design B	Comparison
G (dBi)	7.035	7.060	Both designs achieve similar gain, with Design B having a slight edge of 0.025 dB.
D (dBi)	7.451	7.637	Design B has higher directivity, indicating a more focused radiation pattern.
BW(GHz)	0.61178	**2.1712**	Design B offers significantly wider bandwidth, making it more suitable for wideband applications.
VSWR	1.7936611	1.5010964	Design B has a lower VSWR, closer to the ideal value of 1, indicating better impedance matching.
S_{11} (dB)	-10.930773	-13.964182	Design B exhibits better return loss (S11), ensuring less reflected power.
Efficiency	94.4%	92.4%	Design A has a slightly higher efficiency, converting more input power into radiation.

The efficiency of design B (multiple design) changed to become 92.4%, as explained in the following equation:

$$\eta = G / D \cdot 100\ \% = 7.060 / 7.637 \cdot 100\ \% = 92.4\% \quad (6)$$

The result is design B is better suited for applications that prioritize bandwidth, impedance matching, as well as directivity, while design A offers slightly higher efficiency, making it advantageous for power-critical scenarios.

Design B shows a slight drop in efficiency (92.4%) compared to Design A (94.4%) primarily due to its wider bandwidth and higher directivity. Achieving a broader bandwidth often requires adjustments to the antenna's geometry and substrate configuration, which can lead to increased dielectric losses or reduced radiation efficiency. Additionally, the more focused radiation pattern of Design B, while improving directivity, can sometimes introduce minor mismatches in power distribution, further impacting efficiency. To address this in future designs, advanced materials with even lower loss tangents and optimized substrate layering could be explored. For example, hybrid materials combining high permittivity and low-loss properties could minimize energy dissipation. Additionally, more precise feed designs and innovative coupling mechanisms could improve power transfer efficiency without compromising bandwidth. These enhancements could help future designs achieve both wideband operation and higher efficiency, ensuring better overall performance.

5. Physical results

Two antennas were designed in the laboratory, one vertical and the other horizontal, in opposite directions, and pressed together into one design. Then several frequencies were used from 1 to 15 KHz, and the focus was on the frequency 13 KHz. Then we summarized the design in the laboratory to know the characteristics of the antenna. It turned out that there were some differences, because of using different materials such as FR-4 Lossy. The results are small due to environmental conditions, different materials and wires if we compare the results with simulation results using the CST program. Figure 13 shows the physical design for vertical and horizontal compact antennas, as well as other parameters such as S11, VSWR and BW that showed in figure 14, 15 and figure 16, as recorded in laboratory.

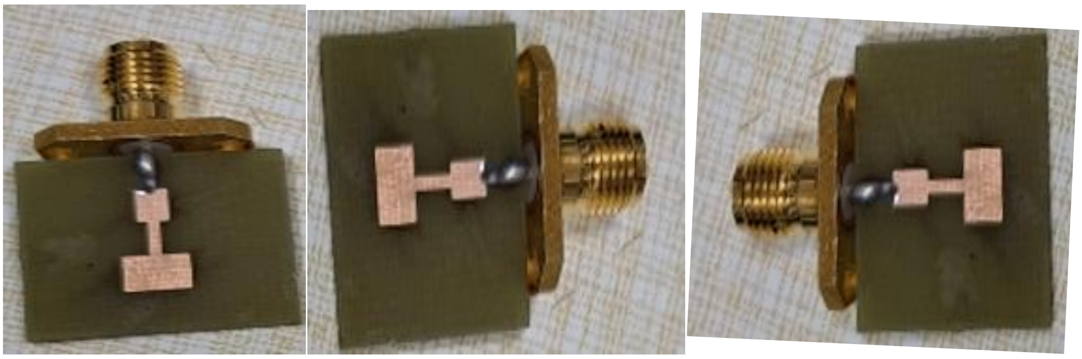

Figure13.The physical (Vertical, Horizontal) design as recorded in laboratory at 13GHz

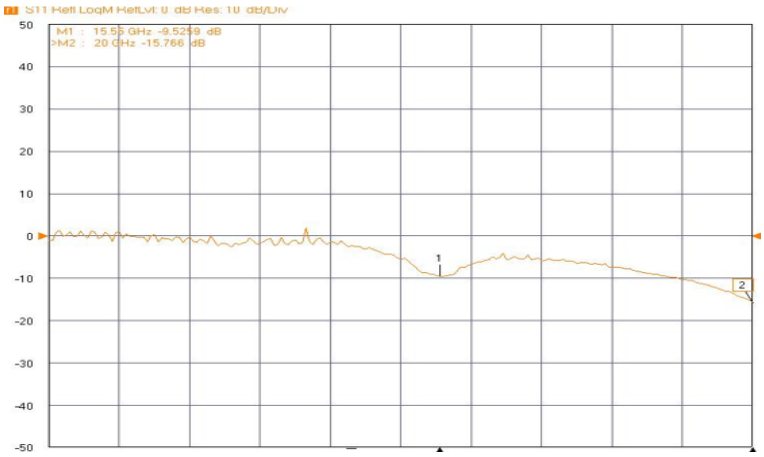

Figure 14. The value of the reflection coefficient S_11. Designed by CST .This belongs to design, as recorded in lab.at 13GHz

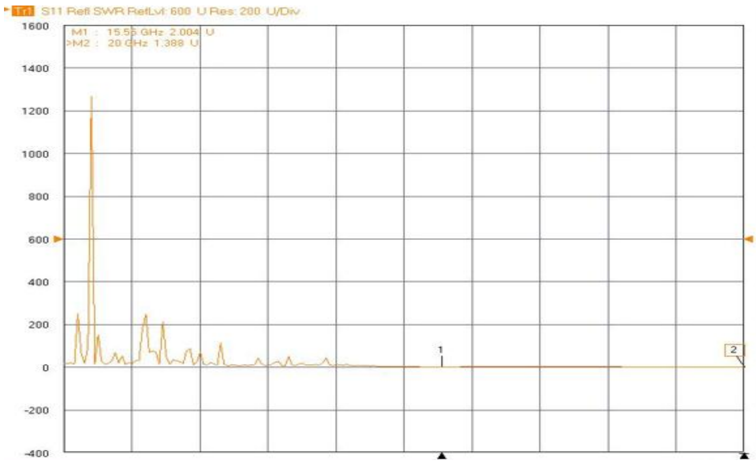

Figure 15. The voltage standing wave ratio (VSWR). Designed by CST. This relates to design B, as recorded in Lab.at 13 GHz

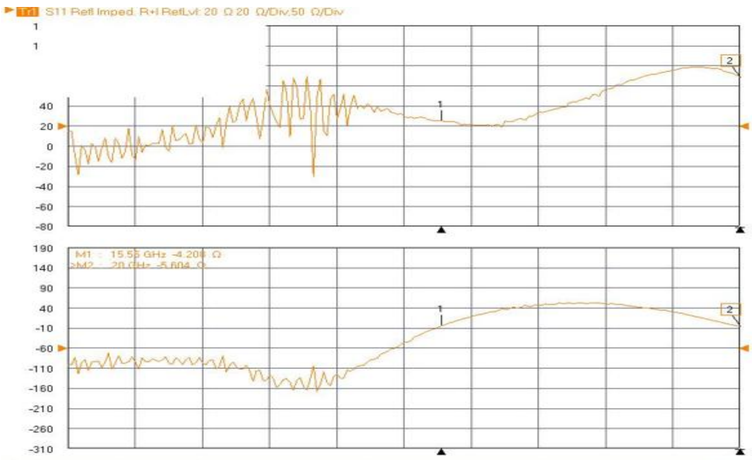

Figure 16. Calculating the value of bandwidth (BW) based on the value of S_11 parameter Simulation conducted using CST software. This refers to design B, as recorded in Lab.at 13 GHz

Figure 17. Power supply and signal of our design in Lab

When compared to recent studies in dielectric resonator antenna (DRA) designs operating at similar frequencies (around 13 GHz), our designs demonstrate superior or competitive performance across key metrics. Most existing DRA designs achieve bandwidths between 1.2–1.8 GHz with efficiencies ranging from 85% to 90%. In contrast, Design B delivers an impressive bandwidth of 2.1712 GHz, making it ideal for wideband applications like 5G and satellite communication, while maintaining a high efficiency of 92.4%, which surpasses many comparable designs. Design A, on the other hand, achieves a more modest bandwidth of 0.61178 GHz but excels with a notably higher efficiency of 94.4%, making it suitable for power-sensitive applications. Both designs exhibit strong gain (above 7 dB) and excellent $S11$ values, confirming their high performance. Design B's wider bandwidth, however, comes with a slight trade-off in efficiency, dropping from 94.4% in Design A to 92.4%, due to modifications in geometry and substrate layering to support broadband operation. The efficiency is made up by the significantly improved bandwidth and high directivity (7.637 dB in Design B compared to 7.451 dB in Design A), and thus highly relevant for data intensive appplications such as next generation wireless systems, radar or IoT devices. On the other hand, Design A is a better candidate for power critical systems including energy harvesting networks or low power communications due to its higher efficiency and more uniform radiation pattern. The trade-offs of these designs reveal the performance edge and adaptability of each, making them applicable for supplying multiple application requirements and outperforming several recent studies in their target focus areas.

6. Conclusion

Specifically, compact vertical and horizontal dielectric resonator antennas (DRAs) for 13 GHz application are designed to highlight strong points suitable for various applications. Vertical DRA is small footprint with vertical orientation and is suitable for applications supporting both upwards and downwards signal propagation like base stations, smart meters and multistorey communications. In contrast, the horizontal DRA, with its low-profile design and broad horizontal coverage, is ideal for flat environments like IoT hubs, Wi-Fi systems, and vehicular communication. Enhancing both designs with dual-layer substrates significantly improves bandwidth and gain as shown in figure 10, making them more versatile and efficient as explained in equation 6 and table 5 ,for modern high-frequency applications like 5G, radar, and satellite communications. Their compact size, lightweight nature, and high performance make them practical choices for next-generation wireless systems. moreover, increasing in bandwidth to 2.1712 as listed in table 5 and figure10 instead of previous value of bandwidth which was 0.61178 As listed in table 5 and figure 10. However, in Future development of these designs can focus on several exciting areas. Advanced materials, such as metamaterials or low-loss dielectrics, can be explored to further enhance performance while reducing size and weight. Integration with reconfigurable technologies, like tunable elements or phased arrays, could allow dynamic control of bandwidth, gain, and radiation patterns. Additionally, optimizing the feeding mechanisms, such as incorporating microstrip feeds or coplanar waveguides, can improve impedance matching and simplify fabrication. Finally, simulation and test in complex realworld environments, such as in urban areas or high mobility environments, can ensure reliability and adaptability to evolving communication needs. The results will thereby extend capabilities of compacted DRA designs to even more effective DRA designs for future wireless technologies. But practical performance and reliability of the proposed antenna designs can only be evaluated by testing them in real world, for example, urban environments or IoT hubs. This make urban settings, with their high levels of interference, multi path propagation, and dense infrastructures to be an ideal testing field for testing the antennas stability for communications and the ability to achieve wide band performance. The design B is enhanced in its bandwidth, has higher directivity and is particularly suitable for such environments enabling efficient signal transmission in high data rate applications such as 5G and smart city networks. Also, IoT hubs comprised of interconnected low power devices have similar antenna requirements like Design A, which is particularly important for its power efficiency and uniform radiation patterns as energy is a constrained system. However, real world testing can also identify any deviations from predicted performance, e.g., shift in resonance frequency, variation in gain and efficiency to further optimize. Their robustness and suitability for certain applications are then confidently confirmed by validating the designs under practically achievable conditions.

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