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Dielectric Resonator Antennas: Designs and Advances

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Abstract—This article presents a comprehensive review of the research carried out on Dielectric Resonator Antennas (DRAs) over the last three decades. Dielectric resonator antennas (DRAs) have received increased attention in various applications due to their attractive features in terms of high radiation efficiency, light weight, small size and low profile. Over last decades, various bandwidth enhancement techniques have been developed for DRAs. In this article, the attention is focused on a type of DRAs that can offer multi-resonance frequencies and these frequencies can be merged into a broad band. In order to effectively review design techniques, DRAs in this article are categorized into three types, broadband, ultra-wideband (UWB) and multiband. The latest developments in DRAs are discussed in the limited scope of this article.

1. INTRODUCTION

Keeping with the market demand, the requirements for the antenna design are changing continuously. Today's consumer market demands electronic systems of high efficiency, wide bandwidth and reduced equipment size. Meeting these demands in the RF and wireless domain is a major challenge since it involves design of an antenna to be embedded into wireless products. Over the last two decades two classes of antennas, i.e., the microstrip antenna and the dielectric resonator antenna (DRA) have been under investigation for modem wireless applications. Being high Q antennas, the microstrip antennas, possess narrow bandwidth. To increase the bandwidth, one of the early proposals was to increase the electrical thickness of the substrate. It had two major disadvantages: increasing the surface waves & Ohmic losses and thereby reducing radiation efficiency.

While research on microstrip antenna was picking up increasing attention around the globe, in early part of eighties, Stuart Long developed the dielectric resonator antenna (DRA) [1]. The DRA is a resonant antenna, fabricated from a high-permittivity (from about 6 to 100) dielectric material mounted on a ground plane and fed by a coaxial probe, slot coupling or a microstrip line in the ground plane, though some low values are being recently explored as antennas [2]. Theoretical and experimental investigations have been carried out with various shapes such as cylindrical, rectangular and hemispherical structure allowing for flexibility in design. The impedance bandwidth for a DRA is a function of material permittivity and aspect ratio (length-to-height ratio) [3]. Higher permittivity can result in size reduction, whereas lower permittivity can broaden the bandwidth. Most of the previous work focused on characterizing the basic properties of DRA for varieties of simple shapes and feed configurations. Also much effort has been put into investigations on linearly polarized wideband DRAs [4].

At mm-wave, the DRA offers advantages like smaller size than conventional antennas by a factor of square root of the dielectric constant of the material (ε_r), high radiation efficiency ($> 95\%$) due to absence of conductor or surface wave losses, increased bandwidth, low cost and compatibility to

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planar antenna feeding techniques. Compared to the microstrip antenna, the DRA has wider impedance bandwidth. For a simple rectangular DRA, a bandwidth of 10% can be achieved for a dielectric constant of 10 or less [1]. The microstrip antenna radiates through two narrow edges of the patch whereas the DRA radiates through its entire surface except the grounded portion. Surface waves are absent in the DRA in contrast to the microstrip antenna [4] improving the efficiency and reducing distortions in the radiation pattern.

It is an off-shoot of the work of Ritchmyer in which he showed in 1939 [5] that a block of dielectric material, with very high dielectric constant, resonates in free space and such a resonator exhibits radiation damping. Dielectric resonators have been used as high Q element in microwave circuit applications following the development of low-loss ceramics in the late 1960s. The initial work on determining resonant frequencies of dielectric resonators greatly facilitated advancements in design of antennas using such resonators as antenna [6, 7]. Many disadvantages of microstrip antenna do not appear in Dielectric Resonator Antennas (DRA), even at millimeter wave frequencies. The impact of DRA in the field of antenna is evident from over 800 reported papers, which include three major review articles. Unlike these previous reviews, this article focuses primarily on broad banding techniques for DRA.

Since the start of this new millennium, many more researchers have begun investigating dielectric resonator antennas. Work has continued in various areas like compact designs, miniaturization techniques, low-profile designs, wideband designs etc.. New areas of research include enhanced gain techniques, finite ground plane effects, multiband and ultra-wideband designs. Most of these works involve study of new dielectric resonator antenna shapes including conical, tetrahedral, hexagonal, pyramidal, elliptical and stair-stepped shapes or hybrid antenna designs using dielectric resonator antennas in combination with microstrip patches, monopoles or slots. A significant number of the more-recent publications focus on designing dielectric resonator antennas for specific applications like Wi-max, WLAN applications, UWB applications, RFID and all dielectric wireless receivers. In the next section, this paper briefly outlines the frequency range and some basics shapes of DRA geometry in use. It is followed by a summarized discussion on some design techniques in areas of wideband DRA, ultra wideband DRA and multi band DRA. Some examples with advantages, disadvantages and configurations for various applications are given in the penultimate section. In the concluding section the review is summarized.

2. FREQUENCY RANGES AND DRA GEOMETRIES

Various factors determine the practical range of operating frequencies over which an antenna can operate. At lower frequencies, the physical properties of the antenna (size and weight) are often the limiting factors, while at higher frequencies; it is mechanical tolerances and electrical losses that often dominate antenna designs. One characteristic of dielectric resonator antennas is that their maximum dimensions (D) is related to the free-space resonant wavelength (λ_0) by the approximate relation $D \propto \lambda_0 \varepsilon_r^{-0.5}$, where ε_r is the relative permittivity of the dielectric resonator antenna. Since the radiation efficiency of a dielectric resonator antenna is not significantly affected by its dielectric constant, a wide range of values can be used. However, the bandwidth of the DRA is inversely related to the dielectric constant, and may limit the choice of values for a given application. By using a material with a high dielectric constant, the size of the DRA can be significantly reduced, making it viable for low frequency operations. There are many published designs of DRAs operating at frequencies from 1 to 40 GHz, with dimensions ranging from a few centimeters to few millimeters and dielectric constants approximately ranging from $8 \leq \varepsilon_r \leq 100$.

Dielectric resonators of any geometric shape can be used for antenna design though rectangular, cylindrical, hemispherical, circular cross-sections are predominant. The design parameters such as permittivity, resonant frequency, input impedance, radiation pattern and coupling mechanisms vary for different shapes and hence the analytical model for analyzing each geometrical configuration is different.

Simplified analysis and mechanical fabrication play important role in selection of shape for antenna. In order to compare the geometries of the DRAs, the dimensional degrees of freedom are considered [4]. For a DRA with rectangular cross section, two of the three dimensions (length, width and height) can be varied for a given resonant frequency and for a fixed dielectric constant. Hence, it has two degrees of freedom. The cylindrical DRA has one degree of freedom. Different values of radius height pairs give different values of bandwidth, directivity and volume occupations [4]. For hemispherical geometry, the radius determines the resonant frequency. The hemispherical DRA has zero degrees of freedom. Therefore, the bandwidth remains fixed and is difficult to optimize for particular requirements and hence the hemispherical DRAs are less frequently used [4]. The rectangular DRA offers practical advantages over the spherical and cylindrical shapes, due to the flexibility in choosing the aspect ratios.

3. RECENT ADVANCES IN BROAD BANDING TECHNOLOGY IN DRA

The DRAs can be used in different configurations to provide significant improvement in parameters such as bandwidth and size. This section includes some of the current broad banding design techniques for wideband DRA, ultra wide band DRA and multi band DRA. Results from several examples are also presented addressing their advantages and disadvantages.

3.1. Wideband Dielectric Resonator Antennas

With the development of modern communication applications, there is an increasing need for antennas that provide both wide bandwidth and miniaturization. The need for increasing the information transfer also demands bandwidth enhancement, without sacrificing performance. Dielectric resonator antennas are versatile elements that can be adapted to numerous applications by properly choosing the design parameters such as the permittivity of the material, Q-factor and the dimensions. The Q-factor of the dielectric resonator is proportional to the permittivity ε_r of the material. High permittivity of the material increases the Q-factor, which results in narrow bandwidth. The high permittivity DRAs tend to have a single resonant frequency with a well-defined internal field structure and hence do not have the bandwidth required for modern communication systems. Several investigations have been carried out in order to achieve bandwidth enhancements for DRAs. Some of the techniques are summarized in the following sections.

3.1.1. Mono DRA

Mono DRA is defined here as a single DRA realized out of a single dielectric material without any restriction on its shapes. Almost for all regular geometries, an approach for broad-banding is to remove portions from DRA [6]. Another approach is to modify geometry so as to obtain various shapes, such as a tetrahedron and triangular [8], truncated tetrahedron [9], spilt cylinder [10], conical DRA [11]. These approaches have advantages like keeping the DRA in a single volume and thereby maintaining compact size. Also, the modified geometries have more design parameters, so better performance can be obtained by optimizing these parameters. However, since the excited modes are very sensitive to the dimensions of the DRA, more design parameters may also increase difficulty in designs. In addition, due to the hardness of DRA materials, re-shaping geometry of a DRA is not easy in fabrication. In a recently reported work, a simple cylindrical DR provides broadband operation by merging two different modes in a mode family [12], it has a simple shape and a single volume but it needs very precise dimensions

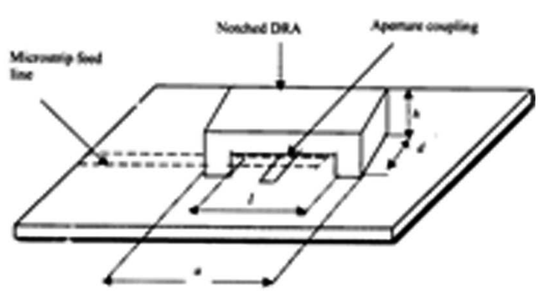

Figure 1. Notched rectangular DRA with aperture slot coupling [6].

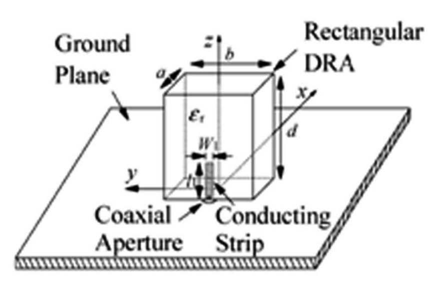

Figure 2. Configuration of strip-fed rectangular DRA [15].

that lead to dual modes in a mode family, which increases significantly the difficulty in simulations and fabrications.

Simple rectangular DRA investigated in the literature can offer impedance bandwidths of up to 10% [6]. To obtain wider bandwidths, a slot-fed rectangular DRA with its central portion removed to provide a notch as shown in Figure 1, has been shown to offer bandwidths up to 28% [6]. Removing the notch causes a decrease in the effective dielectric constant of the DRA, which lowers the radiation Q-factor, thus increasing the bandwidth. By varying the relative dimensions of the notch, the DRA can be used for broadband or dual band operation. This method of bandwidth enhancement is very convenient, as it does not require additional matching network [6]. Coulibaly et al. [13] achieved broad banding using microstrip-fed DRA for X-band. This antenna suffers from periodic mismatch, particularly at high-frequency end. A list of several single DRA designs is provided in Table 1.

With the introduction of fractals in antenna engineering, Hajihshemi and Abiri investigated DRAs with fractal shape and reported that with increase in fractal iteration the ratio of surface to volume

Table 1. Mono DRA designs (ε_r is the dielectric constant of the DRA; BW is the $-10\,\text{dB}$ S_{11} bandwidth).

S.N.	DRA geometry	ε_r	Feed mechanism	BW ($-10\,\text{dB}$)	Ref.
1.	Flipped staired pyramid	12	Slot	∼62%	[14]
2.	Strip-fed Rectangular DRA (Figure 2)	9.8	Conducting strip	∼43%	[15]
3.	Inverted L-shaped DRA	9.2	Probe	∼38%	[16]
4.	Cylindrical DRA	12	Probe	∼30%	[17]
5.	Half-hemispherical DRA	10	Probe	∼35%	[18]
6.	Cylindrical cup DRA	10.2	L-shaped probe	∼32%	[19]
7.	Two step Stair shaped DRA	12	slot (square cross-section)	∼54.3%	[20]
		10.2	probe (circular cross-section)	∼40%	
8.	Rectangular DRA with an offset well	20	Slot	∼ 18%	[21]
9.	U-shaped DRA	9.8	Elliptical patch	∼72%	[22]
10.	Rectangular DRA with a tunnel	20	Slot	∼20%	[23]
11.	H-shaped DRA	9.8	trapezoidal patch	∼ 62%	[24]
12.	L-shaped DRA	9.8	Conformal inverted-trapezoidal patch	∼71.4%	[25]
13.	High aspect ratio (5.2 : 1) rectangular DRA	25	Micro strip line	∼16%	[26]
14.	Rectangular DRA with a moat	20	Slot	∼33%	[27]
15.	Cylindrical DRA	10	Conformal metallic strip connected to SMA probe	∼66%	[28]
16.	Rectangular DRA placed on a concave ground plane	9.8	probe	∼55%	[29]
17.	Embedded multisegment Rectangular DRA	9.8	Vertical feeding strip	∼49.5%	[30]
18.	Trapezoidal DRA shown in Figure 3	10	Probe	∼55%	[31]
19.	Cylindrical DRA	10.2	Dual coaxial probe	∼68%	[32]
20.	Bowtie DRA (Figure 4)	9.8	Probe	∼49.4%	[33]
21.	Cylindrical DRA (Figure 5)	10.5	Narrow slot in a rectangular waveguide	∼20%	[34]
22.	Circular Disk DRA (Figure 6)	10.5	Waveguide probe	∼50%	[35]

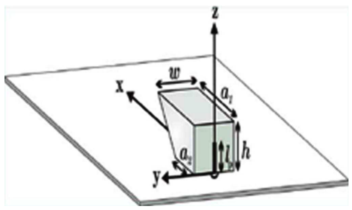

Figure 3. Probe fed trapezoidal DRA [31].

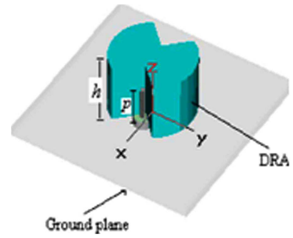

Figure 4. Broadband bowtie DRA [33].

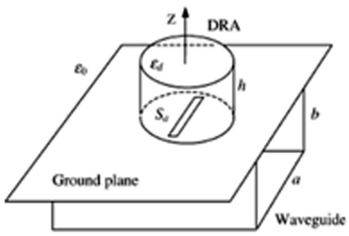

Figure 5. Geometry of the DRA excited by a narrow slot in a rectangular waveguide [34].

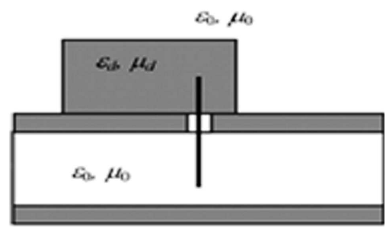

Figure 6. Waveguide-probe-excited circular disk DRA [35].

in dielectric resonator increases and thereby enhance the Q-factor which tends to increase in antenna impedance bandwidth [36]. Fractal DRA for wireless application is also reported by Gangwar et al. in [37]. Fractal rectangular curve [38] is used to achieve wideband performance covering the Body Area Network and also the IEEE 802.11a frequencies. It also accomplishes miniaturization of 50% of a rectangular DRA using a modified rectangular fractal curve along the cross-sectional boundary.

3.1.2. Poly Dielectric Resonators

Poly DRA is defined as a combination of multiple units consisting of same or different dielectric materials, which may or may not load each other. The excited modes in the resonators may or may not be the same. For the same modes, the corresponding radiation performances have a good agreement. For different modes, similar patterns can also be obtained by adjusting suitable parameters.

In this category, an earlier design is a pair of slot coupled-DRAs [39]. It consists of two rectangular dielectric resonators that are displaced near the two edges of a single slot on a ground plane shown in Figure 7. Since the two DRAs have the same shape and material but different sizes, it may be possible to get the same resonance modes at different resonance frequencies. The advantage of this

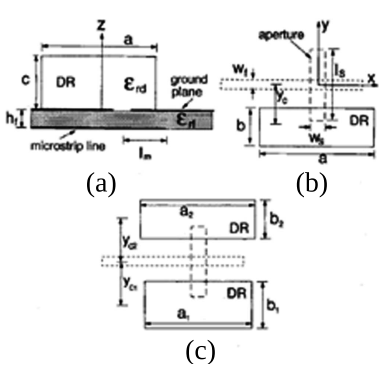

Figure 7. (a) Side and (b) top views of a DR element coupled by a slot in the ground plane of a microstrip line. (c) Top view of two DR elements coupled by a single slot [39].

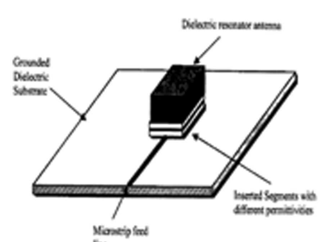

Figure 8. Multisegment DRA.

approach is that each resonator can be tuned more or less independently, allowing for a great deal of design flexibility, reducing the complexity in trial designs. The disadvantage lies in the additional space requirement, which increases the size of antenna and may preclude some of these configurations from being used in an array environment. There is also one alternative approach proposed for combining two dielectric resonators together as if one resonator is loading the other. For example, a dielectric resonator is stacked on the top of the other [40–43], or a smaller dielectric resonator is inserted into another lager dielectric resonator [44, 45]. In this approach, the combination of two dielectric resonators can operate either in the same mode or at different modes.

For efficient coupling, a DRA with high permittivity is required since the Q-factor of the resonator is proportional to permittivity of the dielectric material. Hence the bandwidth is narrow due to high Q-factor. O'keefe and Kingsley [46] reported RF range liquid DRA that uses water as dielectric which adds a new range of dielectric antenna research. Lai et al. [47] revisited the radiation efficiency of DRA and by using Wheeler cap method confirmed that radiation efficiency of DRA is much higher than microstrip antenna in millimeter wave frequencies. Moreover, the problem of poor radiation efficiency can be overcome by using an array of DRAs over the microstrip line, each DRA radiating small amounts of power. However, to make an efficient array, many DRAs are required to maximize the radiated power. In addition, the amount of energy coupled between the DRAs and the microstrip line is small. To overcome these disadvantages, a multi-segment DRA was investigated by Kishk and Kajfez [48]. It consists of a rectangular DRA with relatively low permittivity, under which one or more thin segments of higher permittivity are inserted as shown in Figure 8. The segments help in matching the impedance of the DRA to the microstrip line which helps in improving the coupling performance. The permittivity and thickness of the inserts affect the resonant frequency, impedance bandwidth and coupling level. Stacking the dielectric elements provides good bandwidth, but the design is not compact and not feasible for microwave integrated circuits. However, by limiting the number of segments, the MSDRA can be easily integrated with microwave printed circuits. Besides, a DRA of multiple layers can be used to enhance the bandwidth [49], and multiple layers can also be used to enhance the bandwidth of loaded dielectric resonator antennas [50]. A list of poly-dielectric DRA designs is provided in Table 2.

Table 2. Poly-dielectric DRA designs.

S.N.	DRA geometry	Feed mechanism	BW (−10 dB)	Ref.
1.	Four-elements Cylindrical DRA (Figure 9)	Probe	29%	[51]
2.	Stacked and Embedded Cylindrical DRAs shown in Figure 10	Probe	68.1%	[52]
3.	Multi-layered cylindrical DRA (MCDRA)	Probe	66%	[53]
4.	DRA with metal coating	CPW	47%	[54]
5.	Two-layer hemispherical DRA	Slot	55%	[55]
6.	Dual segment rectangular DRA	probe	50.25%	[56]

3.1.3. Hybrid DRA

This is a technique adopted from aperture coupled microstrip antennas [57, 58] for broad-banding. It uses a combination of a DRA with other resonators or antennas, such as a microstrip patch or a slot radiator. Each individual radiator in the hybrid structure is designed to radiate in its own separated band. If the two bands are close to each other, a hybrid resonator can offer broadband operation. A disadvantage evident in a dielectric-resonator-on-patch antenna [59] is the power coupling from the microstrip line to the two radiators, which requires two layered substrates, increasing the size and complexity of the antenna. Other alternative designs had also been investigated by using the combination of a dielectric resonator with a strip or a slot radiator. The advantage of such designs is that these structures use only one substrate layer. For instance, a CPW feed T-shaped strip is used to feed a pair of rectangular DRAs [60] or a microstrip fed rectangular slot is employed to feed a rectangular slot [61]. In a cavity backed DRA [62] tuning over a broad bandwidth has been realized. But it shows high front-to-back ratio

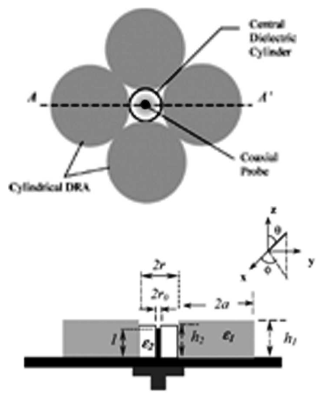

Figure 9. Four elements cylindrical DRA fed by a central coaxial probe [51].

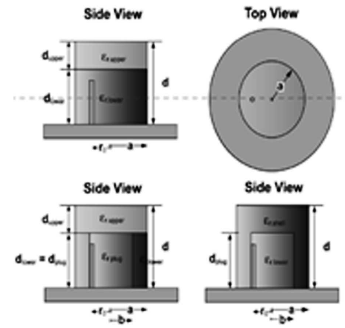

Figure 10. Stacked and embedded cylindrical DRA [52].

and asymmetry in the E-plane radiation patterns from both the DR and the slot. Further improvements may be obtained by designing the slot to resonate at the upper frequency band and exciting both the DR & the slot at their centers.

Hybrid resonator antennas have advantages in terms of low profile and compact size. The disadvantage usually comes from the interactions among resonators, which makes it difficult to tune resonance frequencies for individual component. A list of several hybrid DRA designs is provided in Table 3.

Table 3. Hybrid DRA designs.

S.N.	**DRA geometry**	**Feed mechanism**	**BW (-10 dB)**	**Ref.**
1.	Cylindrical DRA where backing cavity is placed beneath the stub.	Circular aperture coupled by a microstrip feed line with a microstrip fork-like tuning stub.	40%	[62]
2.	Cylindrical DRA	Modified microstrip line	26%	[63]
3.	Rectangular DR and a CPW inductive slot	slot	28.9%	[64]
4.	Rectangular DR and a conductor-backed coplanar waveguide (CB-CPW) slot etched on a small ground plane.	probe	23.5%	[65]
5.	Cylindrical DRA utilizing a pair of 90° hybrid couplers.	Quadruple strip feed	34.5%	[66]
6.	Rectangular DRA integrated with a surface mounted short horn.	slot	25%	[67]
7.	Rectangular DRA	Two vertical strips quadrature in phase	32.8%	[68]
8.	Cylindrical DRA	Conformal lines	50%	[69]
9.	Hollow Rectangular DRA	Conducting Strips	33.8%	[70]

3.1.4. Variants of Circular Cylindrical DRA

An annular DRA, a consequence of dielectric ring resonators of very high permittivity, is realized by removing a portion from the central section to form an annular ring and feeding it with a probe placed

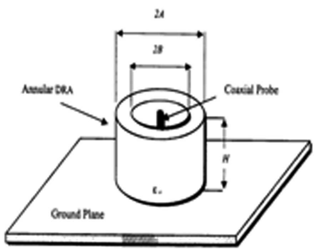

Figure 11. Probe fed annular DRA.

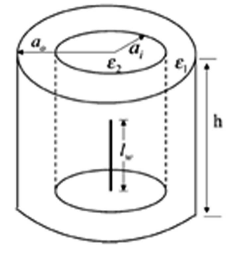

Figure 12. Proposed stacked double annular-ring DRA [72].

at the center (Figure 11). Following notched rectangular DRA, Shum and Luk [71] proposed a modified annular DRA in which the air gap between the DRA and the ground plane is used to enhance the bandwidth. Guo et al. proposed stacked double annular-ring DRA [72] shown in Figure 12, which offers an impedance bandwidth of ∼42% in reference to $-10\,\mathrm{dB}$ of S_{11}. Chair et al. presented a wideband perforated DRA (PDRA) [73], where the effective permittivity of the dielectric resonator was altered by drilling holes into a circular ring lattice inside the DRA. The PDRA is equivalent to an annular ring with lower permittivity outside the cylindrical disk which is capable of impedance bandwidth enhancement. The measured bandwidth of a prototype PDRA with relative permittivity 10.2 is 26.7% ($S_{11} < -10\,\mathrm{dB}$). A novel feeding technique for dielectric ring resonator antennas, with 2 : 1 VSWR bandwidth greater than 25% at 5.5 GHz, covering the WLAN upper band is reported by Chang and Feng [74].

3.1.5. Parasitic DRA

Simons and Lee [75] have shown that wide bandwidth can also be achieved with parasitic DRAs (Figure 13). The central DRA is a slot coupled to a microstrip feed line, while the outer DRAs are electromagnetically coupled to the center DRA. The three DRAs can be tuned to different frequencies for either wide band or multi-frequency response. They have then improvised the configuration to a compact one using a cylindrical DRA that is embedded in a concentric ring (Figure 14). This antenna is fed with a single probe. Each of the two DRAs is individually tuned for wideband response. The air gap between the DRAs and the ground plane is used to improve the bandwidth. Leung and Ng have explored the use of parasitic elements for broad-banding & circular polarization [76]. In [76], they used a single parasitic patch for circular polarization (CP) excitation of the DRA. In [77] they undertook a rigorous study of aperture-coupled hemispherical DRA with a parasitic patch. Using Green's function they formulated integral equations for the unknown patch and slot currents and solved them using the method of moments. For the wide-band CP antenna, they were able to obtain a maximum bandwidth of 22%, much wider than the previous bandwidth of 7.5% with no parasitic patch.

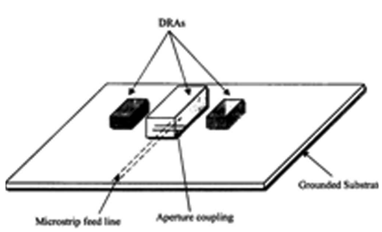

Figure 13. Slot fed rectangular DRA with two parasitic elements [75].

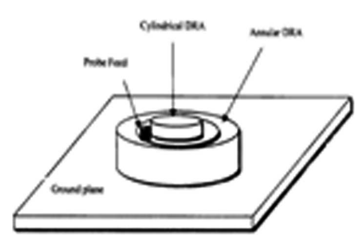

Figure 14. Probe-fed annular DRA with embedded parasitic cylindrical DRA [75].

3.2. Ultra-Wideband Dielectric Resonator Antennas

Ultra wideband (UWB) DRA was first conceived and studied by a Canadian research group. Many new designs showing improved bandwidth and radiation characteristics have been reported in the mean time. Various designs of UWB DRAs available are discussed, and physical insights into achieving wide impedance bandwidth have been indicated. This comprehensive review indicates some areas not adequately addressed so far. This study may be listed as monopole geometries, composite DRAs using composite shapes and/or composite materials, modified ground plane shapes and use of defected ground structure to modify or shaping of radiated beams.

3.2.1. Monopole Geometry

The first candidate, examined in [78–80] used a single annular-shaped dielectric ring resonator (DRR) placed on ground plane surrounding a vertical monopole as shown in Figure 15. The $\frac{\lambda}{4}$ monopole is actually extended form of the coaxial feed used in earlier designs [81–85] and thus it appears to be the simplest form amongst the UWB DRA family. The subsequent developments show the changes in both monopole and DRA shapes. The main aim has been enhancing the impedance bandwidth maintaining the design simplicity and cost. A list of monopole UWB DRA geometries are provided in Table 4.

Table 4. Monopole UWB DRA geometries.

S.N.	Geometry	ε_r	Operating freq. (GHz)	BW	Ref.
1.	Annular ring DRA centrally excited by $\lambda/4$ monopole	10	6.0–18.0	3 : 1	[79]
2.	Similar as above studied to develop design guideline	10	6.0–18.0	3 : 1	[86]
3.	Eye-shaped monopole DRA excited by coaxial probe connected to SMA connector	10	3.0–20.0	6 : 1	[87]
4.	Annular DRR excited by T-shaped monopole (Figure 16)	10	4.5–16.0	3.5 : 1 112%	[88]
5.	Pawn-shaped DRR excited by $\lambda/4$ monopole	10	5.5–22.0	4 : 1	[89]
6.	Inverted truncated annular conical DRA excited by monopole	9.8	3.4–5.0		[90]
7.	Conical DRR excited by $\lambda/4$ monopole	10	5.7–23	4 : 1	[91]
8.	Hemispherical DRR excited by $\lambda/4$ monopole	10	5.7–23	4 : 1	[91]
9.	Stepped radius annular DRR excited by $\lambda/4$ monopole	10	3.0–10.3	110%	[92]

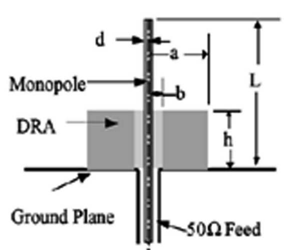

Figure 15. Cross section of the hybrid monopole-DRA [79].

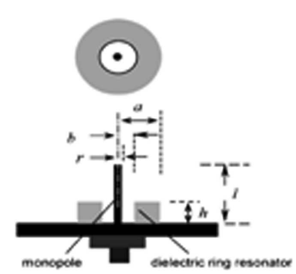

Figure 16. Top and cross-sectional views of a monopole-DRA proposed in [88].

3.2.2. *Composite DRA*

Composite DRAs are defined as the ones formed using composite shapes and/or composite materials, having different sizes with the same or different dielectric materials; they may be loaded or separated from each other. A list of composite UWB DRA is provided in Table 5.

Table 5. Composite UWB DRA.

S.N.	Geometry	Operating freq. (GHz)	BW	Ref.
1.	Dielectric rod antenna consists of two concentric dielectric cylinders.	2.0–8.0	4 : 1	[93]
2.	Rectangular dielectric resonator, a bevel feeding patch connected to a SMA connector and an air gap between the DR and ground plane	2.6–11.0	4.2 : 1 120%	[94]
3.	Sector DRA excited by a coaxial probe connected to a SMA connector	0.466–0.935	2 : 1	[95]
4.	Z-shaped dielectric resonator, a bevel feeding patch and an air gap between the DR and ground plane as shown in Figure 17.	2.5–10.3	4.1 : 1 120%	[96]
5.	Inserted DRA excited by CPW (Figure 18)	3.07–11.5	3.7 : 1	[97]
6.	Rectangular DRA with a side wall conductor and a thin low-permittivity insert (LPI) between a higher permittivity dielectric volume and a ground plane fed by a coaxial probe.	3.1–10.6	3.4 : 1 109.5%	[98]
7.	Rectangular dielectric resonator is excited by a bevel-shaped patch connected to a CPW feeding line.	3.1–10.6	3 : 1 109.5%	[99]

3.2.3. *Modified Ground Plane Shape and Use of Defected Ground Structure*

For many applications, such as ground penetrating radars, high data rate short range wireless local area networks, ultra wideband (UWB) short pulse radars and UWB channel sounding, UWB directional or omnidirectional antenna is required. To have the main radiating beam position frequency independent over the band and achieve higher gain without increasing VSWR, ground shaping will be introduced [89].

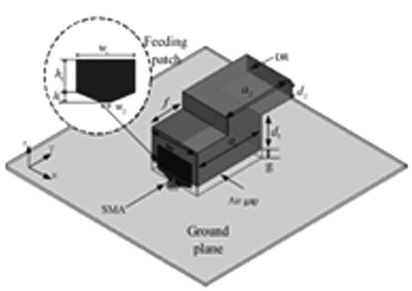

Figure 17. Geometry of Z-shaped UWB DRA [96].

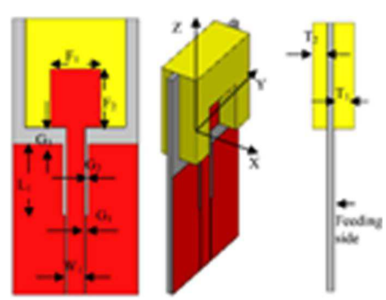

Figure 18. Geometry of the proposed inserted UWB DRA excited by CPW feeding [97].

Figure 19. Configuration of inverted conical DRR with a skirt-shaped ground plane [100].

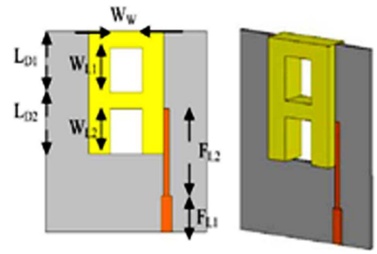

Figure 20. A-shaped DRA mounted on a vertical ground plane edge [101].

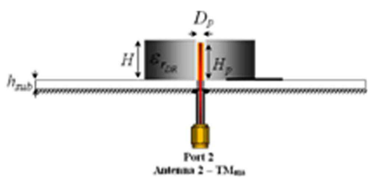

Figure 21. Dual-band DRA [113].

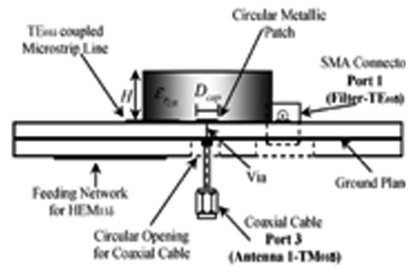

Figure 22. Side view of the triple mode DRA [116].

The use of a new ground shaping technique increases directivity and makes the antenna main beam position almost frequency independent. In [100], three different methods of impedance matching, dielectric and ground plane shaping procedures are applied to considerably enhance the antenna bandwidth. In this design, a skirt monopole antenna is used to excite an inverted conical-ring-shape dielectric resonator (Figure 19). The lower part of the input impedance bandwidth can be adjusted using ground plane shaping and matching method at the feed point of the monopole antenna. The proposed structure can be used for high power ultra wideband applications that require an omnidirectional dipole-shape radiation pattern. Ryu and Kishk [101] proposed a rectangular DRA mounted on a vertical ground plane edge as shown in Figure 20. Mounting the DR in this way reduces the total volume of the antenna compared to the planar ground plane. The proposed structure provides much wider impedance matching bandwidth. Generally using the ground plane edge results in a conceptual 75% volume reduction compared to a perpendicular ground plane and with a lighter antenna weight. In this section of UWB DRA, the shape of ground plane has been changed and the effect of impedance bandwidth observed. Such a type of UWB DRA is listed in the following Table 6.

Table 6. Modified ground plane UWB DRA.

S.N.	**Geometry**	ε_r	**Operating freq. (GHz)**	**BW**	**Ref.**
1.	Modified eye-antenna placed over a shaped ground which is a surface of incomplete conical shape.	10	3.0–20.0	6.5 : 1	[87]
2.	Inverted conical DRR fed by a monopole with a skirt-shaped ground plane	10	2.0–7.0	3.5 : 1	[100]
3.	A-shaped DRA mounted on a vertical ground plane edge excited by a strip feed.	10.2	3.53–9.675	93%	[101]

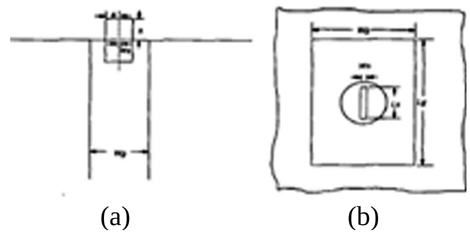

Figure 23. Configuration of waveguide excited DRA (a) side view, (b) top view [121].

3.3. Multiband Dielectric Resonator Antennas

In the last decade, the huge demand for mobile and portable communication systems has led to an increased need for more compact antenna designs. This aspect is even more critical when several wireless technologies have to be integrated on the same mobile wireless communicator. All the new services and increased user density are driving the antenna design toward multiband operation. A dielectric resonator indeed supports more than one resonant mode at two close frequencies, which allows them to meet the requirements of different applications with a unique device. Recently, many studies have been devoted to multiband antennas [102–104], some of them dealing with DRAs [105–107]. Here some of the multi-bands DRAs are listed in Table 7.

Table 7. Multiband DRAs.

S.N.	DRA Geometry	Feed Mechanism	Number of Freq. Band	Ref.
1.	Rectangular DRA	Coaxial probe	Dual band	[108]
2.	Rectangular DRA	slot	Dual band	[109]
3.	Cone shaped DRA	Pair of eccentric dual-ring slot	Dual band	[110]
4.	Splitted Rectilinear DRA	slot	Dual band	[111]
5.	Circular Disk DR	CPW inductive slot	Dual band	[112]
6.	Circular Disk DR (Figure 21)	C-shaped slot	Dual band	[113]
7.	Rectangular DRA	slot	Dual band	[114]
8.	Cylindrical DRA	Printed microstrip feeding network and coaxial probe coupling	Dual band	[105]
9.	Planar inverted L antenna using a ceramic dielectric disk	Microstrip line	Multiband	[115]
10.	Cylindrical DRA (Figure 22)	Micro strip feeding network and coaxial probe coupling	Triple band	[116]
11.	Bridge shaped DRA	Aperture coupling	Dual band	[117]
12.	Rectangular DRA	CPW feed	Dual band	[118]
13.	Rectangular DRA	Printed line	Multiband	[119]
14.	Rectangular DRA	slot	Dual band	[120]
15.	Cylindrical DRA (Figure 23)	Waveguide excited	Dual band	[121]

4. CONCLUSION

The intent of this paper has been to provide a historical overview and a summary of the current state of the art of dielectric resonator antennas, in order to highlight the high degree of flexibility and versatility that dielectric resonator antennas can offer. The attention is focused on a type of DRAs that can offer multi-resonant frequencies, and these frequencies can be merged into a broad band. These bandwidth enhancement techniques are based on multi-frequency resonance and classified into three categories according to their frequency range: wideband DRA, ultra-wideband DRAs and multiband DRAs. Since broadband DRA designs have been a current topic, and a lot of interest has been reported through paper work from many researchers, it is impossible to collect all the papers. However, based on our available search techniques nowadays DRAs can fall into the above three categories. Therefore, the bandwidth enhancement techniques mentioned in this article can offer antenna designers wide choice flexibility and design guidance for the implementation of broadband DRAs. A comprehensive review emphasizing the physical insight into the UWB design is also presented. This comprehensive review indicates some areas not adequately addressed so far. This article features some of the recent advances in dielectric resonator antenna technology at the Communications Research Centre. Several novel elements are presented that offer significant enhancements to parameters such as impedance bandwidth, circular-polarization bandwidth, gain, or coupling to various feed structures. The findings to date have been very encouraging, although a significant amount of work is still required in areas such as long-term environmental effects, as well as in the area of analysis and design. As DRA technology matures, however, it should prove a viable alternative to the more-established antenna candidates, offering the engineer more options to solve potentially challenging problems.

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