Chapter 2

Revisited the design techniques of Dielectric Resonator Antenna

2.1 Objective
The objective of this chapter is consolidation of the literature on dielectric resonator antennas (DRAs) and fractal antennas that we have surveyed during the course of this work. It includes over the last three decades of work on DRA. Major research activities in each decade are highlighted. Over a decade has passed since incorporation of fractal geometry in design of compact, wideband, ultra-wideband, multiband antennas. A number of designs reported by various researchers are summarized in this chapter. One of the advantages of this exercise is that the information provided in the following sections will help antenna designers to get better understanding of their potential and perhaps consider them as alternatives to conventional low-gain elements when undertaking new designs. It can also serve as reference for dielectric resonator antenna, providing a summary of the current achievements and listing benchmarks against which performance of new dielectric resonator antenna designs can be compared. This chapter covers the achieved frequency ranges of dielectric resonator antenna prototypes, low profile, compact designs and wideband dielectric resonator antennas available in literature.

2.2 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 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 ($\varepsilon_r$), high radiation efficiency (>95%) due to absence of conductor or surface wave losses, increased bandwidth, low cost and compatibility to 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 offshoot of the work of Ritchtmyer 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 2.3, 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 section 2.4. The concept of fractal antenna is given in penultimate section. In the concluding section 2.6 the review is summarized.

2.3 Frequency range and DRA geometry

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 (λ₀) by the approximate relation \( D \propto \lambda_0 \varepsilon_r^{-0.5} \), where \( \varepsilon_r \) 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.

2.4 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.

2.4.1 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 $\varepsilon_r$ 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.

2.4.1.1 Mono DRA

Here, a Mono DRA means 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 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 Fig 2.1., 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 mono DRA designs is provided in Table 2.1.
### Table 2.1: Mono DRA designs

(\(\varepsilon_r\) is the dielectric constant of the DRA; BW is the -10 dB \(S_{11}\) bandwidth)

<table>
<thead>
<tr>
<th>S.N.</th>
<th>DRA geometry</th>
<th>(\varepsilon_r)</th>
<th>Feed mechanism</th>
<th>BW (-10 dB)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Flipped staired pyramid</td>
<td>12</td>
<td>Slot</td>
<td>~ 62 %</td>
<td>[14]</td>
</tr>
<tr>
<td>2.</td>
<td>Strip-fed Rectangular DRA</td>
<td>9.8</td>
<td>Conducting strip</td>
<td>~ 43 %</td>
<td>[15]</td>
</tr>
<tr>
<td>3.</td>
<td>Inverted L-shaped DRA</td>
<td>9.2</td>
<td>Probe</td>
<td>~ 38 %</td>
<td>[16]</td>
</tr>
<tr>
<td>4.</td>
<td>Cylindrical DRA</td>
<td>12</td>
<td>Probe</td>
<td>~ 30 %</td>
<td>[17]</td>
</tr>
<tr>
<td>5.</td>
<td>Half-hemispherical DRA</td>
<td>10</td>
<td>Probe</td>
<td>~ 35 %</td>
<td>[18]</td>
</tr>
<tr>
<td>6.</td>
<td>Cylindrical cup DRA</td>
<td>10.2</td>
<td>L-shaped probe</td>
<td>~ 32 %</td>
<td>[19]</td>
</tr>
<tr>
<td>7.</td>
<td>Two step Stair shaped DRA</td>
<td>12</td>
<td>slot (square cross-section)</td>
<td>~ 54.3 %</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.2</td>
<td>probe (circular cross-section)</td>
<td>~ 40 %</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Rectangular DRA with an offset well</td>
<td>20</td>
<td>Slot</td>
<td>~ 18 %</td>
<td>[21]</td>
</tr>
<tr>
<td>9.</td>
<td>U-shaped DRA</td>
<td>9.8</td>
<td>Elliptical patch</td>
<td>~ 72 %</td>
<td>[22]</td>
</tr>
<tr>
<td>10.</td>
<td>Rectangular DRA with a tunnel</td>
<td>20</td>
<td>Slot</td>
<td>~ 20 %</td>
<td>[23]</td>
</tr>
<tr>
<td>12.</td>
<td>L- shaped DRA</td>
<td>9.8</td>
<td>Conformal inverted-trapezoidal patch</td>
<td>~ 71.4 %</td>
<td>[25]</td>
</tr>
<tr>
<td>13.</td>
<td>High aspect ratio (5.2:1) rectangular DRA</td>
<td>25</td>
<td>Micro strip line</td>
<td>~ 16 %</td>
<td>[26]</td>
</tr>
<tr>
<td>14.</td>
<td>Rectangular DRA with a moat</td>
<td>20</td>
<td>Slot</td>
<td>~ 33 %</td>
<td>[27]</td>
</tr>
<tr>
<td>15.</td>
<td>Cylindrical DRA</td>
<td>10</td>
<td>Conformal metallic strip connected to SMA probe</td>
<td>~ 66 %</td>
<td>[28]</td>
</tr>
<tr>
<td>16.</td>
<td>Rectangular DRA placed on a concave ground plane</td>
<td>9.8</td>
<td>probe</td>
<td>~ 55 %</td>
<td>[29]</td>
</tr>
<tr>
<td>17.</td>
<td>Trapezoidal DRA</td>
<td>10</td>
<td>Probe</td>
<td>~ 55 %</td>
<td>[30]</td>
</tr>
<tr>
<td>18.</td>
<td>Cylindrical DRA</td>
<td>10.2</td>
<td>Dual coaxial probe</td>
<td>~ 68 %</td>
<td>[31]</td>
</tr>
<tr>
<td>19.</td>
<td>Bowtie DRA</td>
<td>9.8</td>
<td>Probe</td>
<td>~ 49.4 %</td>
<td>[32]</td>
</tr>
</tbody>
</table>
2.4.1.2 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 early design is a pair of slot coupled-DRAs [33]. It consists of two rectangular dielectric resonators that are displaced near the two edges of a single slot on a ground plane shown in fig. 2.5. Since, the two DRAs have the same shape and material but the different sizes, it may be possible to get the same resonance modes at the different resonance frequencies. The advantage of this 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 one. For example, a
dielectric resonator is stacked on the top of the other [34-37], or a smaller dielectric resonator
is inserted into another larger dielectric resonator [38], [39]. 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. Keefe and Kingsley [40] reported RF range liquid DRA that
uses water as dielectric which adds a new range of dielectric antenna research. Lai et al. [41]
revisited the radiation efficiency of DRA and 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
et al. [42]. It consists of a rectangular DRA of relatively low permittivity, under which one or
more thin segments of higher permittivity are inserted as shown in the Fig 2.6. The segments
help in matching the impedance of the DRA to the microstrip line which helps in improving
the coupling performance. The permittivity and the thickness of the inserts affect the resonant
frequency, impedance bandwidth and the 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 [43], so also loaded dielectric resonators [44]. A list of several poly-
dielectric DRA designs is provided in Table 2.2.

<table>
<thead>
<tr>
<th>S.N.</th>
<th>DRA geometry</th>
<th>Feed mechanism</th>
<th>BW (-10 dB)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Four-elements Cylindrical DRA</td>
<td>Probe</td>
<td>29 %</td>
<td>[45]</td>
</tr>
<tr>
<td>2.</td>
<td>Stacked and Embedded Cylindrical DRAs</td>
<td>Probe</td>
<td>68.1 %</td>
<td>[46]</td>
</tr>
<tr>
<td>3.</td>
<td>Multi-layered cylindrical DRA (MCDRA)</td>
<td>Probe</td>
<td>66 %</td>
<td>[47]</td>
</tr>
<tr>
<td>4.</td>
<td>DRA with metal coating</td>
<td>CPW</td>
<td>47 %</td>
<td>[48]</td>
</tr>
</tbody>
</table>
Fig. 2.5. (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 [33].

Fig. 2.6. Multisegment DRA.

Fig. 2.7. Geometry of ground plane backed, coaxial probe fed, stacked DRA [34].

Fig. 2.8. Four elements Cylindrical DRA fed by a central coaxial probe [45].

Fig. 2.9. Stacked and embedded cylindrical DRA [46].

2.4.1.3 Hybrid DRA

This is a technique adopted from aperture coupled microstrip antennas [51, 52] for broad-bandung. It uses a combination of a DRA with other resonator or antenna, such as a
microstrip patch or a slot radiator etc. 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 [53] is the power coupling from the microstrip line to the two radiators, which requires two layered substrates, increasing the size and the 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 [54] or a microstrip fed rectangular slot is employed to feed a rectangular slot [55]. In a cavity backed DRA [56] tuning over a broad bandwidth has been realized. But it shows high front-to-back ratio 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 2.3.

Table 2.3: Hybrid DRA designs

<table>
<thead>
<tr>
<th>S.N.</th>
<th>DRA geometry</th>
<th>Feed mechanism</th>
<th>BW (-10 dB)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cylindrical DRA where backing cavity is placed beneath the stub.</td>
<td>Circular aperture coupled by a microstrip feed line with a microstrip fork-like tuning stub.</td>
<td>40 %</td>
<td>[56]</td>
</tr>
<tr>
<td>2.</td>
<td>Cylindrical DRA</td>
<td>Modified microstrip line</td>
<td>26 %</td>
<td>[57]</td>
</tr>
<tr>
<td>3.</td>
<td>Rectangular DR and a CPW inductive slot</td>
<td>slot</td>
<td>28.9 %</td>
<td>[58]</td>
</tr>
<tr>
<td>4.</td>
<td>Rectangular DR and a conductor-backed coplanar waveguide (CB-CPW) slot etched on a small ground plane.</td>
<td>probe</td>
<td>23.5 %</td>
<td>[59]</td>
</tr>
</tbody>
</table>
2.4.1.4. 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 at the center (Fig. 2.10). Following, notched rectangular DRA, Shum and Luk [65] proposed a modified annular DRA in which the air gap between the DRA and the ground plane is used to enhance the bandwidth. Y. X. Guo et al. proposed stacked double annular-ring DRA [66] which offers an impedance bandwidth of ~42 % in reference to -10 dB of $S_{11}$. R. Chair et al. presented a wideband perforated DRA (PDRA) [67], where the effective permittivity of the dielectric resonator is 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% ($S_{11} < -10$ 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 W. Chang and Z. Feng [68].
2.4.1.5. Parasitic DRA

Simons and Lee [69] have shown that wide bandwidth can also be achieved with parasitic DRAs (Fig.2.12). The central DRA is 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 (Fig.2.13). This antenna is fed with a single probe. Each of these 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 et al. have explored use of parasitic elements for broad-banding & circular polarization. In [70] they use a single parasitic patch for circular polarization (CP) excitation of the DRA. In [71] they have undertaken a rigorous study of aperture-coupled hemispherical DRA with a parasitic patch. Using Green’s function they have 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%, which is much wider than the previous bandwidth of 7.5% with no parasitic patch.

2.4.2. 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, which are 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.

2.4.2.1. Monopole geometry

The first candidate, examined in [72]-[74] used a single annular-shaped dielectric ring resonator (DRR) placed on ground plane surrounding a vertical monopole. The \( \frac{\lambda}{4} \) monopole is actually extended form of the coaxial feed used in earlier designs [75] - [79] 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 in enhancing the impedance bandwidth maintaining the design simplicity and cost. A list of monopole UWB DRA geometries are provided in Table 2.4.

Table 2.4: Monopole UWB DRA geometries

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Geometry</th>
<th>( \varepsilon_r )</th>
<th>Operating freq. (GHz)</th>
<th>BW</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Annular ring DRA centrally excited by ( \lambda/4 ) monopole</td>
<td>10</td>
<td>6.0-18.0</td>
<td>3:1</td>
<td>[73]</td>
</tr>
<tr>
<td>2.</td>
<td>Similar as above studied to develop design guideline</td>
<td>10</td>
<td>6.0-18.0</td>
<td>3:1</td>
<td>[80]</td>
</tr>
<tr>
<td>3.</td>
<td>Eye-shaped monopole DRA excited by coaxial probe connected to SMA connector</td>
<td>10</td>
<td>3.0-20.0</td>
<td>6:1</td>
<td>[81]</td>
</tr>
<tr>
<td>4.</td>
<td>Annular DRR excited by T-shaped monopole</td>
<td>10</td>
<td>4.5-16.0</td>
<td>3.5:1 112 %</td>
<td>[82]</td>
</tr>
<tr>
<td>5.</td>
<td>Pawn-shaped DRR excited by ( \lambda/4 ) monopole</td>
<td>10</td>
<td>5.5-22.0</td>
<td>4:1</td>
<td>[83]</td>
</tr>
<tr>
<td>6.</td>
<td>Inverted truncated annular conical DRA excited by monopole</td>
<td>9.8</td>
<td>3.4-5.0</td>
<td></td>
<td>[84]</td>
</tr>
<tr>
<td>7.</td>
<td>Conical DRR excited by ( \lambda/4 ) monopole</td>
<td>10</td>
<td>5.7-23</td>
<td>4:1</td>
<td>[85]</td>
</tr>
<tr>
<td>8.</td>
<td>Hemispherical DRR excited by ( \lambda/4 ) monopole</td>
<td>10</td>
<td>5.7-23</td>
<td>4:1</td>
<td>[85]</td>
</tr>
<tr>
<td>9.</td>
<td>Stepped radius annular DRR excited by ( \lambda/4 ) monopole</td>
<td>10</td>
<td>3.0-10.3</td>
<td>110 %</td>
<td>[86]</td>
</tr>
</tbody>
</table>
2.4.2.2. Composite DRA

Composite DRAs are defined as those DRAs which are 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 the Table 2.5.

Table 2.5: Composite UWB DRA

<table>
<thead>
<tr>
<th>S.N</th>
<th>Geometry</th>
<th>Operating freq. (GHz)</th>
<th>BW</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Dielectric rod antenna consists of two concentric dielectric cylinders.</td>
<td>2.0-8.0</td>
<td>4:1</td>
<td>[87]</td>
</tr>
<tr>
<td>2.</td>
<td>Rectangular dielectric resonator, a bevel feeding patch connected to a SMA connector and an air gap between the DR and ground plane</td>
<td>2.6-11.0</td>
<td>4.2:1</td>
<td>120 %</td>
</tr>
<tr>
<td>3.</td>
<td>Sector DRA excited by a coaxial probe connected to a SMA connector</td>
<td>0.466-0.935</td>
<td>2:1</td>
<td>[89]</td>
</tr>
<tr>
<td>4.</td>
<td>Z-shaped dielectric resonator, a bevel feeding patch and an air gap between the DR and ground plane</td>
<td>2.5-10.3</td>
<td>4.1:1</td>
<td>120 %</td>
</tr>
<tr>
<td>5.</td>
<td>Inserted DRA excited by CPW</td>
<td>3.07-11.5</td>
<td>3.7:1</td>
<td>[91]</td>
</tr>
<tr>
<td>6.</td>
<td>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.</td>
<td>3.1-10.6</td>
<td>3.4:1</td>
<td>109.5 %</td>
</tr>
<tr>
<td>7.</td>
<td>Rectangular dielectric resonator is excited by a bevel-shaped patch connected to a CPW feeding line.</td>
<td>3.1-10.6</td>
<td>3:1</td>
<td>109.5 %</td>
</tr>
</tbody>
</table>
2.4.2.3. 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 omni-directional 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 [81]. Use of a new ground shaping technique increases the directivity and makes the antenna main beam position almost frequency independent. In the letter [94], 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. 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 omni directional dipole-shape radiation pattern. K.S. Ryu and A. A. Kishk [95] proposed the rectangular DRA mounted on a vertical ground plane edge shown in Fig. 2.19. Mounting the DR in this way reduces the total volume of the antenna as compared to the planar ground plane. The proposed structure provides much wider impedance matching bandwidth. Generally using the ground plane edge resulted in a conceptual 75% volume reduction as compared to a perpendicular ground plane and in a lighter antenna weight. In this section of UWB DRA, shape of ground plane has been changed and observed the effect of impedance bandwidth. Such type of UWB DRA has been listed in the following Table 2.6.
Table 2.6: Modified ground plane UWB DRA

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Geometry</th>
<th>( \varepsilon_r )</th>
<th>Operating freq. (GHz)</th>
<th>BW</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Modified eye-antenna placed over a shaped ground which is a surface of incomplete conical shape.</td>
<td>10</td>
<td>3.0-20.0</td>
<td>6.5:1</td>
<td>[81]</td>
</tr>
<tr>
<td>2.</td>
<td>Inverted conical DRR fed by a monopole with a skirt-shaped ground plane</td>
<td>10</td>
<td>2.0-7.0</td>
<td>3.5: 1</td>
<td>[94]</td>
</tr>
<tr>
<td>3.</td>
<td>A-shaped DRA mounted on a vertical ground plane edge excited by a strip feed.</td>
<td>10.2</td>
<td>3.53-9.675</td>
<td>93 %</td>
<td>[95]</td>
</tr>
</tbody>
</table>

2.4.3. 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 the 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. DRAs present a major advantage for multi-standard devices when compared to other kinds of antennas. Recently, many studies have been devoted to multiband antennas [96]–[98], some of them dealing with DRAs [99]–[101]. Here some of the multi-bands DRAs are listed in Table 2.7.
Table 2.7: Multiband DRAs

<table>
<thead>
<tr>
<th>S.N.</th>
<th>DRA Geometry</th>
<th>Feed Mechanism</th>
<th>Number of Freq. Band</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Rectangular DRA</td>
<td>Coaxial probe</td>
<td>Dual band</td>
<td>[102]</td>
</tr>
<tr>
<td>2.</td>
<td>Rectangular DRA</td>
<td>slot</td>
<td>Dual band</td>
<td>[103]</td>
</tr>
<tr>
<td>3.</td>
<td>Cone shaped DRA</td>
<td>Pair of eccentric dual-ring slot</td>
<td>Dual band</td>
<td>[104]</td>
</tr>
<tr>
<td>4.</td>
<td>Splitted Rectilinear DRA</td>
<td>slot</td>
<td>Dual band</td>
<td>[105]</td>
</tr>
<tr>
<td>5.</td>
<td>Circular Disk DR</td>
<td>CPW inductive slot</td>
<td>Dual band</td>
<td>[106]</td>
</tr>
<tr>
<td>6.</td>
<td>Circular Disk DR</td>
<td>C-shaped slot</td>
<td>Dual band</td>
<td>[107]</td>
</tr>
<tr>
<td>7.</td>
<td>Rectangular DRA</td>
<td>slot</td>
<td>Dual band</td>
<td>[108]</td>
</tr>
<tr>
<td>8.</td>
<td>Cylindrical DRA</td>
<td>Printed microstrip feeding network and coaxial probe coupling</td>
<td>Dual band</td>
<td>[99]</td>
</tr>
<tr>
<td>9.</td>
<td>Planar inverted L antenna using a ceramic dielectric disk</td>
<td>Microstrip line</td>
<td>Multiband</td>
<td>[109]</td>
</tr>
<tr>
<td>10.</td>
<td>Cylindrical DRA</td>
<td>Microstrip feeding network and coaxial probe coupling</td>
<td>Triple band</td>
<td>[110]</td>
</tr>
<tr>
<td>11.</td>
<td>Bridge shaped DRA</td>
<td>Aperture coupling</td>
<td>Dual band</td>
<td>[111]</td>
</tr>
<tr>
<td>12.</td>
<td>Rectangular DRA</td>
<td>CPW feed</td>
<td>Dual band</td>
<td>[112]</td>
</tr>
<tr>
<td>13.</td>
<td>Rectangular DRA</td>
<td>Printed line</td>
<td>Multiband</td>
<td>[113]</td>
</tr>
<tr>
<td>14.</td>
<td>Rectangular DRA</td>
<td>slot</td>
<td>Dual band</td>
<td>[114]</td>
</tr>
</tbody>
</table>

Traditional approaches to the analysis and design of antenna systems have their foundation in Euclidean geometry. There has been a considerable amount of recent interest with the possibility of developing new types of antennas that employ fractal rather than Euclidean geometric concepts in their design. This new and rapidly growing field of research has been referred as fractal antenna engineering. Because fractal geometry is an extension of classical geometry, its recent introduction provides engineers with the unprecedented opportunity to
explore a virtually limitless number of previously unavailable configurations for possible use in the development of new and innovative antenna designs.

2.5. Fractal Dielectric Resonator Antennas

Wireless applications, requiring multi-frequency operations, put new demands on antennas pertaining to size, gain, efficiency, bandwidth, etc. One promising approach in this regard is to use fractal geometries to find the best distribution of currents within a volume to meet a particular design goal.

The term “fractal”, which stems from the Latin term ‘fractus’, means broken or irregular fragments. It was coined by Benoit Mandelbrot (1983) a French mathematician, who introduced the term about 20 years ago in his book “The fractal geometry of Nature” [115], to describe a family of complex shapes that possess an inherent self-similarity or self-affinity in their geometrical structure.

Recent progress in the study of fractal antennas suggests some attractive solutions for using a single small antenna operating in several frequency bands. The self-similar properties of certain fractals result in a multiband behavior of the antennas while, the highly convoluted shape of these fractals makes possible the reduction in size, and consequently in mass and volume, of certain antennas which has been investigated by Puente et al. [116]. These reductions make it possible to combine multimedia, communication and tele-detection functionalities in a reduced space like a handy phone, a wristwatch or a credit card e.g. a fractal antenna can provide GPS (Global Positioning System) services within a conventional mobile cellular phone. In the last few years, the fast growing development of mobile communication brought the need for devices that require their components to be ever smaller and lighter, capable of adjusting its frequency of operation and to operate in a multiband mode. Some recent results by Puente [117] and Puente [118] showed that fractal antennas have excellent multiband properties and low resonant frequencies. An overview of the early work on these antennas is summarized by Werner [119]. Radiation efficiency and impedance bandwidth decrease with the size of the antenna, making small antennas inefficient by nature, for these effects are accompanied by high currents in the conductors, high ohmic losses and large values of energy stored in the antenna near field. Hence in order to meet the following attributes for antenna designs, i.e. the compact size, low profile, conformal and multiband or broadband, a number of approaches for designing multi-band antennas have been summarized by Maci [120]. Recently, the possibility of developing antenna designs that
exploit in some way the properties of fractals to achieve these goals, at least in part, has attracted a lot of attention.

There are primarily two active areas of research in fractal antenna engineering. These include the study of fractal-shaped antenna elements and the use of fractals in the design of antenna arrays. Fractals are space-filling contours, meaning electrically large features can be efficiently packed into small areas. Since the electrical lengths play an important role in antenna design, this efficient packing can be used as a viable miniaturization technique. Since these antennas are becoming increasingly popular, it is important to careful study of electrical performance versus technological complexity trade-offs to provide answers about the potential interest of fractal antennas.

Fractal antenna theory uses a modern (fractal) geometry that is a natural extension of Euclidian geometry. A fractal can fill the space occupied by the antenna in a more effective manner than the traditional Euclidean antenna. This can lead to more effective coupling of energy from feeding transmission lines to free space in less volume. Therefore, Fractals can be used in two ways to enhance antenna designs. The first method is in the design of miniaturized antenna elements. These can lead to antenna elements which are more discrete for the end user. The second method is to use the self similarity in the geometry to blueprint antennas which are multiband or resonant over several frequency bands. This would allow the operator to incorporate several aspects of their system into one antenna.

A fractal element antenna, or FEA, is one that has been shaped in a fractal fashion, either through bending or shaping a volume, or introducing holes. They are based on fractal shapes such as the Sierpinski triangle, Mandelbrot tree, Koch curve, and Koch island. The advantage of FEAs, when compared to conventional antenna designs, center around size and bandwidth. Fractals come in two major variations [121]:

1. Deterministic fractal
2. Random fractal

The first category consists of those fractals that are composed of several scaled down and rotated copies of itself, such as Koch curve, they are called Geometric fractals. Julia set also falls in same category. The whole set can be obtained by applying a non-linear iterated map to all arbitrary small section of it. Thus the structure of Julia set is already contained in any small fraction. They are called algebraic fractals. Hence both algebraic and geometric fractals are termed deterministic fractals. Since the generation requires use of a particular mapping or rule which is repeated recursively over and over again, they exhibit the property of strict self similarity. The second category (Random Fractals) includes those fractals which have an
additional element of randomness allowing for simulation of natural phenomenon, so they exhibit property of statistical self similarity.

To define a fractal dimension, Mandelbrot gives a suggestive example. Take an arbitrary unit of length x, and see how many times you are using this unit to cover the entire length of the fractured line. Let us say you used it N times, so the total length of your fractal is N*x. In this case the fractal dimension according to Mandelbrot is:

\[ D = \lim_{x \to 0} \frac{\log(N)}{\log(x)} \]

The fractal dimension D is called also the “the crippling factor” of a Fractal and can be written in a more simple form like

\[ D = \frac{\ln(N)}{-\ln(\gamma)} \]

where N is the number of the non-overlapping copies of the whole and \( \gamma \) is the scaling factor of these copies.

The triangle in Fig. 2.22, called the Sierpinski triangle, is a common self-similar geometrical figure. One starts with the black equilateral shape and takes afterwards, in different steps, the middle of the sides and generates respectively 3, 9, 27, 81, triangles which are self similar and exactly scaled down versions of the initiating shape.

![Zero iteration, First iteration, Second iteration](image)

**Fig.2.22.** Three iteration of Sirepinski gasket.
Different iteration of Carpet and variation of area and circumference is shown in the following figure 2.23.

![Zero iteration, First iteration, Second iteration](image)

Fig. 2.23. A three iteration of Sierpinski Carpet.

It has been observed that the higher the order of iteration of a fractal, the lower its resonant frequency. This observation may help overcome some of the fundamental limitations of antenna engineering, since fractals do not obey Euclidian geometry.

Following the introduction of fractals in antenna engineering, Hajihsami and Abiri investigated DRAs with fractal shape and reported that with increase in fractal iteration the ratio of surface to volume in dielectric resonator increases and thereby reduce the Q-factor which tends to increase in antenna impedance bandwidth [122]. Based on above concept a Sierpinski carpet fractal patterned plugged rectangular DRA is presented [123] for the first time that exhibits improvement in impedance bandwidth. An improvement of 6.5 % in impedance bandwidth is observed when a Sierpinski carpet fractal pattern is plugged on to rectangular DRA. The design is tuned for Wi-Max and WLAN Application. Fractal DRA for wireless application is also reported by Gangwar et al. in [124]. Fractal rectangular curve shaped DRA is investigated in [125]. Fractal rectangular curve is used to achieve wideband performance covering Body Area Network and also the IEEE 802.11a frequencies. It also reveals miniaturization of 50 % of a rectangular DRA using a modified rectangular curve along the cross-sectional boundary.

2.6. Summary

This chapter briefly summarizes the review of broadband design techniques in dielectric resonator antennas (DRAs). The attentions focus 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 they are
classified into three categories according to their frequency range: wideband DRA, ultra-wideband DRAs and multiband DRAs. Since broadband DRA designs have been being a current topic, and a lot of interest has been reported through paper work from many researchers, it is impossible to collect all these papers. However, based on our search available techniques nowadays can be fell 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 in to the UWB design is also presented. This comprehensive review indicates some areas, which are not adequately addressed so far. This chapter 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 research has focused on novel DRA elements to meet the continually increasing challenges posed by emerging communications systems. 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.

This article also presented a comprehensive overview of fractal antenna engineering. Fractal antenna theory uses a modern (fractal) geometry that is a natural extension of Euclidian geometry. Recent efforts by several researchers around the world to combine fractal geometry with electromagnetic theory have led to an emergence of new and innovative antenna designs. Unique properties of fractals have been exploited to develop a new class of antenna-element designs that are multi-band and compact in size and have been shown to possess several highly desirable properties, including multi-band performance, low side lobe levels, and its ability to develop rapid beam forming algorithms based on the recursive nature of fractals. The purpose of this article is to introduce the concept of the fractals and to provide a study and implementation of rapidly growing field of fractal antenna engineering including recent developments. Research in this area has recently yielded a rich class of new designs for antenna elements as well as arrays. The field of fractal antenna engineering is still in the relatively early stages of development, with the anticipation of much more innovative advancement to come over the months and years ahead.
References


