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REVIEW ARTICLE

Recent developments in bandwidth improvement of dielectric resonator antennas

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Abstract

This article shows a compressed chronological overview of dielectric resonator antennas (DRAs) emphasizing the developments targeting to bandwidth performance characteristics in last three and half decades. The research articles available in open literature give strong information about the innovation and rapid developments of DRAs since 1980s. The sole intention of this review article is to, (a) highlight the novel researchers and to analyze their effective and innovative research carried out on DRA for the furtherance of its performance in terms of only bandwidth and bandwidth with other characteristics, (b) give a practical prediction of future of DRA as per the past and current state-of-art condition, and (c) provide a conceptual support to the antenna modelers for further innovations as well as miniaturization of the existing ones. In addition some of the significant observations made during the review can be noted as follows; (a) hybrid shape DRAs with Sierpinski and Minkowski fractal DRAs seems comfortable in obtaining wideband as well as multiband, (b) combination of multiple resonant modes (preferably lower modes) can lead to wider impedance bandwidth, (c) at proper matching wider patch with slotted dielectric resonator can exhibit better bandwidth.

KEYWORDS

antenna performance, antenna review, bandwidth, dielectric resonator antenna

1 | INTRODUCTION

Dielectric resonator antenna, known as DRA or sometime DR-antenna, has been brought remarkable attention around the globe in last three and half decades. Though, the concept of the dielectric resonator (DR) as a high Q-factor material has been brought by Richtmyer[1] in 1939 but it was used as an effective electromagnetic radiator in 1983.[2] Since then, it has grown up rapidly with various improvements. The potential reasons behind its techno-popularity can be considered as follows: (a) DRAs made of dielectric material and has three dimensional design flexibility (Figure 1). Here the permittivity, physical dimension of DR controls its resonant frequency as well as Q-factor. Like radius for hemispherical shape, height-to-radius ratio for cylindrical shape and width-to-length ratio for rectangular shapes, affects the resonant frequency. The presence of nonconducting material minimizes the conductor losses, even at millimeter wave frequencies and achieves >95% efficiency, which is quite challenging for other antennas.[3–5] (b) it supports wide range of coupling techniques which enables excitation of several modes guaranteeing improved radiation pattern with more coverage. This kind of flexibility is rarely available with other conventional antennas.[3,4] These techniques can be improved further with integration of array concept, (c) the size of the DRA depends on free space wavelength (λ_0) as well as relative permittivity (ε_r), whereas other antenna size depends upon only λ_0, means the DRAs are characterized by comparatively smaller form factor than other antennas.[3,4] By each passing years investigations on different modeling techniques and performance improvements have been carried out by the researchers in order to meet the demand of modern wireless applications.

The several modeling techniques and applications have already been well discussed by the authors in two review articles,[4,5], respectively. Few other limited review articles[6–10] have also been published in the open lierature. The available

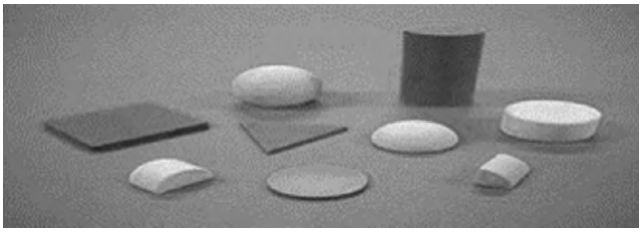

FIGURE 1 Different shapes of dielectric resonators

book[3] and review articles[6,7] mainly highlights different performances (such as gain, circular polarization, and mutual coupling reduction) in DRAs as well as in hybrid shape DRAs. Some authors have highlighted the recent advances say bandwidth, compactness, reconfigurability, array, and so on.[8,9] The recent advances pointing toward broadband, ultra-wideband, and multiband have been reported in Reference.[10]

However, to the best of authors' knowledge no such review is available in References [6,7] covering all the developing technologies and mechanisms dedicated to DRA bandwidth improvement. And this type of review article seems to be equally important among the researchers working on DRA. Hence, the sole intention of this review article is to bring out the notable research carried out on DRA targeting to performance characteristics like; bandwidth, gain, directivity, circular polarization, and mutual coupling reduction, by the means of physical parameters optimizations. For a fruitful technical understanding, based on research and development trends, the sections are chronologically arranged and well discussed. This review article is abridged as follow: The basics of DRA and its major parts are briefed in Section 2. Section 3 describes research carried out on DRA for bandwidth. To bring the attention of readers a well-organized summery of this whole review process is kept in Section 4 followed by the conclusion in Section 5. For ease of understanding, the overall flow of this review process is tabulated in Table 8.

2 | DR AS AN ANTENNA AND ITS MAJOR PARTS

Initially, the DRs were used in filter and oscillator applications intending for storing of energy. Because of its inherent high Q-factor, it led the resonator to store more energy by checking the radiation.[1] In 1983, a research group headed by Long,[2] explored that, when the Q-factor is lowered, placed on a metal plate, and excited, the radio waves bounce back and forth in-between the resonator boundary and creates standing radiowave. And this standing radio waves can penetrate out from the resonator boundary by means of radiation once it is excited at proper resonating mode. Briefly, the DR antenna needs three basic parts, that is, DR, ground plane, and coupling mechanism.

In case of DR, hemispherical, cylindrical, and rectangular shapes are considered as the most common shapes.[1,2] In addition to these regular shapes, some other modified shapes like, hemispherical, hybrid DR by stacking, variation of permittivity, fractal, electromagnetic band gap (EBG), superstrate, horn, and so on have also been well analyzed for performance regulation[2,3] as per the application requirement. Moreover, different coupling mechanism say, aperture coupling, probe coupling, microstrip line coupling, coplanar coupling, dielectric image guide coupling, and so on, also plays an important role in regulating the performance.[2,3] It can be noted that, DRA can be placed above thick metallic ground plane or above dielectric substrate backed by thin ground plane.

3 | DRA RESEARCH ON BANDWIDTH

DRA deals with many advanced features, among which wide bandwidth is considered to the prominent one.[1] By each passing years, different advanced approaches are being reported either for further enhancement of default bandwidth or creation of dual-/multi-band operation using resonator shape. Broadly, these approaches can be divided into four categories; firstly, according to the antenna geometry (DR shape/fractal/EBG/metamaterial), secondly, the coupling mechanism (feeding type/aperture shape), thirdly, the DR permittivity, and lastly, according to the excitation of specific mode. From ease of readers' point of view, these techniques are discussed separately for single-band,[11–169] dual-band,[170–180] and multi-band,[181–186], respectively. Moreover, some other characteristics say radiation/notch[187–191] are also discussed in the preceding part of this section. The organization of this section is summarized in Figure 2.

3.1 | Bandwidth improvement in single band operation

The literature on research of single bandwidth based DRA[11–169] is broadly divided into by means of antenna geometry, coupling scheme, DR permittivity, and mode of operation. The discussion flow is summarized in Figure 3.

3.1.1 | Bandwidth improvement using different antenna geometry

During this reviewing process, it has been noticed that, the researchers have reported bandwidth improvement by

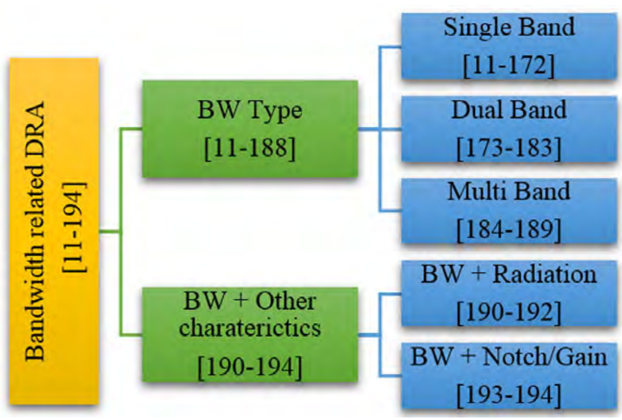

FIGURE 2 Shows the flow of bandwidth related DRA analysis

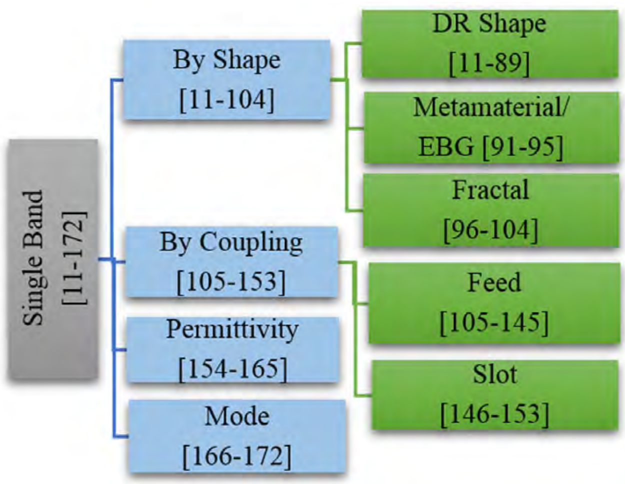

FIGURE 3 Shows categorization of analysis flow of single band DRAs

means of DR shape modification,[11–89] incorporation of EBG/metamaterial,[91–95] or fractal.[96–104]

Different shapes of DR for bandwidth improvement

As it is known that, DR is 3D object its dimension plays an important role in controlling the operation range. The very familiar concept, that is, stacking (one DR upon another DR) was first introduced by Kishk[11] in 1989. In this case, two DRs have two resonant frequencies, and when they are stacked dual resonance concept works out for broadening the antenna bandwidth. This technique can be extended for triple/multiple stacking in-order to further enhance the bandwidth. Apart from this, the concept of parasitic coupling[3] and multiple DR with single feed[3] are also being used by placing a DR near to a parent DR. These techniques ultimately require an extra DR which can be considered as a drawback. Hence, the approaches with single DRA element for the same purpose, are quite interesting. The most popular/tradition technique is lowering the inherent Q-factor. As Q-factor is directly related to dielectric constant (permittivity), then by decreasing the dielectric constant the Q-factor can be lowered resulting wider bandwidth.[2]

$$BW = \frac{s-1}{Q\sqrt{s}} \times 100\% \tag{1}$$

Where, s-desired VSWR at the input port of the DRA.

Hence, different approaches have been reported targeting lower Q-factor for bandwidth widening. This involves, intrusion of any sort of air gap inside the DR or in-between the DR and ground plane. This is supplemented by a shift in resonant frequency and increase in volume.[3] Some researchers have also introduced spilt DR,[21] segmented DRs[39] for the same purpose. Briefly, it can be said that, the alteration of aspect ratio of DR mostly plays a crucial role in controlling the bandwidth. The concept of hybrid DR (ie, combination two or more DR shapes) has also been reported for obtaining wide band and ultra-wideband.[58] In this regard some super shaped DRs, say EYE-shape,[30] A-shape,[61] Z-shape,[66] pentagon shape,[84] dumbbell shape,[86] as shown in Figure 4 have also been proposed. The complete compressive literature is discussed here.

Kishk et al.[11] have explored the concept of wide band DRA with 25% impedance bandwidth in a co-axial probe fed cylindrical shaped DRA placed on a conducting ground plane. Lee and Simons,[12] have reported a novel Substantial bandwidth improvement technique, that is, placing parasitic resonator directly above (stacked form) and on both sides of the main resonator which gave comparatively more impedance bandwidth than that of single element DRA. Wong and Chen[13] have explored that, a dielectric coating can act as a transition between inner wave of the DR and free space wave and lead for a wider impedance, which has been proved in case of a hemispherical DRA. Shum and Luk[14] have explored the stacking and air gap intrusion concept for bandwidth enhancement purpose in a DR antenna while

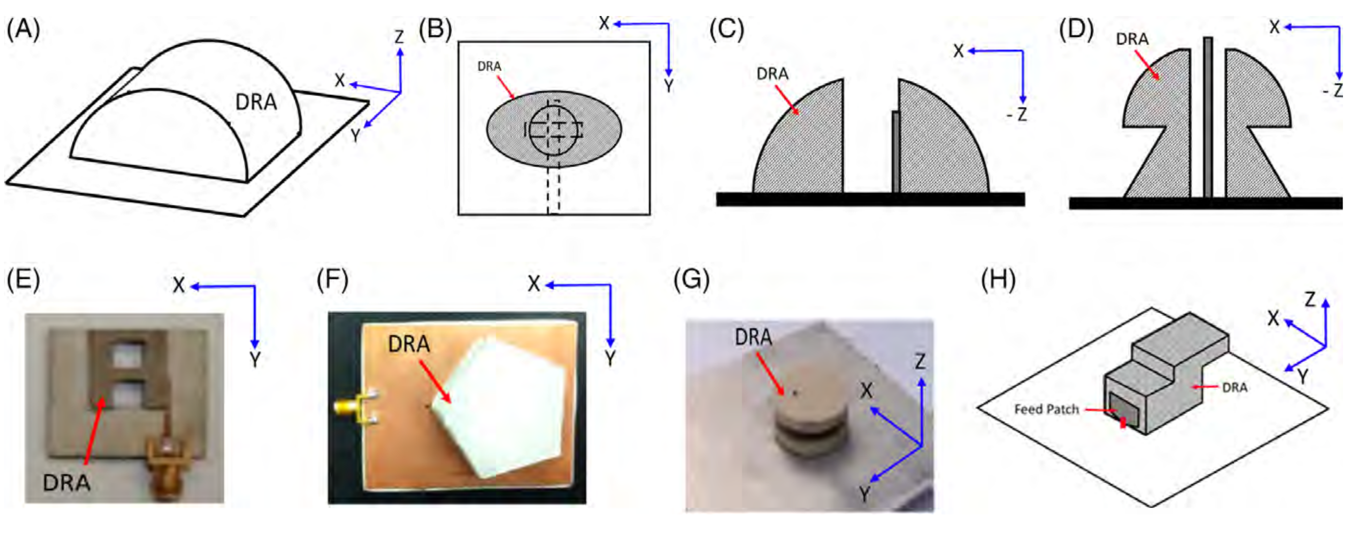

FIGURE 4 Different shapes of DRA developed for wide bandwidth purpose: (A) Split CDRA,[21] (B) EYE Shape DRA,[30] (C) Half HDRA,[39] (D) Pawn shape DRA,[58] (E) A-shape DRA,[61] (F) Pentagon shape DRA,[84] (G) Dumbbell shpae DRA,[86] (H) Z-shape DRA[66]

experimenting a probe fed DRA (5% for single element DRA while 20% for stacked with air gap). Chen et al.,[15] have reported that a dielectric coated DR antenna doubles the impedance bandwidth than that of without coating. Luk et al.[16] have investigated theoretically a hemispherical DR antenna with concentric conductor for wide impedance bandwidth (19% VSWR <2), by using Greens' function and MoM method. After this, a two/three element slot coupled DR antenna was investigated by Fan and Antar[17] for obtaining better bandwidth as compared to single element which can further be utilized for dual band purpose also.

Sangiovanni et al.[18] have demonstrated a coaxial probe fed cylindrical DRA offering >30% impedance bandwidth by taking another annular dielectric ring inside of same height and of different permittivity. Mongia[19] has studied the effect of antenna size on bandwidth and frequency. Drossos et al.[20] have studied the effect air-gap intrusion between the DR and microstrip feed for wider bandwidth. Kishk et al. [21] have studied a coaxial probe fed split cylindrical DRA on a conducting ground plane using MoM operating in HEM_{11} or HEM_{12} modes to achieve wideband of 35% as well as dual-band by inserting a resonator of a different dielectric material inside another resonator. Kishk et al.[22] have studied the effect of conical DR orientation on bandwidth and concluded that inverted cone has much wider bandwidth than noninverted one, but however the split cone achieved the highest, that is, 50% impedance BW which supports more modes. Ong et al. ,[23] have investigated a disc ring resonator and found 47% BW when inner DR permittivity is taken higher than the outer one and 30% when inner dielectric is lower than the outer one.

Kishk[24] has explored the triangle-cylinder (special case of truncated tetrahedron) fed by a coaxial probe operating over a wide range of 40% bandwidth. Gupta et al.,[25] experimented the bandwidth of individual circular and rectangular patch suspended on a dielectric material of $\varepsilon_r = 3.05$ for 18% and 13% impedance bandwidth, respectively. Lapierre et al.,[26] have achieved 74% impedance bandwidth by exciting an annular ring DR with a monopole antenna in $TM_{01\delta}$. Nannini et al.,[27] have observed that stacking and air intrusion improved the bandwidth of a slot fed CDRA. Guo et al.,[28] have reported something more for the bandwidth enhancement and found stacked annular CDRA operating for 42% impedance BW while 18% for only stacked one. Denidni et al.,[29] have reported a coaxial probe fed two equiangular-triangle across sections to give broad side radiation pattern operating between 1.71 and 2.51 GHz, that is, 38% impedance bandwidth. Chair et al.,[30] have designed an EYE shaped DRA excited through a narrow slot for X-band application with 27% BW.

After that, wideband cylindrical and rectangular DRA were proposed by Young et al.[31] They attained an impedance bandwidth of 30%, by considering radius-to-height and length-to-width ratio for cylindrical and rectangular DRA, respectively. Coulibaly et al.,[32] have studied the effect of intermediate substrate for bandwidth enhancement in a microstrip stepped patch DRA by 43%. A co-axial fed T-shaped compact DRA having two equilateral-triangle cross sections has been studied by Rao et al. [33] for a wideband width of 60% covering several application oriented bands like; DCS, PCS, UMTS, WLANS. Chair et al.,[34] have found perforated DRA as a substitute of having annular ring DRA with lower permittivity outside the cylindrical disk, which resulted with enhanced 26.7% impedance bandwidth.

Rezaei et al.,[35] have analyzed a two segment rectangular DRA separated by a metal plate for 76.8% impedance bandwidth and also informed that, high permittivity gives better coupling while lower ones give wide bandwidth. Ruan et al.,[36] have achieved 67% impedance bandwidth in a 2-layer stacked resonator by considering the material combination and probe length with feed position. Ge et al.,[37] have suggested to insert relatively low dielectric permittivity segment between the DR of high permittivity and the ground plane in order to have a wideband and also achieved a BW (6.7-20) GHz with a notch (16.5-17) GHz. Guha and Antar[38] have investigated a four-element DRA combination for monopole like radiation pattern over 29% impedance bandwidth and 4 dBi gain with $HEM_{11\delta}$, which is double than that of the normal bandwidth of monopole having height two times of the proposed DRA. Again Guha et al. ,[39] have demonstrated a 99.08% efficient two element half-hemispherical DR-antenna operating over 35% with monopole like radiation pattern and 5 dBi peak gain and in[40] Guha et al. have suggested some novel guidelines in view of ultra-wideband (5-13 GHz) monopole DRA.

Ruan et al.,[41] have reported a UWB double annular-ring DR-antenna covering 3 to 11.2 GHz range where radius and heights played an important role for bandwidth enhancement. Chair et al.,[42] have analyzed stacked DRA with both co-axial and aperture feeding mechanism for getting BW > 40% while >30% for one step with 5 dBi gain. Chang and Kiang,[43] have designed a CPW-fed three side metal coated rectangular DR-antenna of 4.2 to 6.8 GHz operating range (47% BW) for WLAN application by modeling the dielectric-air interface as perfect magnetic conductor. Huang and Kishk,[44] have modeled a stacked DRA for wide band of 66% for co-axial probe feed while 32% for aperture coupling mechanism. Kumar et al. ,[45] have designed a microstrip along with vertical strip feeding mechanism for a low radiation Q-value novel cylindrical DR-antenna operated over 35% BW centered at 3 GHz. Ghosh et al.,[46] have designed a wide band trans-receive monopole fed DRA with wide band (4.8-11.0 GHz) characteristics for Bluetooth technology. Again, a 110% impedance bandwidth T-shaped monopole fed DRA was designed by Ghosh et al.[47] Chang et al.,[48] have found 20% impedance bandwidth (4.76-5.86 GHz) with broadside radiation pattern in a DRA. Rocha et al. ,[49] have improved the bandwidth up to 13.2% of a probe fed vertically stacked two cylindrical disks of dielectrics Cr0.75Fe1.25O3 (CRFO) and

Fe0.5Cu0.75Ti0.75O3 (FCTO) by exciting in $HEM_{11\delta}$ mode. A skirt monopole fed conical ring DR-antenna operating in higher order modes (TM_{012+6} and TM_{016}) has been giving a bandwidth ranging 1.8-6.9 GHz was proposed by Jazi et al.[50] Li et al.,[51] have developed conformal patch fed hemispherical DRA covered a wide band of 40% centered at 3.1 GHz and which could be shifted to 3.5 GHz adjusting the length and width of the feeding patch. Denidni and Weng,[52] have proposed a rectangular-DRA with bevel-shaped patch feed and an air-gap inserting technique for obtaining 120% bandwidth ranging 2.6 to 11 GHz. Rashidian and Klymyshyn[53] have developed a 5.2:1 aspect ratio DRA of $\varepsilon_r = 25$ with dual mode and wideband (>16%) characteristics. Chang and Feng[54] have modeled a L-shaped microstrip monopole type feed for achieving 25% impedance bandwidth centered at 5.5 GHz. Apart from this, an annular slot excited two layered hemispherical DRA with wide band characteristics (reduced from 55% to 31%) has been experimented using Green's function and MoM approach by Leung and So.[55]

Rashidian and Klymyshyn,[56] have explored that dual mode operation with high aspect ratio DR structure that leads to bandwidth improvement by adopting two segment DRA techniques for bandwidth better than 11%. Ryu and Kishk,[57] have got 81% impedance bandwidth in a simple and compact DRA using partial ground plane in vertical direction. Guha et al.[58] have investigated a quarter wave monopole fed novel pawn shaped hybrid DR-antenna operating over a wide range of 122% bandwidth (5.5-23 GHz) and 4-6 dBi gain. In 2009, an extremely compact co-axial fed DR-antenna achieving 109.5% (3.1-10.6 GHz) has been reported by Ge and Esselle.[59] Rashidian and Klymyshyn,[60] have designed a microstrip-fed miniaturized antenna for obtaining broadband (16%) with stable radiation pattern and low cross-polarization. Ryu and Kishk,[61] have reported an A-shaped UWB DR-antenna for achieving more than 93% and 95% impedance bandwidth and antenna efficiency, respectively. Again, Ryu and Kishk[62] have designed a CPW fed UWB (115%) DRA followed by a triangularly notched cylindrical DRAs placed laterally on the ground plane offering UW bandwidth of 76.7% (4.5-10.1 GHz). Jazi et al.,[64] have reported a 10 GHz bandwidth DR-antenna with monopole like radiation. Guha et al.,[65] have modeled and realized a 120% impedance bandwidth in a monopole fed hybrid dielectric ring resonator with monopole like radiation over the entire operating bandwidth. Denidni et al. ,[66] have investigated rigorously a novel Z-shaped DRA with air-gap and bevel shaped patch to achieve a wide bandwidth of 120%. Ge et al.,[67] have suggested to adopt standard conducting mirror wall technique to reduce the volume of the UWB DRA. Ahmed et al.,[68] have demonstrated a microstrip type printed monopole fed DR-antenna for wideband applications, where inner grove inside the DR helped in enhancing the bandwidth as well as controlling the slot width. Two split ring resonator ($\varepsilon_r = 7.4$) fed by a T-junction ended type coaxial line has been developed to achieve a wide impedance bandwidth of 43.2% and 31.4% radiation bandwidth by Wang et al.[69]

Chaudhary et al.,[70] have stacked ZST and Epoxy composite system for getting wide impedance bandwidth of ~58.7% with peak gain of 6.3 dB for X-band applications. Guha et al.,[71] have developed an UWB DRA using conical and hemispherical DRA for achieving of 126% bandwidth (4:1) and 4 to 5 dBi gain. Rashidian et al.,[72] have proposed a parallel fed standing strips rectangular DRA for achieving more than 60% impedance bandwidth with 5.5 to 9.5 dBi gain. Ge,[73] has used a rectangular DRA with a thin dielectric segment for enhancing the bandwidth up to 67% ranging between 0.8 and 1.6 GHz and used a shorting plate to reduce the volume. Abedian et al.,[74] have proposed a compact two-segments DRA using a U-shaped feed for achieving UWB band ranging 3.14 to 10.9 GHz, that is, 110% BW apart from this the U-shaped slot helped in achieving a strong field distribution and symmetry radiation pattern.

Ge[75] has demonstrated and suggested that by cutting a groove on the bottom of the DR and using metallic patch connected to a coaxial probe for excitation purpose can increase the band and also achieved himself a bandwidth of 109.5% with a measured gain of 6 dBi. Oliveira et al.,[76] have used CaTiO3 ($\varepsilon_r = 20$) for designing of a low profile DRA for achieving 7.42% bandwidth. Chaudhary et al.,[77] have proposed wideband multilayer multi permittivity half-split coaxial probe fed CDRA excited at $TM_{21\delta}$ $(0 < d < 1)$ mode for covering 63.7% impedance bandwidth ranging 4.05 to 6.9 GHz with an average gain of 5.79 dB. Ge et al.,[78] have used bottom side cutting groove and square patch with probe feed technique in a rectangular DRA for UWB operation. Alja'afreh et al.,[79] have proposed a comparatively small sized U-shaped DRA covering 2.4 to 3.0 GHz range (ie, about 22%), while Batcha et al.,[80] have reviewed and suggested some technique for bandwidth enhancement along with the improvement of other characteristics. A planer coplanar wave guide excited monopole antenna integrated with narrow band cylinder shaped DRA has been developed by Wang et al.[81] which provided a 2:1 voltage standing wave ratio (VSWR) bandwidth for 3.05 to 13.5 GHz and 5.1 to 5.8 GHz, respectively, by exciting $HEM_{11\delta}$ mode and apart from this a triple band could be attained instead of a NB antenna by moving the DR toward to Port 1 or Port 2, which is achieved by exciting other two modes.

Pahadsingh and Sahu[82] have reported multiple modified feeding mechanism in a cylindrical DRA for ultra wideband (UWB) operation over 3 to 12 GHz targeting to cognitive radio application. Wang and Wei,[83] have proposed a compact ultra-wideband (2.5-11 GHz) rectangular shaped DRA while excited by a planar monopole and narrow band (5.1-5.5 GHz) while excited by a slot. Sharma and Brar,[84] have designed regular and irregular pentagon shaped DRA for covering BW of 42% (from 2.55 to 3.9 GHz) and 45.8% (from 2.57 to 4.1 GHz), respectively. Mukherjee et al.,[85] have proposed a half hemispherical shaped DRA where array of slot were realized for obtaining a wide impedance bandwidth of 1.3 GHz, that is, . >29%. Chaudhary et al.,[86] have proposed a dumb-bell shaped DRA for enhancement of bandwidth and achieved to be of 57.59% ranging between 4.11 and 6.69 GHz with an average gain of 4.88 dB. Fang and Leung,[87] have excited a two layered hemispherical DRA at TM_{101} mode using a coaxial probe which gave 31.9% impedance bandwidth that to 14.2% while in a single layer. This improved bandwidth has been achieved with 20% expense of antenna diameter.

Haraz et al.[88] have achieved 90% impedance bandwidth over 4.5 to 11.8 GHz in a microstrip-line fed (printed monopole) loaded with a half-cylindrical DRA. Recently Guha et al.,[89] have proposed a hybrid mushroom shaped DRA to achieve 137% bandwidth, which seems to be the widest in its category. Laribi and Hakem[90] have used lens technique with DRA to improve the bandwidth up to 9.5 GHz with gain ~19 dB. Fakhte and Oraizi[91] have excited uniaxial stacked DRs using probe and finite conducting sheet to get wideband of 19.4% and 8.1 dB peak gain. Recently, Ranjan and Gangwar[92] have been used a probe coupled half split cylindrical DRA rectangular DRA to reach 51% impedance bandwidth with 5.94 dBi gain. From all these available literatures it can be concluded that the shape of the DRA has a significant role on controlling the bandwidth. Apart from standard geometrical shapes the effect of hybrid shapes as well as perforated shapes and stacking concepts seem more effective in enhancing the bandwidth by way of increasing radiation. Different bandwidth ranges covered by different shapes of DRAs are summarized in Table 1.

TABLE 1 Percentage bandwidth of DRAs related to different DR shapes

Bandwidth	Shaped DR and Refs.
0%-9%	Cylindrical parasitic,[12] cylindrical,[27] rectangular[76]
10%-19%	Rectangular,[25] (cylindrical),[27] stacked-cylindrical,[49] High aspect ratio rectangular,[53] two segmented-high aspect ratio rectangular[56]
20%-29%	Stacked cylindrical,[11] stacked ring resonator,[14] eye-shaped,[30] perforated-cylindrical,[34] Four-element cylindrical,[38] rectangular with tunnel,[48] ring-resonator,[54] U-shaped[79]
30%-39%	Cylindrical-embedded,[18] split-cylindrical,[21] L-shaped,[29] cylindrical + rectangular,[31] half-hemispherical,[39] cylindrical,[45] two-layered hemispherical,[55] half-hemispherical with array of slots,[85] two-layer transparent hemispherical[87]
40%-49%	Disc-ring,[23] tetrahedron and triangular,[24] stacked double annular-ring,[28] rectangular,[32] stair-shaped,[42] meal coated rectangular,[43] half-hemispherical,[51] split-ring resonator,[69] pentagon shape[84]
50%-59%	Conical,[22] two-layer rectangular,[70] dumbbell-shape,[86] conical[22] stacked-rectangular,[75] dumbbell-shaped[86]
60%-69%	T-shaped DRA,[33,36] multi-layer cylindrical,[44] rectangular,[72] rectangular,[73] half-split cylindrical,[77] cylindrical[82]
70%-79%	Cylindrical,[26] two-segment rectangular[35]
80%-89%	Rectangular[57]
90%-99%	Edge mounted rectangular,[61] half-cylindrical[88]
≥100%	Cylindrical,[47] rectangular,[52] pawn-shaped,[58,59] rectangular inserted[62] conical and hemispherical,[65] Z-shaped,[66] conical and hemispherical ring,[71] two-segment rectangular,[74] rectangular stacked,[75] hybrid shapes[89]

Fractal loaded/planar DRA for bandwidth improvement

Fractal concept defines the increase of electrical length with decrease in volume by the occurrence of similar pattern in a reduced manner.[93] The incorporation of this concept in DRA has been reported firstly by Hajihashemi and Abiri.[94] This concept is quite popular as it exploits compactness and multiband characteristics. It can be noted that, the increase in number of iteration lowers the Q-factor and improved bandwidth. However, proper attention is needed in finding the critical iteration point for optimum result. Different types of fractals namely Sierpinski,[95] Minkowski,[97] Apollonian Gasket,[99] and so on have been reported in literature[95–104] in context of DRA as shown in Figure 5.

In 2009, Karmakar et al. ,[95] have implemented the Sierpinski fractal concept in a cylindrical DRA for achieving 50% (covering X-band) impedance bandwidth. Again, the same fractal concept has been used by Soren et al.[96] on a rectangular DRA to achieve 87.86% impedance bandwidth with 4.6 dBi gain. Dhar et al. ,[97] have done Minkowski boundary fractal along with CPW-feeding loop slot to improve the impedance bandwidth up to 64% with 2.5 to 4.9 dBi gain. Azari et al.,[98] have proposed a unique super wideband fractal compact DRA covering 2 to 40 GHz, which is one of the highest bandwidth for DRA with acceptable gain and radiation pattern. Mukherjee et al.,[99] have designed a hemispherical DRA with Apollonian Gasket of circles type fractal concept for achieving 47% impedance bandwidth with resonant frequency of 3.6 GHz. A co-axial probe fed a novel Sierpinski carpet fractal based photonic band gap (PBG) structure has been developed by Mukherjee et al.,[100] for bandwidth enhancement from 10.4% to 21% with 6.4 dBi gain and 90% efficiency while excited for TE_{111} mode. Dhar et al.,[101] have investigated a CPW-fed slot antenna with Minkowski fractal for confirming bandwidth and gain enhancement with exhibiting a hepta-band performance with 3.1 dBi gain. Fan et al.,[102] have shown that, using offset distance of each DR in a parasitic coplanar three-element DRA makes a threefold increase in the bandwidth, that is, 10.3%. Mukherjee et al.,[103] have used EBG structure to enable broadband and high gain in a hemispherical DRA. Kiran et al.[104] have combined the Sierpinski and Minkowski fractal to obtain wideband of 66%.

Though all the fractal concept has been popular since their inception in DRA, however, Sierpinski fractal has been used extensively by many researchers for wideband purpose with an average 36% impedance bandwidth, while Minkowaki fractal technique has been used for wideband as well as multi/heptaband applications. Moreover, the use of combined Sierpinski and Minkowski technique, and planar

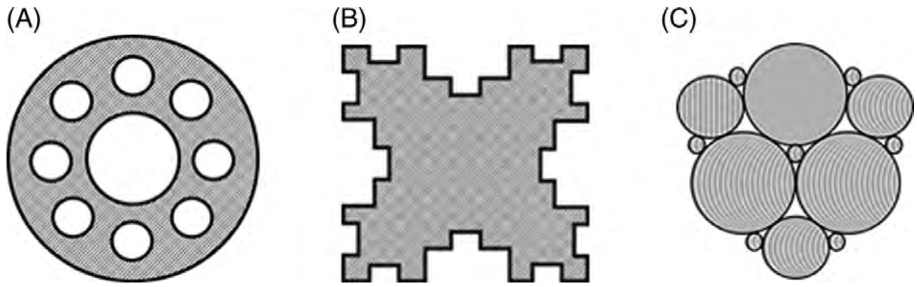

FIGURE 5 Different fractal geometries (top view) used for wide bandwidth purpose: (A) Sierpinski,[95] (B) Minkowski,[97] (C) Apollonian Gasket[99]

concept have been contributed somewhat toward wideband purpose. A comparative study of different fractal loaded DRA are reported in Table 2.

3.1.2 | Bandwidth improvement using coupling mechanism

Next to DRA shape,[11–104] the coupling mechanism plays an important role in controlling performance characteristics of DRA. This technique is also known as bandwidth improvement by means of impedance matching and this can be established either by modification in feeding line[45,105–144] or slot types.[145–152]

Bandwidth improvement via different feed lines

In this approach, primary concern is given to transfer maximum input energy into the DR. It is common fact that, the feed line need to be not only perfectly coupled with the resonator body, but also transfer maximum power/energy up to the coupling point to avoid unnecessary reflection. Hence, instead of traditional feeding line,[105–111] some advanced types say, aperture,[112] parasitic strip,[114] L-shaped probe,[117] elliptical patch,[121] trapezoid patch,[122] bevel shape patch,[126] have been proposed in literature as shown in Figure 6. The complete literature[45,105–144] is discussed here.

Mongia et al.[105] have obtained a 10% frequency bandwidth in a half-split microstrip line-slot fed CDRA with excitation in its dipole mode. Ittipiboon et al.,[106] have suggested that the bandwidth of rectangular ring DRA could be enhanced to 28%. Leung and To,[107] have investigated an aperture coupled DR-antenna with perpendicular feed to operate over 14%. Luk et al.[108] have informed that a vertical strip at the end of the microstrip line can increase the impedance matching in a CDRA up to 19% wide impedance bandwidth, whereas only 7% to 12% in conventional aperture-coupled DRA. Kishk et al.[109] have compared the impedance bandwidth of two different conical structure fed with coaxial probe and concluded that the cone inserted in the ground plane archived the wide band. Kishk et al.[110] have presented a coaxial probe fed DRA to archive 25% impedance and radiation bandwidth. Agrawal et al.[111] have proposed inverted T-shaped feed line coupling with a rectangular DRA to reach 120% impedance bandwidth with peak gain of 8.7 dBi. Chair et al.,[112] have designed an aperture coupled flipped stair structure with rectangular and circular cross section to achieve a bandwidth of 49.3% for square-shape and 32.8% for the square cross-sectional shape.

TABLE 2 Details of fractal/planer DRAs

Bandwidth	Specific geometry	Refs.
50%	Sierpinski fractal on cylindrical DRA	Karmakar et al.[95]
87.86%	Sierpinski fractal on a rectangular DRA	Soren et al.[96]
64%	Minkowski boundary fractal	Dhar et al. ,[97]
2-40 GHz	Koch fractal like monopole	Azari et al.[98]
47%	Hemispherical DRA with Apollonian Gasket of circles type fractal	Mukherjee et al.[99]
21%	Sierpinski carpet fractal based photonic band gap (PBG)	Mukherjee et al.[100]
Heptaband	Minkowski fractal	Dhar et al.[101]
10.3%	Parasitic coplanar 3-element DRA	Fan et al.[102]
~30%	CDRA arrays	Drossos et al.[103]
66%	Combination of Sierpinski and Minkowski fractal	Kiran et al.[104]

Deng et al.,[113] have designed a co-axial fed dual ceramic DRs and tuned the distance between the DRs for obtaining a wide bandwidth of 33.4% (1160 MHz) with good radiation pattern as that of single DRA. Li and Sun,[114] have analyzed and adjusted the feed line (parasitic strip) to achieve wide impedance bandwidth of 12% (270 MHz) in a DRA. Guha et al.[115] have achieved 3.2% impedance bandwidth in a quarter wave monopole fed DRA with monopole like radiation pattern. Gao et al.,[116] have proposed a rectangular DRA and a conductor backed CPW fed through slot achieved 23.5% (4.86-6.15 GHz). Kishk et al.,[117] have proposed L-shaped probe feed at the air filled groove DRA of $\varepsilon_r = 10.2$ giving 32% bandwidth whereas 39% bandwidth for $\varepsilon_r = 4.1$. Kumar et al.,[118] have experimentally analyzed a parasitic conducting strip cylindrical DRA with microstrip feed for achieving a bandwidth of 17.33%. The effect of coupling between the DR and feed-line as well as additional layer on bandwidth enhancement up to 28% has been studied by Rezaei et al.[119] Thirakoune et al.,[120] have analyzed the effect of directors and reflector on the DRA loaded monopole that covers 3 to 8 GHz frequency range with an 11.5 dB peak directivity. Kumar et al.,[45] have proposed a microstrip fed cylindrical shaped DR-antenna ($\varepsilon_r = 20.8$) offering 35% impedance bandwidth whereas 16.5% bandwidth with better matched vertical feed with conical radiation pattern. Zhang et al.,[121] have used a new conformal elliptical patch feeding mechanism to a compact U-shaped DR operating over 72% impedance bandwidth with 4.3 to 7.6 dBi gain for military as well as civilian communications.

An enhanced wide bandwidth of 73.0% has been achieved in a vertical trapezoid patch fed inverted L-shaped DRA by

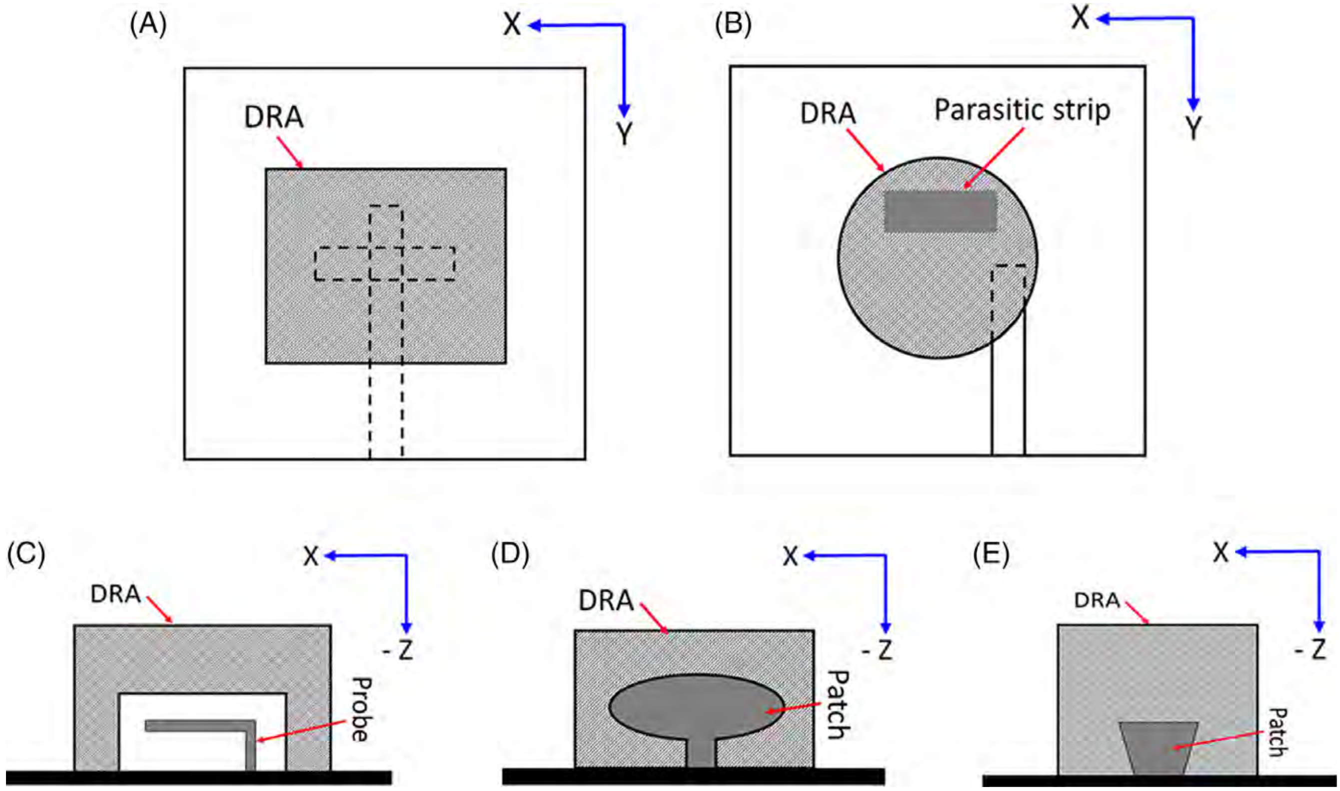

FIGURE 6 Different feeding mechanism used for wide bandwidth purpose: (A) Aperture,[112] (B) Parasitic strip,[114] (C) L-shape probe,[117] (D) Elliptical patch,[121] (E) Trapezoid patch[122]

Liang and Denidni.[122] Ghosh and Chakraborty,[123] have investigated a low mutually coupled two identical DRA loaded with T-shaped monopole antenna for UWB applications. Singh and Sharma,[124] have proposed single probe feed and anti-probe feed for a cylindrical DRA of $\varepsilon_r = 10.2$ operating at 82% (for single probe) and 68% (for anti-probe) with improved radiation pattern gain and cross-polarization. Al-Zoubi and Kishk,[125] have modeled a Mongia et al.[105] have obtained a 10% frequency bandwidth in a half-split microstrip line-slot vertical strip along with a coaxial probe for the feeding of a rectangular DRA where the measured return loss was found to be 65% (7.5 GHz bandwidth) with 8.3 dBi gain. A bevel shaped patch excited with CPW feed line was applied to a rectangular DRA ($\varepsilon_r = 10$) for obtaining a UWB band by Denidni and Weng.[126] Liang and Denidni[127] have used a co-axial probe fed rectangular DRA placed in a concave ground plane for obtaining 55% bandwidth (3.28-5.77 GHz) with 3.7 to 6.2 dBi gain. Liang et al.,[128] have designed an L-shaped DR-antenna fed by a conformal inverted-trapezoidal patch connected to a microstrip line which achieved 71.4% impedance bandwidth ranging 3.87 to 8.17 with 5 to 8.5 dBi gain. Ge and Esselle,[129] have found a $S_{11} < -10$ dB return loss over 3.1 to 10.7 GHz while a coaxial probe was used a feed. Gopakumar et al.[130] have investigated a half split circular, cylindrical profile DR antenna fed by a microstrip feed line offering 36.7% impedance bandwidth. A compact circular shaped-DR coupled by a crescent patch and CPW feed line has been designed for achieving UW band over 1.6 to 15 GHz by Weng et al.[131] Thame and Wu[132] have designed coaxial probe fed Bowtie shaped DRA for 49% bandwidth. Zheng et al.[133] have investigated a UWB monopole excited DRA for giving 110% impedance bandwidth ranging. A microstrip-line-fed Isosceles trapezoidal DRA has been designed by Gopakumar and Mathew[134] to offer the Kakade and Ghosh[135] have found wideband in a rectangular waveguide fed hemispherical DRA. Huynh et al.,[136] have developed a probe fed cylindrical DRA for achieving 46% impedance bandwidth by adjusting the aspect ratio and permittivity. An E-shaped patch with shorting wall technique has been adopted by Gao et al.[137] to achieve a bandwidth of 58% between 4.38 and 7.96 GHz with a rectangular DRA. Chaudhary and Rajni,[138] have excited a ring DRA with annular shaped microstrip feed covering 66.72% impedance bandwidth (3.49-7.2 GHz) with 4.31 dB gain. Rashidian et al.,[139] have investigated the matching of microstrip fed DRA for achieving a bandwidth of 35% by using a tapered microstrip feed. After this, 163.6% impedance bandwidth ranging 2 to 20 GHz with average gain of 5.64 dB using bevel shaped patch and coplanar wave guide excited cylindrical DRA has been proposed by Prachin et al.[140] Ozzaim et al.,[141] have designed a hybrid monopole DRA covering 138% impedance bandwidth. After this, Guha et al.,[142] have examined a UWB hybrid DRA of 137% (5:1) impedance bandwidth with monopole type feeding mechanism. Sunab et al.,[143] have realized a quadrature fed CP DRA for bandwidth of 43.3%, the AR bandwidth of 42.8% axial ratio bandwidth and 40.8% gain bandwidth. Prachi et al.,[144] have proposed a rounded bevel

TABLE 3 Bandwidth of DRAs based on feed line mechanism

Bandwidth	0%-9%	10%-19%
Ref.	NA	105,107,108,114,118
Bandwidth	20%-29%	30%-39%
Ref.	106,110,116,119,134	45,112,113,117,130,139
Bandwidth	40%-49%	70%-79%
Ref.	112,132,136,143	121,122,128
Bandwidth	80%-89%	≥100%
Ref.	124	111,133,140–142,144

shaped fed cylindrical DRA for achieving 124.4% impedance bandwidth covering 4.4 to 18.9 GHz.

Further, the achieved bandwidth using different feed lines are differentiated in terms bandwidth ranges in Table 3. This clearly surmise that, the feeding network put substantial impact on controlling the bandwidth ranges from 10% to more than 100%. However, at the same time the effect of shape of the DR cannot be avoided.

3.1.3 | Bandwidth improvement via different coupling slots

In case of DRA, coupling slot plays a key role in reducing input reflection by transferring maximum energy to the radiator. So, choice of specific shape of coupling-slot as per frequency range, DR shape, and feed line is quite tricky. Of course, depending upon the shape and number of slot(s), the bandwidth varies. All the bandwidth related literatures[145–152] emphasizing slot types are discussed here.

Leung et al.,[145] have reported annular-slot for coupling the DRA to offer better bandwidth of 18% as compared to 8 to 12% than those conventional DRA. Hui and Yung,[146] have analyzed a rectangular-slot coupled antenna loaded by a dielectric hemisphere with double dielectric coatings and also observed that the second dielectric coating layer significantly increased the bandwidth up to 8.5%. So and Leung[147] have studied the effect of slot on impedance bandwidth and utilized parasitic patch to increase the bandwidth frequency (3.75-4.35 GHz) tuning purpose. Buerkle et al.,[148] have merged the slot resonance and dielectric structure itself to achieve 25% impedance bandwidth with 4 dBi gain. Kishk[149] have designed a slot-fed mechanically more rigid structured DRA for achieving 50% impedance bandwidth.

Weng et al.,[150] have used the air dielectric between the rectangular DR and the ground plane for enhancing the bandwidth up to 61%. Deng et al.,[151] have introduced a pair of symmetrical edge resonators to antenna, where each resonator is composed of a T-shaped slot etched on the edge of the radiator and a strip printed on the opposite side of the substrate along with U-slot DFS concept to achieve dual band of 2.4 to 2.48 GHz for Bluetooth and 3.1 to 10.6 GHz for UWB frequency bands. Rahimian et al.,[152] have used branch line coupler to excite a rectangular DRA for operating over more than 90% impedance bandwidth. Moreover, different bandwidth ranges covered by means of slot mechanisms are briefed in Table 4. From this it is confirmed that, different slot types have significant effect on bandwidth range covering up to ~70% impedance bandwidth.

3.1.4 | Bandwidth improvement via high permittivity

During this review process it has been also found some papers related to bandwidth by highlighting permittivity in their title. Mainly the effect of high permittivity on impedance bandwidth is discussed here.[153–164] Mongia et al.,[153] have reported a high permittivity rectangular DRA ($\varepsilon_r = 100$) to achieve 3% impedance bandwidth. Leung et al.,[154] have investigated high permittivity dual disk DRA for getting 4.6 times wider impedance bandwidth than that of single element. Leung et al.,[155] have proposed a low profile DRA disk of high permittivity to achieve a bandwidth of 25%. Guo and Luk[156] have designed a coplanar waveguide fed low permittivity DR-antenna with an extra added vertical strip for improving coupling attained impedance bandwidth of 22% and 5.5 dBi gain. Bijumon et al.,[157] have used high permittivity DRA loaded over a patch to achieve 14% impedance bandwidth centered at 2.32 GHz. Zu[158] has demonstrated some techniques for obtaining broadband DRA. Rashidian et al.,[159] have used strip excitation technique to very low permittivity resonator ($\varepsilon_r = 6$) to get 18% bandwidth whereas 11% for $\varepsilon_r = 10$ and reached to 42% when the strip acted like radiator when mixed with dielectric constant of 4. Rotaru et al.,[160] have found a wide impedance band between 2.4 and 2.5 GHz in a "C" shaped high permittivity DRA.

Huynh et al.,[161] have informed that, the impedance bandwidth could be maximized for a small relative permittivity that is greater than unity while radiation pattern degraded if the permittivity decreases. Wide band of 81.7% has been achieved by Madhuri et al.,[162] in a rectangular ring slot coupled high permittivity rectangular DR-antenna. Avadanei et al.,[163] have proposed to excite high permittivity DR material in superior modes to obtain wide impedance bandwidth, which has been experimented in a rectangular slot fed cylindrical DRA. Liu et al.,[164] have developed low profile multilayered DR with the combination of two high permittivity DR and low permittivity layer in-between them which gave an impedance bandwidth of 10.49% and gain >6 dBi. A compressive details of bandwidth ranges are shown in Table 5.

3.1.5 | Bandwidth improvement via exciting different mode

Though, the physical parameters of any antenna affects the bandwidth performances, still one hypothetical parameter known as mode also affects the same. The behavior of the antenna improves by means of better radiation characteristics by exciting certain radiating modes of the resonator and for this purpose feed type plays an important role. The compressive discussion of some novel ideas of certain mode excitation[85,150,165–169] for bandwidth control is discussed here. The field distribution of some of the common radiating mode of DRA (here only Cylindrical shape) are shown in Figure 7.

Li and Leung,[165] have developed a strip fed DR-antenna for achieving 43% impedance bandwidth by exciting TE_Y

TABLE 4 Bandwidth of DRAs based on slot mechanism

Bandwidth	0%-9%	10%-19%	20%-29%
Ref.	146	145	148
Bandwidth	50%-59%	60%-69%	90%-99%
Ref.	149	150	152

mode and the higher order TE_{Y3}. Chang and Kiang,[166] have proposed a rectangular-slot fed offset well type DRA to attain a bandwidth of 18% with more than 4 dBi gain by exciting TE^{y}_{111} mode. Chang and Kiang,[167] have designed to achieve a 29% wide impedance band by merging three resonant bands of different modes. Again, Chang and Kiang,[168] have merged three resonant modes (ie, TE^{y}_{111}, TE^{y}_{112}, TE^{y}_{113}) to achieve 33% impedance bandwidth (4.89-6.86 GHz), with broadside ration pattern. Weng et al.,[150] have proposed a slot fed DRA with merged resonant modes of the isolated DRs and equivalent DR to achieve wide impedance bandwidth of 62%. Ge et al.,[169] have analyzed a rectangular DRA with sorting conducting wall where the low Q-modes of the overlapping bands were exploited to achieve wide continuous band of more than 109.5%. Mukherjee et al.,[85] have excited a half hemi-spherical DRA in TM_{101} mode by SMA connectors and probe along with the array of slots and achieved ~17.74% bandwidth and when the probe length was increased it enhanced to >29%. Further, different specific modes and their respective bandwidth ranges are highlighted in Table 6. It clears that, single mode gives an average ~25% impedance bandwidth while the merge of modes gives an average >35% impedance bandwidth. However, in every case, the reduction of volume (weight) of the DR is a superior advantage.

3.2 | Bandwidth improvement in dual-band/multi-band operation

The dual-band/multi-band operation of DRA is also quite important from application point of view.[4] Hence, for the same purpose, different techniques have been proposed in context to DRA. For easy and smooth classification, literature based on dual-band[170–180] and on multi-band[181–186] is discussed in this section, respectively.

A microstrip fed ring DRA for dual frequency operation has been proposed by Sung et al.,[170] which can applicable for satellite and wireless applications. Kumar et al.,[171] have designed a microstrip fed cylindrical sector DRA with VSWR bandwidth of 12.35% and 17.82%. Kumar et al. ,[172] have designed microstrip fed cylindrical shaped DR-antenna for operating impedance bandwidth of 2.46% for band 1 (1.684-1.726 GHz) and 1.15% for band 2 (2.426-2.454 GHz). Lim and Leung,[173] have studied dual wide band aperture coupled DRA ($\varepsilon_r = 6$) for operating in (2.21-2.855) GHz and (4.385-5.455) GHz for WLAN applications. Gao et al.[174] have developed dual band rectangular CPW fed hybrid DRA resonating at 2.4 and 5.3 GHz.

Adz et al.,[175] have proposed a E-shaped aperture fed cylindrical DRA for dual band operation at 5 GHz (with conducting strip under DRA) and 2.45 GHz (with metallic top loaded DRA). Kumar et al.[176] have reported a laminated wave-guide fed cylindrical DRA to operate at 9.76, 10.53, and 11.8 GHz with bandwidth 56, 160, and 250 MHz, respectively. Sharma et al.,[177] have excited three different modes ($HEM_{11\delta}$, $TM_{01\delta}$, and $HEM_{12\delta}$) in a cylindrical DRA by means of different feeding techniques resulting multi band operation over 2.5 to 3.02 GHz, 3.76 to 3.86 GHz, and 4.38 to 4.72 GHz. A dual band and wide band microstrip feed excited ring DRA has been developed by Khalily et al.,[178] which covers 73% (2.78-5.95 GHz; wide band) and dual bands of 8% (2.4-2.6 GHz) and 56% (3.3-5.85 GHz). Mehmood et al.,[179] have designed dual band transparent glass DRA fed by a microstrip feed line with perpendicular strip covers 18% (5.15-5.95 GHz), where the modified feed created dual resonance. Zou and Pan,[180] have introduced annular circular slot with two rectangular slot opposite (135° and 45°), to a rectangular DRA ($\varepsilon_r = 12$) for creating dual bands of 3.7%, 9.1% for the lower band and 3.7%, 14.4% for the upper band, respectively. Moreover, the dual band DRA operating frequency details are summarized in Table 7.

Hamsakutty et al.,[181] have modeled a single coaxial fed Hexagonal DRA resonating at 2.215, 2.784, 3.445, and 3.955 GHz. Sangiovanni et al. ,[182] have proposed multi-frequency stacked DRA with 4.9% impedance bandwidth and 1.75 maximum higher to lower frequency ratio. Hamsakutty et al.,[183] have investigated a coaxial probe fed metal-coated DR-antenna for 3 VSWR bands operating at 1.46, 2.41, and 3.23 GHz. Fang and Leung,[184] have designed a rectangular DRA for single-band, dual-band where different excitation sources have used for dual band, wide band designs. Paul et al.,[185] have proposed two identical high permittivity DRA kept 7.5 mm apart from each other for multiband operation resonating at 1.9 and 2.4 GHz. After this, a high permittivity compact DRA of ($\varepsilon_r = 140$), has been proposed by Bit-Babik et al.[186] for multimode operation with enhanced bandwidth of 25%.

3.3 | Bandwidth Improvement with other characteristics

In literature, in-addition to only-bandwidth analysis some researchers have also pointed out some other important characteristics (far-field characteristics)[187–189] and notch.[190,191] These are discussed here. Singh and Sharma[187] have designed a dual co-axial fed cylindrical DRA for 68% impedance bandwidth with broad side radiation pattern and 82% BW with omnidirectional and directional ration pattern as well as high cross polarizations for single probe feed. Ryu

TABLE 5 DRAs details related to permittivity/shape

Bandwidth	0%-9%	10%-19%
Ref.	153,158	157–159,164
Bandwidth	20%-29%	80%-89%
Ref.	155,156	162

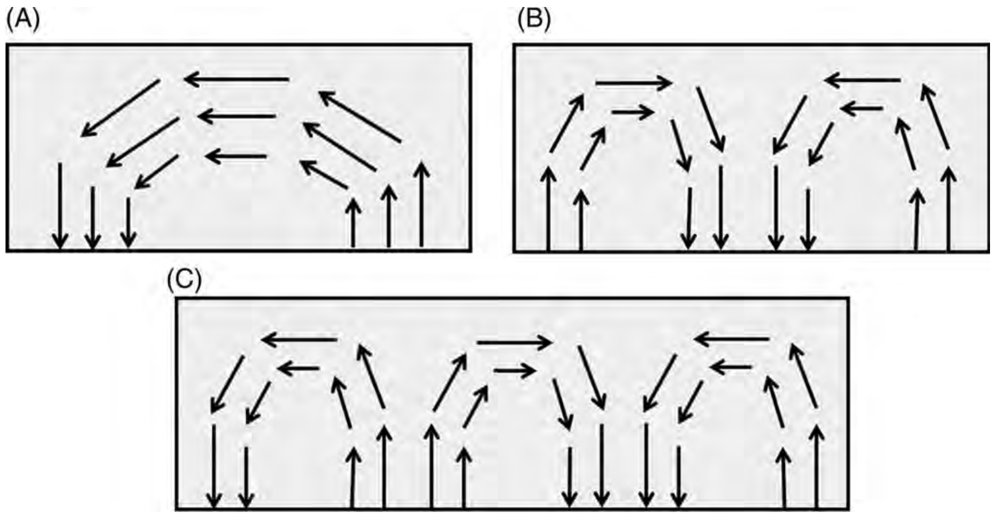

FIGURE 7 E-field distribution (side view) of rectangular DRA: (A) TE^y_{111}, (B) TE^y_{112}, (C) TE^y_{113}

et al.,[188] have proposed a compact coplanar wave guide fed monopole type DRA for UWB operation over 3.1 to 10.6 GHz with omnidirectional radiation pattern and very low cross polarization. Khalily et al.[189] have developed a rectangular DR-antenna with tapered strip excitation on one side while narrow strip on the opposite side to enhance the bandwidth up to 96% (ie, 2.13-6.08 GHz) with improved radiation pattern compared to 66% in convectional one. A circular patch with monopole like radiation, have inserted in to the DR structure by Niroo-Jazi et al.,[190] for controlling of the stop band in between a UWB ranging 2 to 10.7 GHz with stopband response between 5.15 and 5.825 GHz. Shao et al.,[191] have designed probe fed UWB rectangular stacked DRA operating over 3.1 to 10.6 GHz with a band notch generated by a thin printed dipole near the feeding probe.

4 | SUMMARY

In this survey article, the bandwidth related literatures covering more than 180 articles have been discussed. From readers' point of view the bandwidth related articles have been analyzed from different aspects as shown in Table 8. On summarizing this review process, several observations have been stated. The research on DRA for single band is much more

TABLE 6 Bandwidth and mode details of DRAs

BW details	Effects of mode(s)	Refs.
43%	Exciting TE^Y mode + higher order TE^y_3	Li and Leung[165]
18% (5-6 GHz)	Exciting TE^y_{111} mode	Chang and Kiang[166]
29%	By merging three resonant bands of different modes	Chang and Kiang[167]
33% (4.89-6.86 GHz)	Merging three resonant modes (ie, TE^y_{111}, TE^y_{112}, TE^y_{113})	Chang and Kiang[168]
62% (2.4-4.5 GHz)	Resonant modes of the isolated DRs and equivalent merged DR	Weng et al.[150]
109.5%	Low Q-modes of the overlapping bands were exploited	Ge et al.[169]
>29%.	TM_{101} mode excited	Mukherjee et al.[85]

TABLE 7 Details of DRAs related to dual band

Dual/multi band details	Refs.
Dual frequency operation	Sung et al.[170]
Dual VSWR bandwidth of 12.35% and 17.82%	Kumar et al.[171]
2.46% for band 1 (1.684-1.726 GHz) and 1.15% for band 2 (2.426-2.454 GHz)	Kumar et al.[172]
(2.21-2.855) GHz and (4.385-5.455) GHz	Lim and Leung[173]
Dual band resonating at 2.4 GHz and 5.3 GHz	Gao et al.[174]
Dual band operation at 2.45 GHz and 5 GHz	Adz et al.[175]
Operating at 9.76, 10.53, and 11.8 GHz	Kumar et al.[176]
Covering (2.5-3.02) GHz, (3.76-3.86) GHz, and (4.38-4.72) GHz	Sharma et al.[177]
73% (2.78-5.95 GHz) (wide band) and dual bands of 8% (2.4-2.6 GHz) and 56% (3.3-5.85 GHz)	Khalily et al.[178]
18% (5.15-5.95) GHz	Mehmood et al.[179]
3.7%, 9.1% for the lower band and 3.7%, 14.4% for the upper band	Zou and Pan[180]

TABLE 8 Summary of bandwidth based DRAs

Stage 1	Stage 2	Stage 3	Refs.
Bandwidth	Single band	By shape	11–104
		By coupling	45,105–152
		By permittivity	153–164
		By mode	85,150,165–169
	Dual band	–	170–180
	Multi band	By shape	181,182
		By coupling	183,184
		By permittivity	185,186
	Bandwidth with other characteristics	BW + radiation	187–189
		BW+ notch/gain	190,191

than dual/multiband research. Among these, the DR shape has been found to be a major key factor in controlling operation range than the coupling mechanism, permittivity, and mode of operation. At the same time the research on radiation characteristics and notch along with bandwidth is very less. The outcome of this review article can be summarized as, (a) highlights the research based on single band, dual band, and multi band separately, (b) differentiate the techniques by means of shape, coupling, permittivity, and mode of operation, and (c) shows some research based on bandwidth along with other characteristics. The different configurations of DRAs for different features are summarized in Table 8.

5 | CONCLUSION

This review article has highlighted chronologically the advancement of DRA from bandwidth point of view. The open intention of this review work is to show an encouraging path to the antenna modelers for the performance advancement of DRA in terms of bandwidth with miniaturization of the existing ones.

The review article reveals that, DRA has the capability for almost all types of bandwidth characteristics in an improved manner than those convectional antennas. The number of referenced paper gives an idea of tremendous investigation on bandwidth, which indicates a wide control of modern wireless communication covering all bands in near future. From a qualitative point of view, it can be noted that, (a) the shape of the DRA mainly fractal and hybrid shape has much impact on improving bandwidth by means of increasing the radiation, (b) use of extra conducting sheet seems to be more effective in enhancing bandwidth by enabling strong coupling to the DRA, (c) excitation of certain modes enables the energy to come out easily from the DR to the free space resulting enhanced bandwidth.

From a prospective point of view, this article may be helpful in, (a) getting an idea for designing DRA for any specific range of operation or specific band, (b) design of some hybrid shape DR with favorable coupling mechanism, which has not yet been so far, (c) introduction of some hybrid fractal DRA. However, authors recommendations are as follows: (a) from shape point of view hybrid DRA with Sierpinski and Minkowski could be a superior alternative for wideband as well as multiband, (b) from mode point of view combination of multiple modes preferably lower modes can be combined for wider impedance bandwidth, (c) from coupling point of view wider patch with slotted DR could achieve better bandwidth provided perfect matching network.

No doubt the authors have tried at their level best to frame out all novel and important contribution of bandwidth related DRA research starting from innovation to advancement around the globe, still the authors apologize to the great researcher community if any important and novel contribution is skipped unknowingly and unintentionally during this review process.

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