

substitutes for metallic cavities at high frequencies. At the early stage, their use as radiating elements was neither intended nor anticipated. DRAs began as a radiating extension of typical dielectric resonators in which the intrinsic resonant modes are deliberately permitted to leak into free space. DRA is a microwave antenna made of a ceramic block of materials with greater permittivity values that perform well at high frequencies. When the dielectric resonator is not surrounded by a metal cavity and is properly excited, it radiates efficiently, transforming into a radiator.

Following extensive research, R.D. Richtmeyer theoretically established in 1939 that non-metalized objects can resonate and operate as antennas, which are known as Dielectric Resonator Antennas. The concept of the dielectric resonator antenna (DRA) emerged unexpectedly several decades later. In the early 1980s, engineers working with dielectric resonators in cavity-based microwave circuits observed unintended radiation when these structures were not completely enclosed by metallic housing. Initially it was considered parasitic leakage turned out to be a repeatable and controllable radiating behavior. The radiation phenomenon was surprising because dielectric resonators were known for characteristics that traditionally suppress electromagnetic radiation—namely, a high dielectric constant, low loss tangent, and strong electromagnetic field confinement. Yet, when partially exposed, these same properties enabled the resonator to couple energy into free space and support well-defined radiating modes. This resulted in efficient radiation with relatively wide bandwidth, surpassing the performance of many metallic antennas at microwave and millimeter-wave frequencies. This accidental discovery was formalized by S. Long, M. McAllister, and L. Shen in 1983, who demonstrated that dielectric resonators could operate efficiently as antennas when properly excited near a conducting surface.(Long et al.,1983)

DRA has advantages such as high impedance bandwidth, high gain, and, most critically freedom from metallic losses. The dielectric resonators have numerous advantages than microstrip patch antenna. In microstrip antenna radiation occurs due to the narrow slots only whereas in dielectric resonator the radiation is due to the whole surface except the grounded part. The limitations of patch antennas, such as poor gain, limited bandwidth, and narrow beam characteristics, can be solved by utilizing dielectric resonators. They provide three resonant modes: TE, TM, and hybrid HEM, which can be used to generate broadside, omnidirectional,

or ultra-wideband radiation. DRAs, with their compact size, high radiation efficiency, low surface-wave loss, and ease of manufacture, have emerged as crucial technology for modern applications like as 5G, satellite communications, and radar systems

The rectangular dielectric resonator antenna (RDRA) is unique among DRA geometries in that it can be customized to control the resonant frequency and bandwidth by adjusting its three orthogonal dimensions: length, width, and height. Mongia, Ittipiboon, and associates pioneered the RDRA concept, transforming it into a workable, effective, and well-modeled structure. Early studies that proved the feasibility of planar integration set the groundwork for subsequent advancements in miniaturization, bandwidth expansion, and functional versatility (Esselle et al.,1996). A list of several RDRA developed on the past years is given in Table 1

Table 1 Previously Documented RDRA

Structure	Structure investigated Year	Frequency range
Compact RDRA with CPW inductive slot (Gao et al 2006)	2006	4.80GHz - 6.23 GHz
Hybrid RDRA with CPW excitation (Denidni et al., 2010)	2010	3.1 - 10.6 GHz,
Rectangular DRA with tapered strip excitation (Khalily et al., 2011)	2011	2.13-6.08GHz
RDRA with perforations and coaxial feed (Patel et al., 2015)	2014	2.72GHz-4.3 GHz
Two segment RDRA with common microstrip feed (Kshirsagar et al ., 2017)	2017	2.8 GHz–13.49 GHz

Dual-Band Circularly Polarized Aperture Coupled Rectangular Dielectric Resonator Antenna (Gupta et al ., 2018)	2018	3.4 GHz-3.58 GHz, and 5.1 GHz-5.9 GHz.
Multilayer RDRA with coaxial probe excitation (Wang et al., 2019)	2019	5.42GHz – 16.5GHz,
RDRA for Ku Band with aperture coupling (Yadav et al ., 2024)	2024	11.93 GHz- 14.01 GHz
SRR-based RDRA with microstrip feed (Khan et al., 2024)	2024	1.57-1.71GHz,2.95-3.1GHz,4.6-4.9GHz,6.46-6.6GHz

2.Feeding Mechanisms in Dielectric Resonator Antennas

Feeding mechanisms play a crucial role in the design and performance of DRAs. The type of feeding technique and its location plays a major role in determining which modes are excited and how much power is coupled between the port and the antenna. Since DRAs rely on the excitation of specific resonant modes within a dielectric material, the feed must efficiently couple electromagnetic energy into the resonator while maintaining good impedance matching, high radiation efficiency, and stable radiation characteristics. Several feeding techniques have been developed, each offering unique advantages in terms of bandwidth, fabrication complexity, and integration with planar circuits.

The DRAs can be excited by various techniques as stated below

Microstrip feedline: It is one of the approaches for exciting DRA in which the dielectric resonator is placed directly on the PCB substrate's microstrip transmission line. The main disadvantage of this feeding strategy is that an unwanted gap may form between the microstrip line and DRA. As a result, radiation performance may be compromised

Coplanar waveguide: Here a coplanar waveguide feeds a cylindrical DRA. The connection slot underneath the DRA can be changed to improve its radiation performance. The spacing

between the CPW feed and the ground plane allows for excellent radiation efficiency when using this feeding approach. This connection improves antenna efficiency for resonator antennas in the substrate. Coupling can be increased by changing the geometry of the coupling slot. This approach works best with antennas that operate at millimetre wave frequencies.

Coaxial probe feed: In this technique, the coaxial probe can either be used by penetrating through the substrate or can be placed adjacent to DRA. Researchers have examined that input impedance bandwidth can be enhanced by tuning the length and position of the probe. Moreover, it is also observed that the radiation performances can also be enhanced by optimizing the position of the probe

3. Early Developments in RDRA Design

The paper “*Rectangular Dielectric Resonator Antenna*” by M.W. McAllister, S.A. Long and G.L. Conway introduced the rectangular dielectric resonator antenna (DRA), as shown in figure 1 marking a key advancement in antenna technology. The authors demonstrated that a high-permittivity rectangular dielectric block could serve as an efficient radiator when properly excited, eliminating conductor losses common in metallic antennas. They analyzed the fundamental TE_{111} mode, derived approximate resonance equations, and showed that coaxial probe feeding provided good impedance matching and stable broadside radiation patterns. The study highlighted the antenna's compactness, high efficiency, and potential for integration with microwave circuitry, laying the foundation for decades of DRA research in modern communication systems. Later low-profile designs achieved good impedance matching at 11.6 GHz for $\epsilon_r = 10.8$, optimizing the length-to-height ratio ($\sim 6:1$) to preserve magnetic-dipole radiation while reducing height (Esselle et al.,1996).

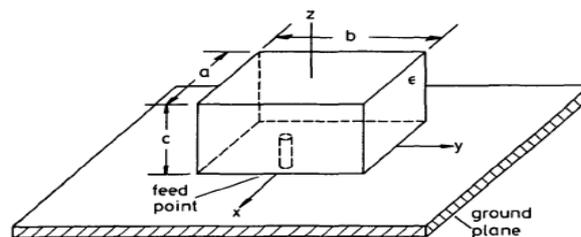


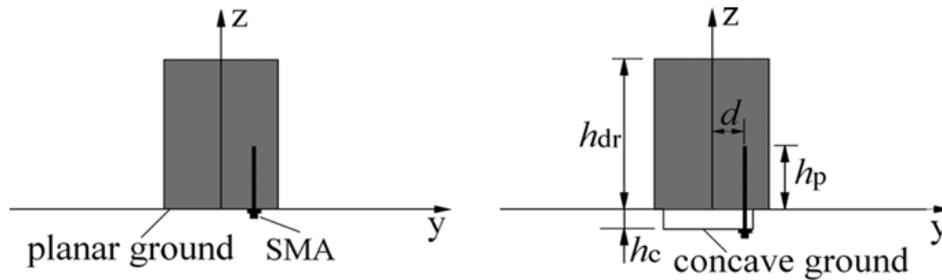
Figure 1: A rectangular dielectric resonator excited by coaxial probe (Long et al.,1983)

A metallized RDRA variation added a top metal layer to lower the resonance frequency and reduce antenna area, however at the cost of reduced bandwidth (Mongia et

al.,1997)This design demonstrated the standard size-bandwidth trade-off associated with small DRAs. The work of R.K. Mongia, A. Ittibipoon, and M. Cuhaci on low-profile (Mongia et al.,1994)dielectric resonator antennas (DRAs) using very high permittivity materials marked an important step in the evolution of compact antenna technology. By employing dielectric constants as high as 100, they demonstrated that DRAs could be made significantly smaller and flatter, offering a practical solution for applications where space and integration constraints are critical. Their study showed that while such antennas achieve excellent miniaturization and maintain reasonable radiation efficiency, the trade-off is a narrow impedance bandwidth of only about 3%, which limits their use in broadband systems. This paper highlighted the fundamental size-bandwidth compromise inherent in DRAs and provided a foundation for subsequent research into bandwidth enhancement techniques.

Bijumon et al. (2005) described a rectangular dielectric resonator antenna (DRA) made from high-permittivity ceramic material ($\text{Ca}_5\text{NbTiO}_{15}$ -based) and energized with a new T-strip microstrip feed. The suggested design achieved a wide impedance bandwidth of around 22% near 2.975 GHz, which is substantial compared to traditional DRAs. The use of high-permittivity ceramics allowed for compact antenna dimensions while maintaining good efficiency and steady radiation characteristics. The T-strip feed form improved coupling and contributed to broadband response, making the antenna appropriate for current wireless applications.

Liang and Denidni proposed a wideband rectangular dielectric resonator antenna design featuring a concave ground plane to enhance impedance bandwidth as shown in figure 2. By modifying the ground plane design, the authors improved coupling between the feed and the dielectric resonator, thereby broadening the operating frequency range. The measured impedance bandwidth of the proposed rectangular DRA with a concave ground plane achieves a wide impedance bandwidth of 55%, covering the frequency range from 3.28 to 5.77 GHz, which is 1.4 times higher than a DRA with a plane ground plane. Radiation patterns remained consistent across the band, with good gain and efficiency, demonstrating the effectiveness of the concave ground plane in achieving wideband performance. This work highlights the significance of ground plane engineering as a simple yet effective strategy for enhancing the bandwidth of DRAs (Liang et al.,2009)



Figure

2:

RDRA with plane and concave ground plane Liang et al.,2009)

4. Bandwidth Enhancement Techniques

Resonant behavior and impedance bandwidth are significantly influenced by feed geometry. In the study of a microstrip-fed RDRA functioning in the $TE_{11\delta}$ mode, Low and Wu [Low et al.,2003] showed that lowering permittivity and thickening the substrate increased the resonant frequency and expanded the impedance bandwidth. In the same manner, lateral displacement decreased the resonant frequency while displacement along the microstrip line increased frequency and bandwidth.

A compact and wideband rectangular dielectric resonator antenna (DRA) integrated with a grounded inverted L-plate was proposed to achieve size reduction and bandwidth enhancement for 2.4 GHz and 5.8 GHz wireless applications. The L-plate effectively lowers the antenna height and reduces its footprint while maintaining desirable radiation characteristics. Two feeding configurations—microstrip-fed T-shaped strip and aperture coupling—were utilized as shown in figure 3, with T-branches incorporated to improve impedance matching. Using a two-step FDTD-based design approach that separately optimizes the radiator and feed structures, the antenna demonstrates simplified design, enhanced bandwidth, and suitability for compact Bluetooth and WLAN systems.(Lan et al.,2005)

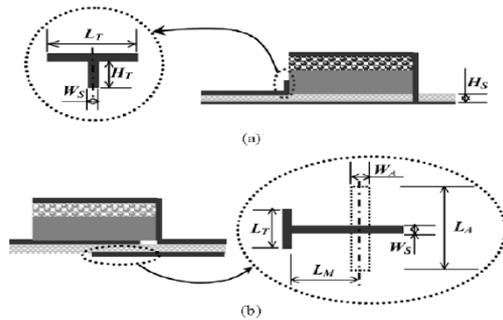


Figure3: Feed structures for the antenna. The antenna fed by (a) vertical T-shaped strip and (b) microstrip with T-branch through an aperture.(Lan et al.,2005)

In order to achieve 61% bandwidth (2.4–4.5 GHz) and stable radiation patterns, a hybrid slot-fed RDRA configuration that combined air and dielectric regions dramatically decreased the Q-factor (Weng et al., 2010) Similar to this, Ge et al. (2011) used a low-permittivity insert between the ground and the resonator to achieve an ultra-wide bandwidth of 60–110%, meeting FCC UWB requirements.

Slot and patch modifications have been employed to further extend the operational bandwidth. Madhuri et al. (2011) achieved wideband operation in high-permittivity RDRA using rectangular ring slots and partial conducting walls, attaining 81.7% bandwidth. Khalily et al. (2011) introduced tapered-strip feeds with grounded narrow strips, yielding 96% bandwidth (2.13–6.08 GHz) with stable broadside radiation. Figure 4 shows the photograph of fabricated RDRA

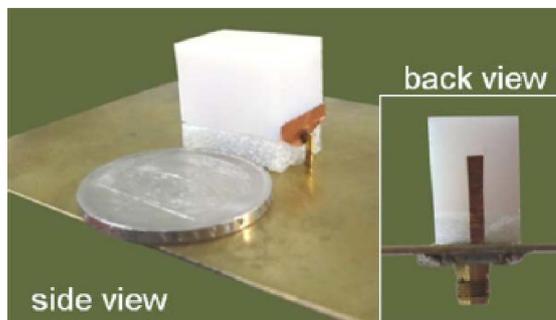


Figure 4: Photograph of fabricated RDRA in different views (Khalily et al., 2011)

5. Stacking and Composite Structures

Stacking multiple dielectric layers of differing permittivities has proven effective in merging adjacent modes and increasing bandwidth. A stacked RDRA with $\epsilon_r = 10$ and 32 as shown in figure 4 achieved 13.6% bandwidth at 5 GHz (Makwana et al., 2012)

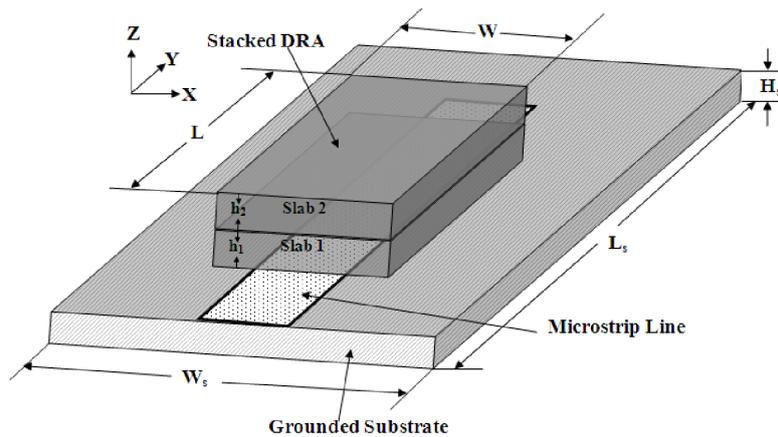


Figure 5: Stacked DRA with microstrip line feed (Makwana et al., 2012)

Bakshi et al. (2019) proposed a two-layer sapphire-stacked rectangular dielectric resonator antenna as in figure 6 to overcome the limitations of conventional ceramic-based DRAs in wireless communication systems. The use of sapphire offered advantages such as high robustness, thermal stability, and low dielectric loss, making it suitable for harsh environments. Designed on an FR4 substrate ($\epsilon_r = 4.4$) and excited through an aperture-coupled feed, as shown in figure 5. The antenna achieved dual-band operation at 7.41–8.21 GHz and 9.11–12.65 GHz, with measured gains of 2.5 dB and 5.5 dB. The stacked configuration enhanced bandwidth and supported multiple resonant modes, indicating its strong potential for rugged and high-frequency communication applications.

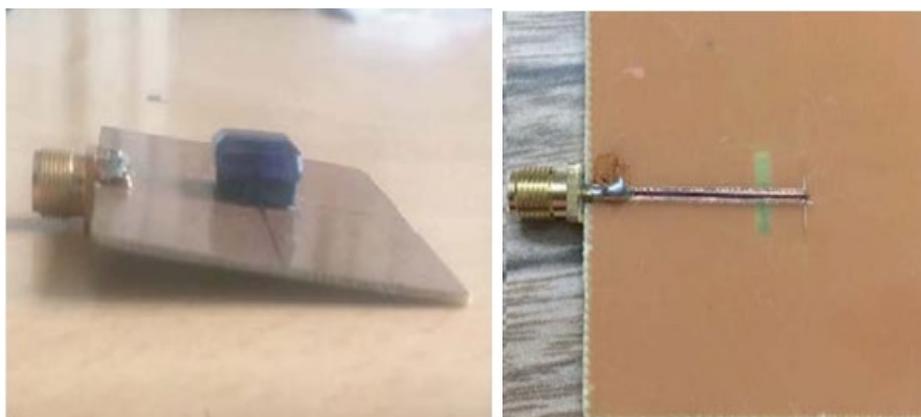


Figure 6: Aperture coupled two layer sapphire-stacked rectangular dielectric resonator

antenna (Bakshi et al., 2019)

The research by Kshirsagar et al (2017) proposes a novel two-segment rectangular dielectric resonator antenna (RDRA) built for ultra-wideband (UWB) applications. The antenna combines two dielectric materials (FR-4 with $\epsilon_r = 4.3$ and Rogers TMM10 with $\epsilon_r = 9.2$) and is driven via a microstrip feed with an impedance transformer. The structure includes a defective ground slot (DGS) to boost bandwidth and reduce cross-polarization, producing a measured impedance bandwidth of 131.24% (2.8-13.49 GHz), peak gain of 7.2 dBi at 10 GHz, and efficiency up to 95% at 3 GHz. In another work a multiband RDRA designed specifically for future 5G wireless communication systems has a vertically stacked dielectric radiator with semicircular slots etched on the upper segment. It is designed to work efficiently at 25.4, 34.6, and 38 GHz, which covers crucial 5G bands (28 and 38 GHz). The antenna achieves wide impedance bandwidths of 7.34, 4.04, and 3.30 GHz at their respective resonances, with return losses of less than -30 dB and a peak gain of 7.6 dBi. It exhibits great radiation efficiency (>90%) and virtually omnidirectional radiation patterns (Anab et al.,2020)

U. Illahi et al (2019) proposes a compact, singly fed rectangular Dielectric Resonator Antenna as shown in figure 7 excited by a novel H-shaped conformal metal strip to achieve wideband circular polarization. The design excites orthogonal higher-order modes (Tex_{13} and Tey_{13}) for improved performance. Measurements show a 27.7% impedance bandwidth, 20% axial ratio bandwidth, and a stable gain of 6.8 dBic with wide beamwidth. The antenna offers simple structure, low cost, and broadband CP, making it suitable for WiMAX and satellite communication applications. Table 2 shows the comparison of bandwidth and gain performance of composite RDRA



Figure 7: H shaped metal strip fed RDRA (U. Illahi et al 2019)

Table 2 Comparison of Bandwidth and Gain of composite RDRA

Structure	Frequency range	Bandwidth (%)	Gain (dBi)
High-permittivity DRA over H-slot (Kim et al.,2019)	~35 GHz	12	1
Substrate-integrated DRA (Al-Yasir et al .,2020)	~35 GHz (Ka-band)	12	5.5
Slot-coupled on-chip RDRA (Zhang et al 2018)	60	6.1	6
Two-layer RDRA with coating, cross-slot (Pan et al 2022)	26	36.5	12.5
Metal strips isolation (MIMO) (Abdel-Wahab et al., 2021)	~28–30 GHz	4.8	9.9
SIW-fed rectangular alumina DR (Chemweno et al., 2022)	122.6–139.5 GHz	13.4	12.3dBi
RDRAwith side DR and vertical strip feed (Trinh-Van et al., 2020)	2.9–6.0 GHz	69.66	6.34 dBic
RDRA WITH DUAL SLOT (Shou et al., 2024)	2.96–5.02 GHz	51.6	~6 dBi

6. Emerging Materials and Hybrid Configurations

A Rectangular dielectric resonator antenna designed for 5G communication at 3.5 GHz, featuring an innovative graphene-based film (GBF) (Xia et al.,2018) microstrip feed as an alternative to traditional copper conductors as in figure 8. Using a high-permittivity ceramic dielectric block ($\epsilon_r=37$) on an FR-4 substrate, the authors fabricated and compared two prototypes—one with copper and one with GBF. Both simulations and measurements demonstrate excellent agreement, with the GBF-fed antenna achieving a -10 dB impedance bandwidth of 3.38–3.57 GHz and a peak gain of 4.52 dBi, closely matching the copper-fed version

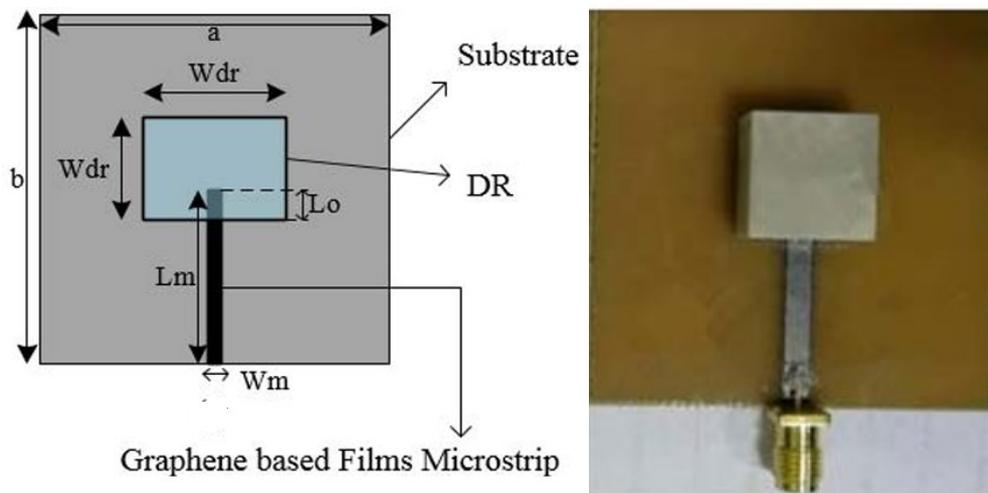


Figure 8: Graphene-based microstrip feed RDRA (Xia et al.,2018)

Gaya et al. (2022) suggested an innovative annular microstrip feed with a cross-slot aperture to enhance bandwidth and gain performance as shown in figure 9. Using a high-permittivity ECCOSTOCK Hik ceramic resonator ($\epsilon_r = 10$) mounted on a Rogers RT/Duroid 5880 substrate, the antenna is designed and simulated through HFSS, with supporting analytical calculations in MATLAB. The study examines how slot geometry, DRA height, and aspect ratio affect impedance bandwidth and resonance characteristics. Simulation and measurement results reveal that the antenna operates in the TE_{1Y1} mode, achieving a broad impedance bandwidth of 20.15% (5.24 GHz) centered at 26 GHz, radiation efficiency of 96%, and a

maximum gain of 6.3 dB. Compared to a rectangular slot-fed DRA, the cross-slot configuration significantly improves impedance matching and reduces cross-polarization and well-suited for 5G small-cell and indoor wireless communication systems.

A small slotted RDRA was created by Sahoo and Patani (2023) for Ku-band satellite communication. The antenna's circular parasitic patch improves radiation performance and bandwidth. It is constructed from alumina (AlO_3) on a Rogers RT/Duroid 5880 substrate. The $10 \times 10 \times 3 \text{ mm}^3$ structure demonstrated strong impedance matching, excellent radiation efficiency (nearing 100%), and circular polarization with a 3 dB axial ratio at 17.04 GHz. The design's suitability for satellite communication terminals that need small, high-gain, circularly polarized antennas was confirmed by simulation and fabrication results in HFSS. Without increasing complexity, the parasitic element's addition enhanced the axial ratio and impedance bandwidths.

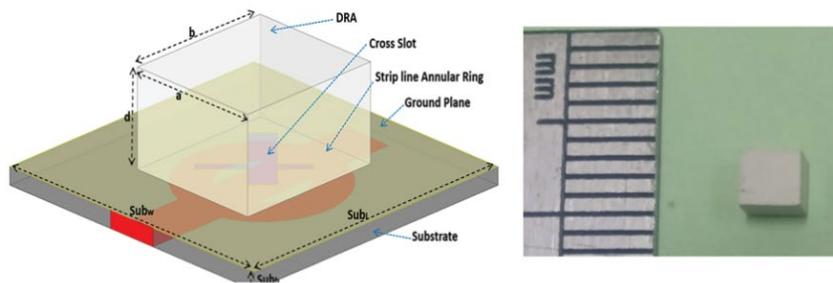


Figure 9: 3D view of DRA fed by annular feed structure and Fabricated DRA (Gaya et al. 2022)

A wideband embedded stacked rectangular DRA that is tailored for X-band applications was presented by Ben Yamoun and Aknin (2024). In order to take advantage of permittivity contrast and attain better bandwidth performance, their design included two different dielectric materials: alumina ($\epsilon_r = 9.9$) and polylactic acid (PLA, $\epsilon_r = 3.45$). As simulated in CST Microwave Studio 2020, the antenna, excited by a coaxial probe on a $60 \times 60 \text{ mm}^2$ aluminum ground plane, showed dual resonances at 9.4 GHz and 10.6 GHz, with a fractional bandwidth of 22.7% (8.75–11 GHz) and a maximum gain of 7.7 dB. Radar and satellite communications, where compactness and environmental compatibility are desired, can benefit from the design's

enhanced impedance matching and environmental sustainability due to the hybrid stacking of biodegradable PLA and high-dielectric alumina.

A volume-reduced dual-band hybrid dielectric resonator antenna (RDRA) with four rhombus-shaped elements with semi-circular subtractions is presented by Konch et al (2023) is shown in figure 10. It is excited by a cross-shaped microstrip patch and a centrally located coaxial feed. The antenna operates at 3.0 GHz and 4.6 GHz, corresponding to TE₁₁₁ and HEM₂₂₈ modes, respectively, delivering omnidirectional radiation at the lower band and multi-directional radiation at the higher band. It has a radiation efficiency of up to 80%, impedance bandwidths of 4.26% and 4.34%, and gains of 3.8 dBi and 4.5 dBi. Interestingly, the design offers a 56% volume reduction over traditional rectangular DRAs, which makes it appropriate for reconfigurable wireless systems and small IoT devices.

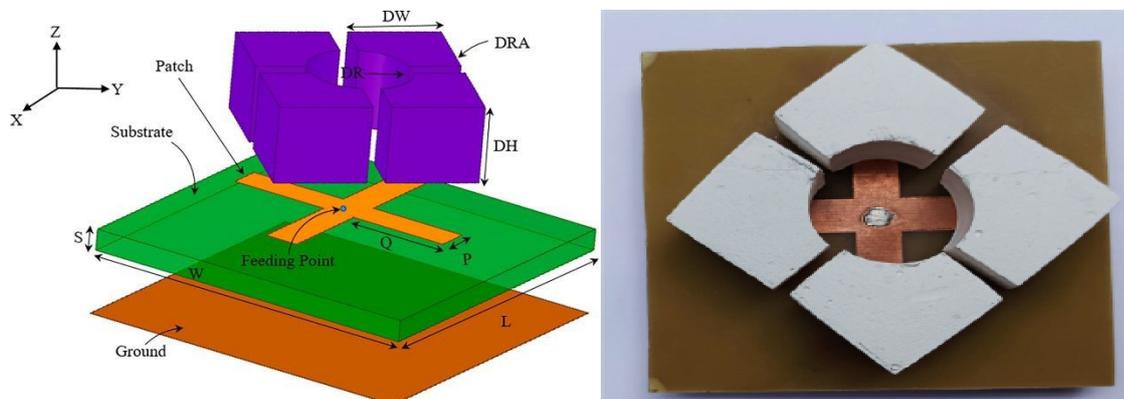


Figure 10: Schematic and Top view of the fabricated antenna (Konch et al ., 2023)

Chaitanya et al (2023) suggested a tiny hybrid rectangular dielectric resonator antenna (RDRA) for tri-band wireless applications, including WLAN, WiMAX, and WAIC. The design supports resonant frequencies of 2.68, 3.26, and 4.31 GHz and includes a modified microstrip feed with an octagonal ring and a plus-shaped ground slot. The antenna, with DR dimensions of 19×20×18 mm³ on a FR4 substrate, displays consistent omnidirectional radiation patterns in both the E- and H-planes, with a measured gain of up to 5.125 dBi. This structure is ideal for

next-generation wireless systems because to its good impedance matching, compact size ($32 \times 35 \times 19.6 \text{ mm}^3$), and strong correlation between simulated and measured findings

A compact quad-band rectangular dielectric resonator antenna (RDRA) that symmetrically integrates two square split-ring resonators (SRRs) along an extended microstrip feedline was presented by Khan et al. recently is shown in figure 11. The SRRs and rectangular DR on a FR4 substrate with a ceramic dielectric ($\epsilon_r = 10$) allow the antenna to operate at four different frequencies: 1.62 GHz, 3.03 GHz, 4.7 GHz, and 6.56 GHz. With impedance bandwidths varying from 5% to 9.2% across the bands, it attains a radiation efficiency of 93% and a peak gain of 2.3 dBi. Strong agreement between CST and ADS software simulations and stable radiation patterns are displayed by the design. This is the first RDRA that has been documented to use SRRs for multiband operation, providing a small and easy-to-fabricate solution for 4G, 5G, Bluetooth, Wi-Fi, and upcoming 6G wireless applications (Khan et al., 2025). Table 3 shows the Performance Comparison of the above discussed RDRA

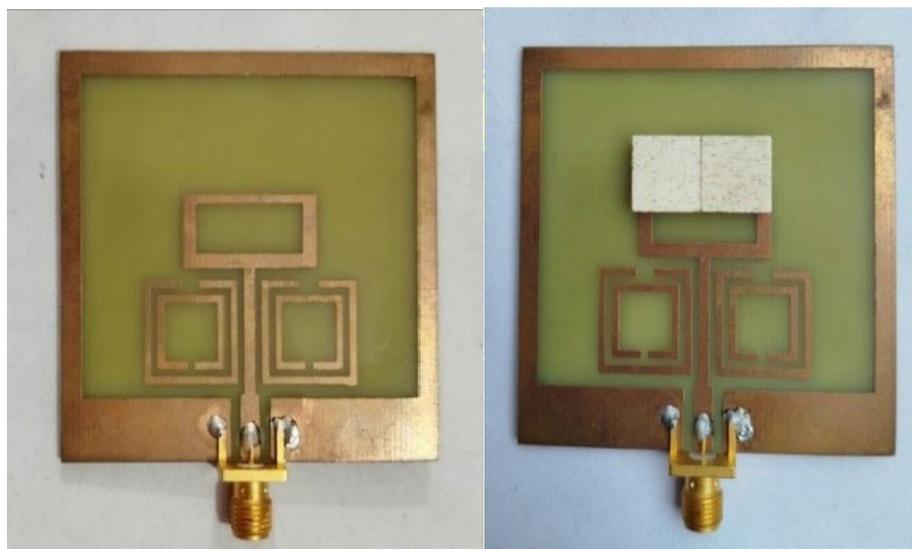


Figure 11. Fabricated design top view (a) without DRA (b) with DRA (Khan et al., 2025).

Table 3: Performance Comparison of Hybrid RDRA

Antenna Type / Key Feature	Materials & Substrate	Band width	Gain	Radiation Efficiency	Notable Advantages
Graphene-based microstrip-fed RDRA	Graphene conductor	3.38–3.57 GHz	4.52 dBi	Comparable to copper	Flexible, lightweight, graphene as alternative to copper
Annular microstrip feed with cross-slot aperture	ECCOSTOC K Hik ($\epsilon_r = 10$) on Rogers 5880	20.15% (5.24 GHz)	6.3 dB	96%	Strong impedance matching, low cross-pol., good for 5G small cells
Small slotted RDRA with circular parasitic patch	Alumina (AlO_3) on Rogers 5880	–	–	Near 100%	Circular polarization, 3 dB axial ratio, compact Ku-band satellite antenna
Embedded stacked rectangular DRA (hybrid)	Alumina ($\epsilon_r=9.9$) + PLA ($\epsilon_r=3.45$)	22.7% (8.75–11 GHz)	7.7 dB	–	Eco-friendly, dual-resonance X-band, improved impedance match

PLA– Alumina)					
Volume-reduced dual-band hybrid RDRA (rhombus-shaped elements)	(ceramic DRA implied)	4.26% & 4.34%	3.8 dBi & 4.5 dBi	Up to 80%	56% volume reduction, suitable for IoT & reconfigurable systems
Tri-band hybrid rectangular RDRA (octagonal ring + plus-slot)	DR (19×20×18 mm ³) on FR4	–	Up to 5.125 dBi	–	Compact, omnidirectional, suitable for WLAN/WiMAX/WAIC
Quad-band RDRA with dual square SRRs	Ceramic DR ($\epsilon_r = 10$) + SRRs on FR4	5%–9.2%	2.3 dBi	93%	First RDRA using SRRs for multiband, covers 4G/5G/Wi-Fi/Bluetooth/6G

7. Conclusion

Rectangular dielectric resonator antennas (RDRAs) have substantially benefited modern wireless communication systems due to its small size, excellent radiation efficiency, and broad bandwidth. Extensive research has enabled numerous design refinements, including as shape

modification, hybrid feeding methods, and dielectric material selection, which have enhanced RDRA performance across a wide range of frequency bands, including millimeter-wave and 5G applications. To improve gain, polarization diversity, and downsizing, current trends include RDRA integration with multiple-input multiple-output (MIMO) systems, metamaterials, and substrate integrated waveguides (SIW). Overall, RDRA continue to have high potential for next-generation communication and sensing systems, providing a versatile platform that strikes a balance between efficiency, compactness, and design freedom. Future research is likely to focus on reconfigurable designs, better dielectric materials, and seamless integration with upcoming technologies such as 6G and Internet of Things (IoT) systems.

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