# Dielectric Resonator Antennas: A Historical Review and the Current State of the Art

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## Abstract

This article presents a historical review of the research carried out on dielectric resonator antennas (DRAs) over the last three decades. Major research activities in each decade are highlighted. The current state of the art of dielectric-resonator-antenna technology is then reviewed. The achievable performance of dielectric resonator antennas designed for compactness, wide impedance bandwidth, low profiles, circular polarization, or high gain are illustrated. The latest developments in dielectric-resonator-antenna arrays and fabrication techniques are also examined.

Keywords: Dielectric resonator antennas; history; technology assessment

## 1. Introduction

Over the last three decades, significant progress has been made in various aspects of dielectric-resonator-antenna technology, as evidenced by the more than 800 publications and over two dozen issued patents. The last few years have also seen the release of the first two books on dielectric resonator antennas [1, 2]. These investigations have shown the dielectric resonator antenna to be a versatile, efficient radiator, the design flexibility of which makes it an attractive alternative to traditional low-gain antennas.

The intent of this article is to review dielectric-resonator-antenna technology, and to feature performance capabilities and design versatility. A historical review is first carried out, highlighting the major accomplishments in dielectric-resonator-antenna research achieved in the 1980s and 1990s. The article then looks at the latest developments in dielectric-resonator-antenna technology and presents the current state of the art in various selected areas, to give readers a sense of the flexibility offered by dielectric resonator antennas and their potential advantages compared to traditional low-gain antennas. The hope is that the information provided in the following sections will allow antenna designers who are unfamiliar with dielectric resonator antennas to get a 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 a reference for new researchers entering the dielectric-resonator-antenna field, providing a convenient summary of the current achievements, and listing benchmarks against which they can compare the performance of new dielectric-resonator-antenna designs. This article will cover the achievable frequency range of published dielectric-resonator-antenna prototypes, low-profile and compact designs, wideband dielectric resonator antennas, circular-polarization techniques, dielectric resonator antennas with enhanced gain, reconfigurable designs, a survey of linear and planar arrays, and integrated dielectric resonator antennas.

## 2. Historical Review

Dielectric resonators have been used as high-$Q$-factor elements in microwave-circuit applications since the development of low-loss ceramics in the late 1960s. Dielectric resonators offer a more-compact alternative to waveguide-cavity resonators, and are more amenable to printed-circuit integration. For these applications, cylindrically shaped (puck) dielectrics resonators are typically used, fabricated from materials with relatively high dielectric constants ($\varepsilon_r \geq 35$) for compactness. The dielectric resonators are also often enclosed in metal cavities to prevent radiation and to maintain a high $Q$ factor, important for filter or oscillator designs.

By removing the shielding and with the proper feeding to excite the appropriate mode, it was found that these same dielectric resonators could actually become efficient radiators. In addition, by reducing the dielectric constant, this radiation could be maintained over a relatively wide range of frequencies. A systematic study of dielectric resonators as radiating elements was first carried out in the 1980s by Long, McAllister, and Shen, who examined the characteristics of dielectric resonator antennas (DRAs) of hemispherical, cylindrical, and rectangular shapes [3-5]. Their research demonstrated that dielectric resonator antennas could be considered to be attractive alternatives to traditional low-gain antenna elements, such as microstrip patches, monopoles, and dipoles. A linear array of dielectric resonator antennas fed by a dielectric image guide [6] and a planar array of circular-polarized dielectric resonator antennas [7] were also demonstrated in this decade.

In the late 1980s and early 1990s, the bulk of the research focused on analyzing the various modes of excitation of dielectric resonator antennas with simple shapes, examining a variety of feed mechanisms, and applying analytical and numerical techniques to determine the input impedance, $Q$ factor, and radiation patterns of dielectric resonator antennas. Much of this work was carried out by

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three research teams: one led by Kishk, Glisson, and Junker [8-20], one by Luk and Leung [21-31], and one by Mongia [32-43]. A significant amount of this early work on characterizing the performance of dielectric resonator antennas with simple shapes was summarized in a much-cited paper published in 1994 by Mongia and Bhartia [44]. In this paper, they proposed to standardize the mode nomenclature being used to characterize the dielectric resonator antennas. They also provided a set of simple equations for predicting the resonant frequency and $Q$ factors for several modes of various dielectric-resonator-antenna shapes.

By the mid- to late 1990s, attention also started turning to linear and planar arrays of dielectric resonator antennas. Publications ranged from reporting on simple two-element arrays, up to complex planar phased arrays of over 300 elements with electronic phase-steering capabilities [45-70]. This period also saw the development of low-profile [29, 30, 40, 71-73] and compact [43, 74- 79] designs, mutual-coupling analysis of array elements [48, 80-84], circular-polarized dielectric resonator antennas [41, 68, 69, 85-93], multi-band/wideband designs [94-102], active/tunable dielectric resonator antennas [103-109], and the beginnings of hybrid antenna designs [110-112].

Since the start of this new millennium, many more researchers have begun investigating dielectric resonator antennas, and the rate of publications has significantly increased. Figure 1 shows the approximate number of dielectric-resonator-antenna publications per half decade, starting from the 1980s to the present. Work has continued in the areas of compact designs, miniaturization techniques, low-profile designs, circular polarization, and multi-band and wideband designs. New areas of research include enhanced-gain techniques, finite-ground-plane effects, tunable dielectric resonator antennas, reconfigurable patterns, ultra-wideband designs, polarization agility, and dual-function designs (where the dielectric resonator antenna is used both as a resonator and as an antenna). Much of this work involves the 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. The use of magneto-dielectrics, electromagnetic bandgap (EBG) structures, and liquids is also being investigated to enhance dielectric-resonator-antenna performance. A significant number of the more-recent publications involved designing dielectric resonator antennas for specific applications, including integration into mobile handsets for PCS, IMT-2000, and WLAN applications; use in cellular base-station antennas; UWB applications; radar applications; breast-cancer imaging; RFID; spatial power combining; direction finding; and all-dielectric wireless receivers. Techniques for improving dielectric-resonator-antenna array manufacturing, integration in systems, and packaging techniques are also being studied. The references for these publications are too numerous to all be listed in this review article, but the interested reader is directed to [2], which has an extensive bibliography. Highlights of the major dielectric-resonator-antenna achievements are summarized in the following sections.

## 3. Frequency Range

Various factors determine the practical range of 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 dimension ($D$) is related to the free-space resonant wavelength ($\lambda_0$) by the approximate relation $D \propto \lambda_0 \varepsilon_r^{-0.5}$, where $\varepsilon_r$ is the dielectric constant of the dielectric resonator antenna. Since the radiation efficiency of a dielectric resonator antenna is not significantly affected by the dielectric constant, a wide range of values can be used (low-loss microwave dielectric material is commercially available with values ranging from $2 < \varepsilon_r < 140$). However, the bandwidth of the dielectric resonator antenna 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 dielectric resonator antenna can be significantly reduced, making it viable for low-frequency operations. There are many published designs of dielectric resonator antennas operating at frequencies from 1 to 40 GHz, with dimensions ranging from a few centimeters down to a few millimeters, and dielectric constants approximately ranging from $8 \le \varepsilon_r \le 100$.

To date, 55 MHz is the lowest published frequency for which a dielectric resonator antenna has been designed and fabricated [109]. The dielectric resonator antenna, intended for use in a radar application, is sketched in Figure 2a. It consisted of a water-filled ($\varepsilon_r \sim 84$) cylindrical plastic tube, having a diameter of 550 mm ($0.1\lambda_0$) and a height of 200 mm ($0.037\lambda_0$), mounted on an octagonal ground plane (800 mm across the flat edges). The authors of [109] also stated that practical designs in the HF band (3-30 MHz) are achievable using their dielectric-resonator-antenna configuration. The highest published frequency for dielectric resonator antennas is currently 94 GHz [113], where an array of 128 rectangular dielectric resonator antennas (1 mm × 1.1 mm × 0.16 mm high) was etched on a high-resistivity silicon substrate using micromachining techniques. A subarray of this antenna is sketched in Figure 2b. The array was designed as a feed for a reflector antenna, and was found to have better radiation efficiency than a corresponding microstrip-array design. (Dielectric resonator antennas have less conductor loss, and do not suffer from surface-wave losses.) The use of micro-machining techniques can ensure fine fabrication accuracy, which should allow the upper frequency limit

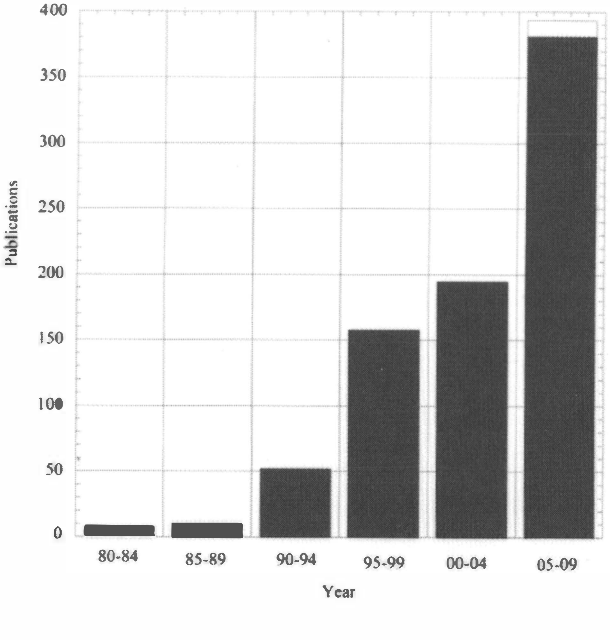


**Figure 1. Dielectric resonator antenna publications.**

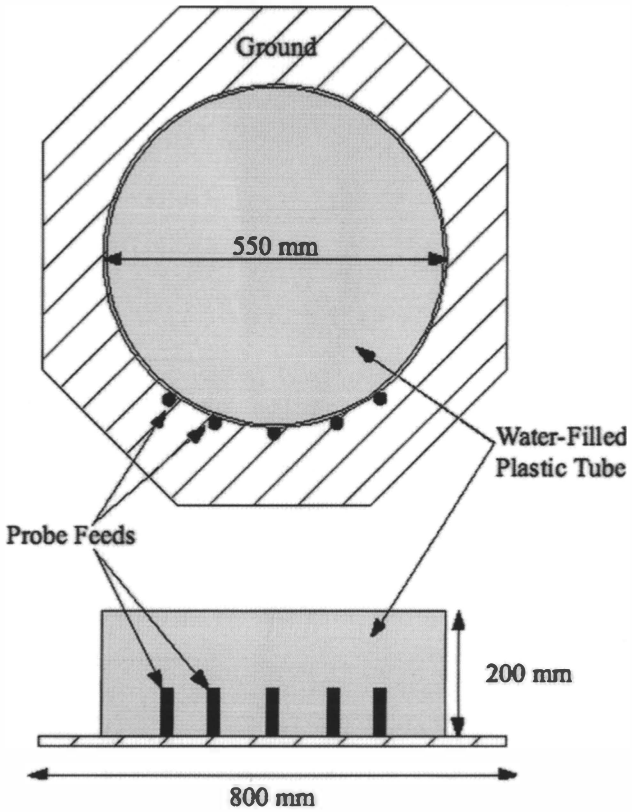


**Figure 2a. The lowest-frequency published design (55 MHz) for a dielectric resonator antenna (from [109]).**

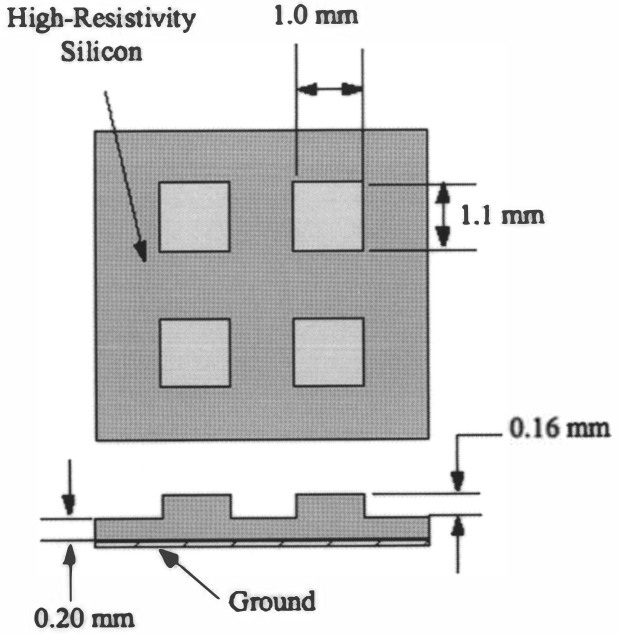


**Figure 2b. The highest-frequency published design (94 GHz) for a dielectric resonator antenna (from [113]).**

of dielectric resonator antennas to extend beyond 100 GHz. Very few antenna elements can boast such a wide frequency range for practical designs as has been demonstrated by the dielectric resonator antenna.

## 4. Low-Profile and Compact Designs

Unlike many other resonant antennas, the aspect ratio of most shapes of dielectric resonator antennas can be altered while maintaining the same resonant frequency, for a given dielectric constant. A tall, thin dielectric resonator antenna can thus have the same resonant frequency (but not necessarily the same bandwidth) as a low, wide dielectric resonator antenna. This allows for a certain degree of flexibility in shaping the dielectric resonator antenna to suit specific requirements. This section examines dielectric resonator antennas designed with either a low profile or a compact size, and highlights the achievable bandwidth performance.

### 4.1 Low-Profile Dielectric Resonator Antennas

For applications needing low antenna profiles, the dielectric resonator antenna can be made very thin, and by using a high dielectric constant, the other dielectric-resonator-antenna dimensions can be kept small. Figure 3 shows examples of low-profile dielectric resonator antennas of different shapes. Table 1 summarizes some of the published lowest-profile dielectric-resonator-antenna designs. By choosing values of the dielectric constant in the range $80 \le \varepsilon_r \le 100$, the dielectric-resonator-antenna height ($h$) can be kept in the range $0.025\lambda_0 < h < 0.035\lambda_0$, while maintaining impedance bandwidths of up to approximately 3.5%.

### 4.2 Compact Dielectric Resonator Antennas

Numerous applications, especially for consumer wireless, require compact antennas to be integrated into small packages, such as cell phones, laptops, or other portable devices. In addition

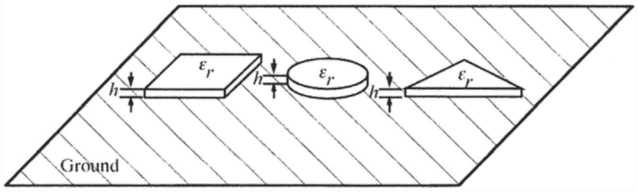


**Figure 3. Low-profile dielectric resonator antennas using high-dielectric-constant material.**

**Table 1. Low-profile, linearly polarized dielectric-resonator-antenna designs ($f_0$ is the resonant frequency; $BW$ is the $-10$ dB return-loss bandwidth)**

| DRA Shape | $f_0$ (GHz) | $\varepsilon_r$ | Maximum Dimension ($M$) | Height ($h$) | Aspect Ratio ($M/h$) | Feed Type | $BW$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| Rectangular | 7.72 | 100 | $0.327\lambda_0$ | $0.026\lambda_0$ | 12.6 | Slot | 3.2% | [40] |
| Rectangular | 4.57 | 100 | $0.152\lambda_0$ | $0.031\lambda_0$ | 4.9 | Slot | 1.2% | [40] |
| Rectangular | 2.09 | 79 | $0.195\lambda_0$ | $0.034\lambda_0$ | 5.7 | Coplanar | 2.4% | [114] |
| Cylindrical | 4.18 | 82 | $0.174\lambda_0$ | $0.028\lambda_0$ | 6.2 | Strip | 3.6% | [72] |
| Triangular | 7.59 | 82 | $0.506\lambda_0$ | $0.028\lambda_0$ | 18.1 | Slot | 3.0% | [73] |
| Triangular | 8.80 | 82 | $0.587\lambda_0$ | $0.029\lambda_0$ | 20.24 | Probe | 3.3% | [115] |

**Table 2. Compact DRA designs.**

| DRA Shape | $f_0$ (GHz) | $\varepsilon_r$ | Maximum DRA Dimension | Height | Feed Type | Maximum Ground Plane Dimension | $BW$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| Cylindrical | 0.82 | 12 | $0.067\lambda_0$ | $0.052\lambda_0$ | Probe | N/A | 1.7% | [76] |
| Cylindrical | 2.89 | 20 | $0.096\lambda_0$ | $0.08\lambda_0$ | Probe | N/A | 2.5% | [43] |
| Cylindrical | 0.05 | 84 | $0.096\lambda_0$ | $0.035\lambda_0$ | Probe | $0.147\lambda_0$ | 1.7% | [109] |
| Cylindrical | 1.90 | 35.5 | $0.19\lambda_0$ | $0.067\lambda_0$ | Microstrip | $0.76\lambda_0$ | 5.3% | [116] |
| Quarter-Cylinder | 1.99 | 12 | $0.12\lambda_0$ | $0.12\lambda_0$ | Probe | $\lambda_0$ | 6.5% | [79] |
| Rectangular | 3.00 | 70 | $0.084\lambda_0$ | $0.076\lambda_0$ | Probe | N/A | 1.3% | [117] |
| Rectangular | 1.30 | 25 | $0.11\lambda_0$ | $0.052\lambda_0$ | Probe | $\lambda_0$ | 1.9% | [118] |
| Rectangular | 1.27 | 10 | $0.12\lambda_0$ | $0.064\lambda_0$ | Probe | N/A | 2.2% | [119] |
| Rectangular | 2.40 | 90 | $0.120\lambda_0$ | $0.04\lambda_0$ | Microstrip | $0.33\lambda_0$ | 5.0% | [120] |
| Rectangular | 5.25 | 12.6 | $0.131\lambda_0$ | $0.07\lambda_0$ | Slot | $1.5\lambda_0$ | 12.0% | [121] |

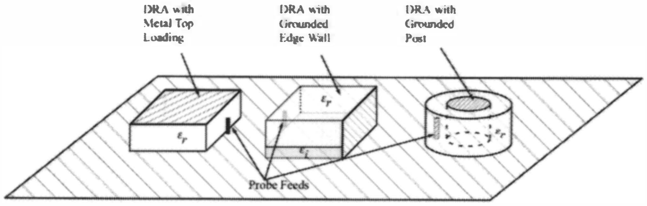


**Figure 4. Examples of compact dielectric resonator antennas with metal loading.**

to using high dielectric constants to reduce the size, dielectric resonator antennas can be made compact by the judicious application of metal plates. Figure 4 shows a few examples of compact dielectric resonator antennas loaded with metal plates. Another technique for size reduction involves removing pie-shaped sectors from cylindrical dielectric resonator antennas [79]. A list of several compact dielectric-resonator-antenna designs is provided in Table 2. To date, the most-compact design (in terms of wavelengths) was a top-loaded cylindrical dielectric resonator antenna resonant at 820 MHz, with a diameter of $0.067\lambda_0$, and a height of $0.052\lambda_0$ [76]. More-compact designs should be possible by using a combination of metal loading and high dielectric substrates. Although this will come at the expense of a reduction in bandwidth, it may find use in narrowband applications. It should also be noted that the size of the finite ground plane may have a significant impact on the radiation pattern, gain, and bandwidth of the dielectric resonator antenna. Table 2 lists the maximum linear dimension of the ground planes used in the measurements (when specified). The dimensions of the ground plane should be included in the determination of the overall size of the dielectric resonator antenna, in order to make a proper comparison with other antenna technologies. It is suspected that for most of the cases listed in Table 2, the size of the ground plane was chosen for convenience, not necessarily to minimize its dimensions. Ground planes as small as about $0.15\lambda_0$ have been reported, and this dimension can be further reduced if the designer is willing to sacrifice gain and bandwidth performance.

## 5. Wideband Designs

Many existing and emerging wireless applications, as well as many radar applications, operate over wide frequency bands, and thus require broadband antennas. In this section, the achievable bandwidth of dielectric resonator antennas of simple shapes is first examined, before presenting various techniques that have been proposed to enhance bandwidth.

Since the bandwidth of the dielectric resonator antenna is inversely related to its dielectric constant, wideband performance is best achieved by dielectric resonator antennas with low values of $\varepsilon_r$. By using simple analytical models to predict the radiation quality factor of cylindrical and rectangular dielectric resonator antennas, it was estimated that for $\varepsilon_r = 10$, rectangular dielectric

Table 3. Bandwidths achieved by simple DRAs ( $f_c$ is the center frequency, $\lambda_c$ is the center wavelength, $l$ is the length, $d$ is the depth, $h$ is the height, and $r$ is the radius).

| DRA Shape | $f_c$ | $\varepsilon_r$ | Excitation | DRA Dimensions | *BW* (GHz) | *BW* | Ref. |
|---|---|---|---|---|---|---|---|
| Rectangular | 3 | 48 | Microstrip | $l = 0.26\,\lambda_c,\ d = 0.12\,\lambda_c,\ h = 0.056\,\lambda_c$ | 2.49-3.125 | 22% | [122] |
| Rectangular | 3.8 | 10.2 | Annular | $l = 0.30\,\lambda_c,\ d = 0.30\,\lambda_c,\ h = 0.10\,\lambda_c$ | 3.35-4.25 | 23% | [123] |
| Rectangular | 5.6 | 10.2 | Annular | $l = d = 0.373\,\lambda_c,\ h=0.093\,\lambda_c$ | 4.92-6.21 | 23% | [124] |
| Rectangular | 2.45 | 80 | Microstrip | $l = 0.19\,\lambda_c,\ d = 0.02\,\lambda_c,\ h = 0.20\,\lambda_c$ | 2.17-2.77 | 25% | [125] |
| Rectangular | 2.6 | 12 | Slot | $l = 0.23\,\lambda_c,\ d = 0.23\,\lambda_c,\ h = 0.14\,\lambda_c$ | 2.15-2.76 | 25% | [126] |
| Rectangular | 5.5 | 10.2 | CPW | $l = 0.40\,\lambda_c,\ d = 0.40\,\lambda_c,\ h = 0.09\,\lambda_c$ | 4.71-6.30 | 29% | [127] |
| Rectangular | 4.5 | 9.8 | Probe | $l = 0.21\,\lambda_c,\ d = 0.38\,\lambda_c,\ h = 0.39\,\lambda_c$ | 3.4-5.3 | 42% | [128] |
| Half-Cylinder | 2.8 | 35.5 | Microstrip | $r = 0.11\,\lambda_c,\ h = 0.11\,\lambda_c$ | 2.48-3.11 | 24% | [129] |
| Cylindrical | 2.7 | 48 | Microstrip | $r = 0.11\,\lambda_c,\ h = 0.06\,\lambda_c$ | 2.4-3.08 | 26% | [130] |
| Cylindrical | 3.5 | 12 | Probe | $r = 0.10\,\lambda_c,\ h = 0.31\,\lambda_c$ | 3.04-3.98 | 27% | [131] |
| Cylindrical | 5.75 | 10.2 | Slot | $r = 0.25\,\lambda_c,\ h = 0.09\,\lambda_c$ | 5.1-6.7 | 27% | [132] |
| Cylindrical | 3 | 20.8 | Microstrip | $r = 0.12\,\lambda_c,\ h = 0.073\,\lambda_c$ | 2.43-3.47 | 35% | [133] |
| Cylindrical | 6.5 | 10 | Aperture | $r = 0.132\,\lambda_c,\ h = 0.25\,\lambda_c$ | 5.3-7.75 | 38% | [134] |

resonator antennas of practical dimensions could achieve a bandwidth of about 20%, and cylindrical dielectric resonator antennas could achieve a bandwidth between 30-40% for the lowest mode orders [2, pp. 119-120]. These estimates were based on single-mode operation, and did not include the loading effects from the feed. Table 3 summarizes some of the published bandwidth results achieved for simple rectangular and cylindrical dielectric resonator antennas. The rectangular dielectric resonator antennas that achieved bandwidths of 25% or more have done so by operating in two or more modes. In many cases, the radiation patterns of these modes are quite similar, and therefore do not significantly degrade the antenna's performance over the impedance bandwidth. The compact size and wideband performance achieved by these simple dielectric resonator antennas give them an advantage over many other resonant antennas, which typically exhibit much narrower-band performance.

Dielectric resonator antennas can attain even broader impedance bandwidths by adopting various enhancement techniques. There are many examples of improved bandwidths using multiple dielectric resonator antennas in various stacked or coplanar embedded configurations, with impedance bandwidths ranging from 25% to nearly 80% [99, 100, 135-141]. Similar bandwidth results can be achieved by modifying the shape of the dielectric resonator antenna or by adopting new feeding structures [97, 142-152]. Finally, hybrid designs, where dielectric resonator antennas are combined with other antenna elements such as microstrip patches or monopoles, have also led to wideband designs with impedance bandwidths of up to 117% [153-158]. Table 4 lists many of these designs, and a selected number are sketched in Figure 5. The configurations in Figures 5b to 5f combine two or three dielectric resonator antennas, and use their multiple resonances to achieve the wide impedance bandwidth. The configurations in Figure 5a and 5h place the dielectric resonator antenna on a small ground plane. These dielectric resonator antennas behave similarly to printed flat monopole antennas, which have also been shown to offer wideband performance. Finally, Figures 5g and 5i are examples of hybrid antennas, combining a dielectric resonator antenna with a monopole. Again, the resonances of the individual antennas are combined, resulting in a broadband response. Most of these designs rely on combining multiple resonances to achieve the wide impedance bandwidths. A majority of the designs use dielectric resonator antennas with a dielectric constant of $\varepsilon_r \sim 10$, and the maximum dimensions are on the order of a half wavelength at the center of the frequency band.

# 6. Circular-Polarization Designs

As with other low-gain antenna elements, such as the microstrip patch and the crossed dipole, dielectric resonator antennas can be designed to radiate circular polarization. For individual dielectric-resonator-antenna elements, various configurations using single or multiple feeds have been proposed for achieving circular polarization. Single-point feed designs are relatively simple to implement, but typically result in fairly narrow axial-ratio bandwidths. Multiple-feed designs attain wider bandwidths, but are more complicated to implement. In array configurations, a technique known as sequential rotation has been adopted, which results in reasonably wide axial-ratio-bandwidth performance. This section examines some of these circular polarization configurations and their axial-ratio performance.

## 6.1 Single-Point-Fed Dielectric Resonator Antennas

The technique for generating circular polarization using a single excitation relies on exciting two quasi-degenerate modes in the dielectric resonator antenna that are spatially orthogonal and in phase quadrature. The technique is well known and has been applied to microstrip patch antennas, which typically achieve 3 dB axial-ratio bandwidths between 1% to 2%. If the two quasi-degenerate modes of the antenna are modeled using simple *RLC* circuits, an analysis reveals that the achievable 3 dB axial-ratio bandwidth is approximately equal to half the 10 dB return-loss bandwidth of the antenna [2, pp. 178-181].

Figure 6 shows examples of single-point-fed dielectric resonator antennas designed to radiate circular polarization. Examples are shown for probe-fed (Figures 6a-6e) and aperture-fed (Figures 6f-6h) dielectric resonator antennas; however, other feeding methods could also be used. Circular polarization from single-point-fed dielectric resonator antennas can be obtained using various techniques, such as making minor modifications to the basic dielectric resonator antenna shape (Figures 6a, 6b); using new dielectric-resonator-antenna shapes (Figures 6c, 6d, 6f); metal loading of the dielectric resonator antenna (Figure 6e); or making modifications to the feed (Figure 6g). These techniques have resulted in 3 dB axial-ratio bandwidths ranging between 1% to

**Table 4a. Bandwidths achieved by composite DRAs: stacked/embedded designs ($f_c$ is the center frequency, $\lambda_c$ is the center wavelength, $H$ is the maximum height, $L$ is the maximum length, and $D$ is the maximum diameter).**

| Description | $f_c$ (GHz) | $\varepsilon_r$ | Excitation | Maximum Dimensions | $BW$ (GHz) | $BW$ (%) | Ref. |
|---|---|---|---|---|---|---|---|
| 2 Stacked Disk DRAs | 8.9 | 4.5, 10.5 | Probe | $H = 0.2\lambda_c\ D = 0.415\lambda_c$ | 7.8-10.0 | 25% | [135] |
| 2 Stacked Disk DRAs | 5.2 | 9.5, 82 | Slot | $H = 0.26\lambda_c\ D = 0.43\lambda_c$ | 4.6-5.8 | 25% | [136] |
| Embedded Ring and Disk DRA | 6.05 | 30.5, 36.7 | Probe | $H = 0.48\lambda_c\ D = 0.04\lambda_c$ | 5.1-7.0 | 38% | [100] |
| 2 Stacked Disk DRAs | 4 | 9.5, 9.5 | Slot | $H = 0.31\lambda_c\ D = 0.29\lambda_c$ | 3.4-4.6 | 40% | [99] |
| 2 Embedded Disk DRAs | 11.4 | 4.1, 12.3 | Slot | $H = 0.23\lambda_c\ D = 0.42\lambda_c$ | 8.8-14+ | >50% | [137] |
| 2 Embedded Hemisphere DRAs | 6.25 | 1, 4.5 | Slot-Ring | $H = 0.26\lambda_c\ D = 0.52\lambda_c$ | 4.7-7.8 | 51% | [138] |
| 2 Stacked Rectangular DRAs | 12.7 | 2.2, 10.2 | Slot | $H = 0.24\lambda_c\ L = 0.44\lambda_c$ | 9.0-16.4 | 59% | [139] |
| 2 Stacked Triangle DRA | 2.35 | 9.2 | Probe | $H = 0.24\lambda_c\ L = 0.50\lambda_c$ | 1.6-3.1 | 64% | [140] |
| 3 Stacked Disk DRAs | 10.3 | 2.32, 6.15, 10.2 | Probe | $H = 0.29\lambda_c\ D = 0.48\lambda_c$ | 6.9-13.7 | 66% | [141] |
| 2 Stacked Rectangular DRAs | 11.85 | 2.2, 9.2 | Probe | $H = 0.36\lambda_c\ L = 0.55\lambda_c$ | 7.2-16.5 | 78% | [142] |

**Table 4b. Bandwidths achieved by composite DRAs: modified shapes ($f_c$ is the center frequency, $\lambda_c$ is the center wavelength, $H$ is the maximum height, $L$ is the maximum length, and $D$ is the maximum diameter).**

| Description | $f_c$ (GHz) | $\varepsilon_r$ | Excitation | Maximum Dimensions | $BW$ (GHz) | $BW$ (%) | Ref. |
|---|---|---|---|---|---|---|---|
| Notched Rectangular DRA | 11.9 | 10.8 | Slot | $H = 0.12\lambda_c\ L = 0.40\lambda_c$ | 10.1-13.7 | 28% | [97] |
| Truncated Tetrahedron DRA | 2.5 | 12 | Probe | $H = 0.20\lambda_c\ L = 0.55\lambda_c$ | 2.0-3.0 | 40% | [143] |
| Split Conical DRA | 1.57 | 12 | Probe | $H = 0.26\lambda_c\ L = 0.27\lambda_c$ | 1.18-1.95 | 50% | [144] |
| Rectangular DRA with Cavity | 4.53 | 9.8 | Probe | $H = 0.29\lambda_c\ L = 0.21\lambda_c$ | 3.28-5.77 | 55% | [145] |
| Notched Disk DRA | 2.4 | 10 | Probe | $H = 0.12\lambda_c\ D = 0.49\lambda_c$ | 1.6-3.2 | 60% | [146] |
| Semi Trapezoid DRA | 7.75 | 9.8 | Probe | $H = 0.41\lambda_c\ L = 0.62\lambda_c$ | 5.5-10.0 | 62% | [147] |
| Flipped Staired Pyramid DRA | 10.85 | 12 | Slot | $H = 0.16\lambda_c\ L = 0.51\lambda_c$ | 7.5-14.2 | 62% | [148] |
| Strip-Loaded Rectangular DRA | 12.5 | 10.2 | Probe | $H = 0.40\lambda_c\ L = 0.47\lambda_c$ | 8.6-16.4 | 65% | [149] |
| L-Shaped DRA | 6.02 | 9.8 | Patch | $H = 0.25\lambda_c\ L = 0.32\lambda_c$ | 3.87-8.17 | 71% | [150] |
| U-Shaped DRA | 5.97 | 9.8 | Patch | $H = 0.25\lambda_c\ L = 0.48\lambda_c$ | 3.82-8.12 | 72% | [151] |
| Embedded Rectangular DRA | 5.94 | 10.2 | Microstrip | $H = 0.25\lambda_c\ L = 0.09\lambda_c$ | 3.46-8.42 | 84% | [152] |

**Table 4c. Bandwidths achieved by composite DRAs: hybrid antennas ($f_c$ is the center frequency, $\lambda_c$ is the center wavelength, $H$ is the maximum height, $L$ is the maximum length, and $D$ is the maximum diameter).**

| Description | $f_c$ (GHz) | $\varepsilon_r$ | Excitation | Maximum Dimensions | $BW$ (GHz) | $BW$ (%) | Ref. |
|---|---|---|---|---|---|---|---|
| Rectangular DRA & Microstrip Patch | 5.83 | 9.2 | Patch | $H = 0.23\lambda_c\ L = 0.29\lambda_c$ | 5.14-6.51 | 24% | [153] |
| Rectangular DRA & Folded Monopole | 3.25 | N/A | Probe | $H = 0.24\lambda_c\ L = 0.20\lambda_c$ | 2.2-4.3 | 67% | [154] |
| Rectangular DRA & Planar Monopole | 10.35 | N/A | Microstrip | $H = 0.09\lambda_c\ L = 0.26\lambda_c$ | 5.75-14.94 | 89% | [155] |
| Annular DRA & Monopole | 11.75 | 10 | Probe | $H = 0.32\lambda_c\ L = 0.39\lambda_c$ | 6.5-17.0 | 89% | [156 |
| Annular DRA & Monopole | 10.0 | 10 | Probe | $H = 0.33\lambda_c\ L = 0.40\lambda_c$ | 4.0-16.0 | 110% | [157] |
| Conical DRA & Monopole | 4.35 | 10 | Probe | $H = 0.52\lambda_c\ L = 0.53\lambda_c$ | 1.8-6.9 | 117% | [158] |

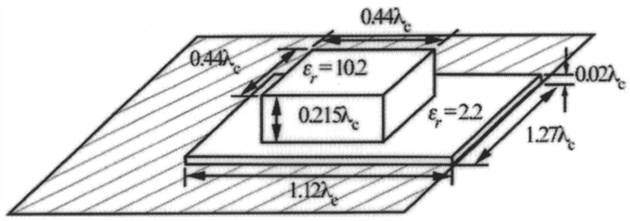


**Figure 5a. An example of a broadband composite dielectric resonator antenna: $f_c = 12.7$ GHz, $BW = 59\%$ ($f_c$ is the center frequency, and $\lambda_c$ is the center wavelength) (from [139]).**

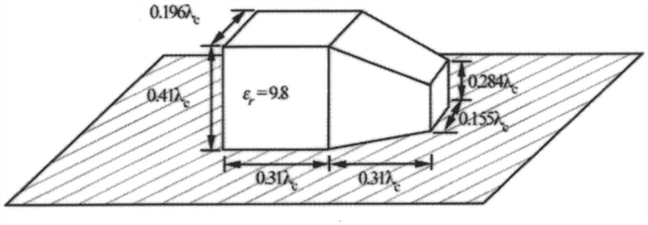


**Figure 5b. An example of a broadband composite dielectric resonator antenna: $f_c = 7.75$ GHz, $BW = 62\%$ (from [147]).**

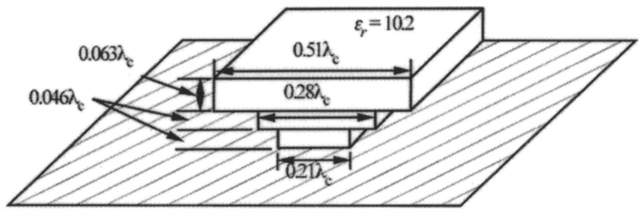


**Figure 5c. An example of a broadband composite dielectric resonator antenna: $f_c = 10.85$ GHz, $BW = 62\%$ (from [148]).**

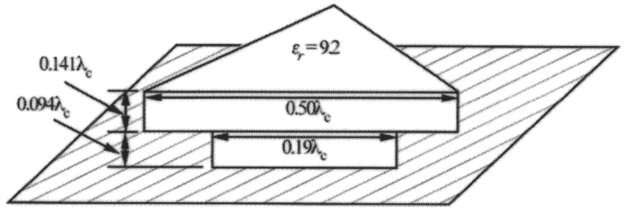


**Figure 5d. An example of a broadband composite dielectric resonator antenna: $f_c = 2.35$ GHz, $BW = 64\%$ (from [140]).**

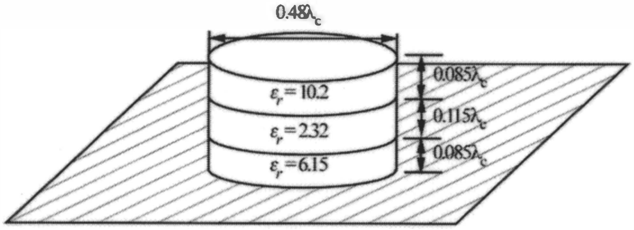


**Figure 5e. An example of a broadband composite dielectric resonator antenna: $f_c = 10.3$ GHz, $BW = 66\%$ (from [141]).**

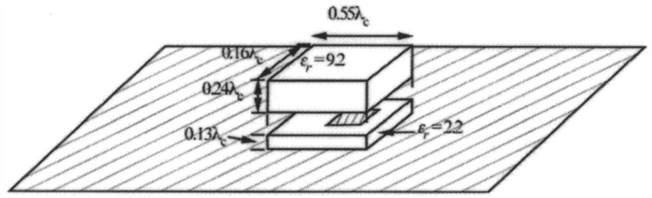


**Figure 5f. An example of a broadband composite dielectric resonator antenna: $f_c = 11.85$ GHz, $BW = 78\%$ (from [142]).**

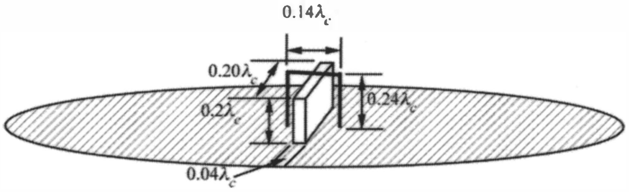


**Figure 5g. An example of a broadband composite dielectric resonator antenna: $f_c = 3.125$ GHz, $BW = 67\%$ (from [154]).**

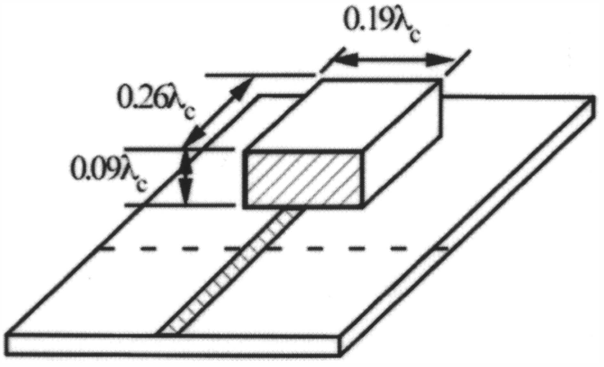


**Figure 5h. An example of a broadband composite dielectric resonator antenna: $f_c = 10.35$ GHz, $BW = 89\%$ (from [155]).**

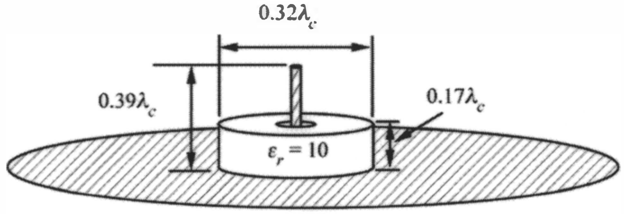


**Figure 5i. An example of a broadband composite dielectric resonator antenna: $f_c = 11.75$ GHz, $BW = 89\%$ (from [156]).**

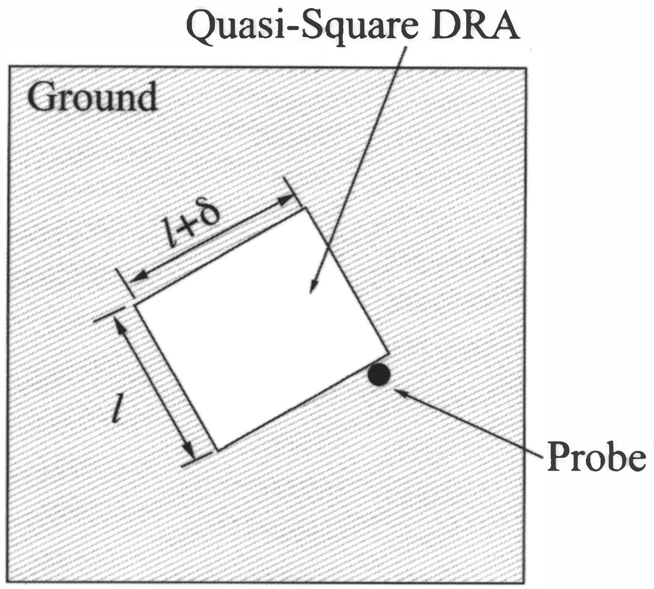


**Figure 6a. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 6.6\%$ ($BW_{cp}$ is the –3 dB axial-ratio bandwidth) (from [159]).**

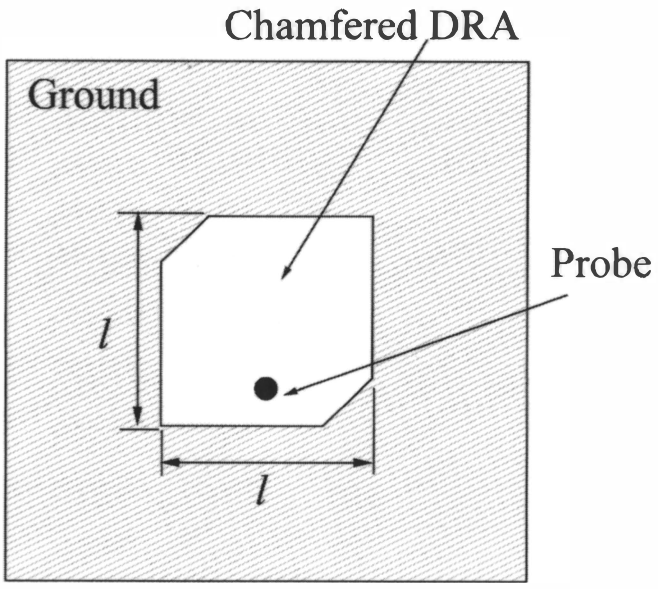


**Figure 6b. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 4\%$ (from [7]).**

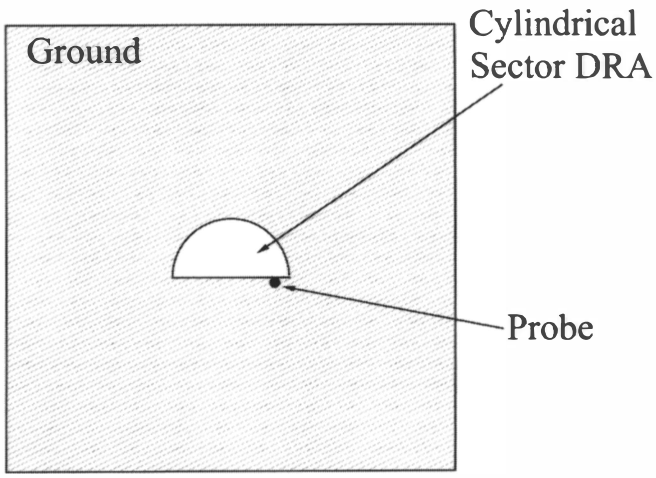


**Figure 6c. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 10\%$ (from [160]).**

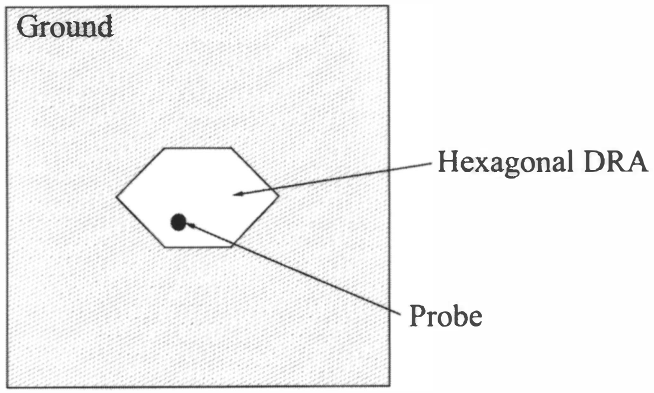


**Figure 6d. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 14.8\%$ (from [161]).**

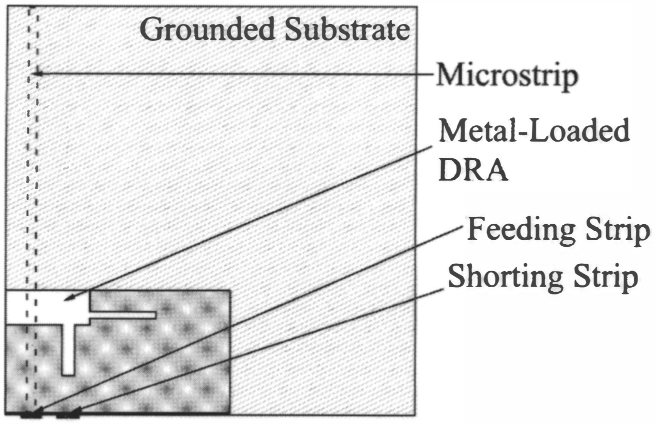


**Figure 6e. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 7.35\%$ (from [162]).**

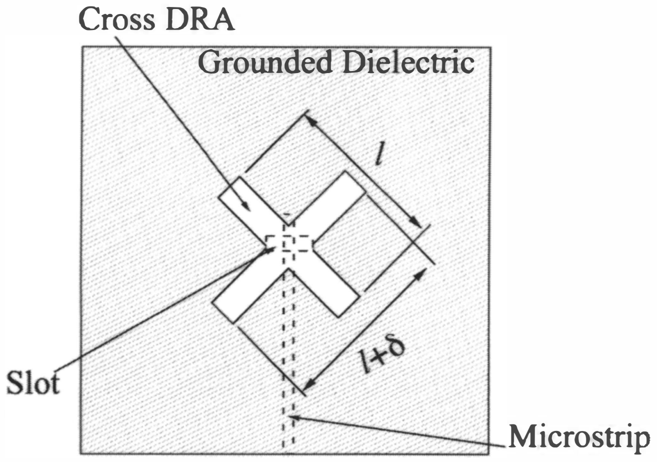


**Figure 6f. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 4.5\%$ (from [85]).**

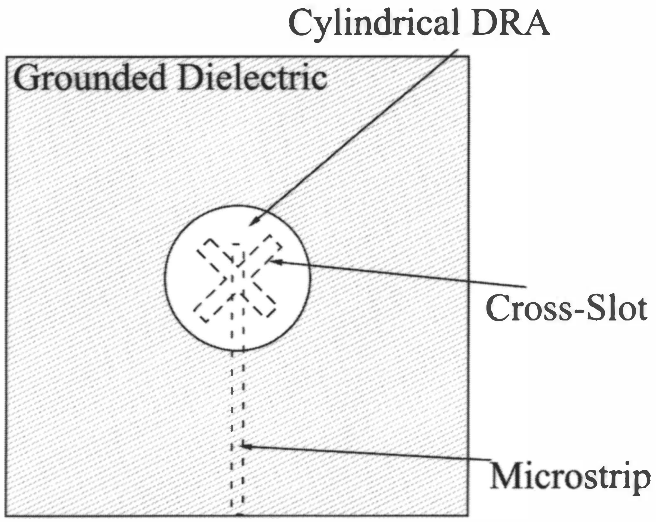


**Figure 6g. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 3.9\%$ (from [91]).**

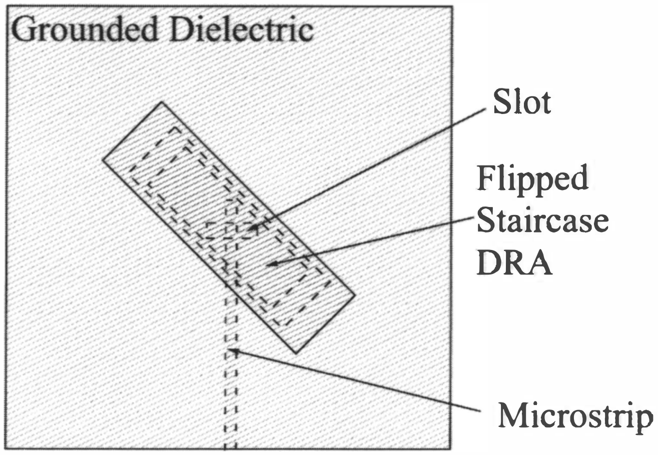


**Figure 6h. An example of a single-point-fed circular-polarized dielectric resonator antenna: $BW_{cp} = 10.2\%$ (from [163]).**

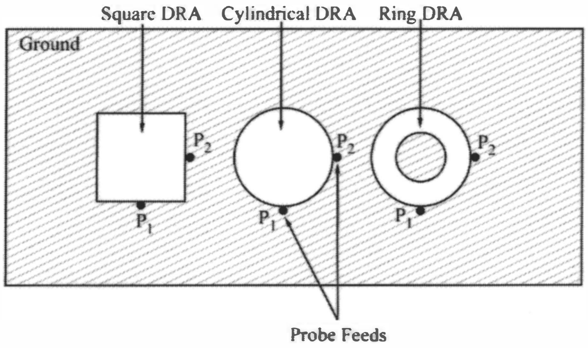


**Figure 7. Examples of dual-point-fed circular-polarized dielectric resonator antennas.**

**Table 5. Circularly polarized DRA designs ($BW_{cp}$ is the 3 dB axial-ratio bandwidth, $M$ is the maximum of the DRA's length or depth, $h$ is the DRA's height).**

| Number of DRAs | DRA Shape | $f_0$ (GHz) | $\varepsilon_r$ | Number of Feeds | Aspect Ratio ($M/h$) | Excitation | $BW_{cp}$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| 1 | Rectangular | 5.4 | 40 | 1 | 0.91 | Slot | 1.8% | [86] |
| 1 | Rectangular | 14.75 | 10.8 | 1 | 5.40 | Slot | 3.0% | [87,88] |
| 1 | Disk | 2 | 79 | 1 | 5.77 | Cross-Slot | 3.9% | [91,92] |
| 1 | Chamfered Square | X-Band | 9.4 | 1 | 1.25 | Probe | 4.0% | [7] |
| 1 | Modified Disk | 4.75 | 10 | 1 | 2.00 | Probe | 4.0% | [164] |
| 1 | Cross in Cavity | 18.5 | 10.2 | 1 | 3.00 | Slot | 4.0% | [89] |
| 1 | Cross | 11.2 | 10.8 | 1 | 4.00 | Slot | 4.5% | [85] |
| 1 | Disk | 5.75 | 9.8 | 1 | 5.92 | Cross-Slot | 4.7% | [165] |
| 1 | Rectangular | 5.4 | 10.8 | 1 | 1.10 | Slot | 6.6% | [159] |
| 1 | Rectangular | 2.45/5.8 | 9.7 | 1 | 3.37 | Coplanar Waveguide | 7.4%/6.6% | [162] |
| 1 | Half-Disk | 2.7 | 12 | 1 | 2.40 | Probe | 10.0% | [160] |
| 1 | Inverted Stepped Stair | 9.5 | 12 | 1 | 4.17 | Slot | 10.2% | [163] |
| 1 | Hexagonal | 3.2 | 59 | 1 | 2.84 | Probe | 14.8% | [161] |
| 1 | Ring | 4.2 | 36.2 | 2 | 2.66 | Probes | >11.0% | [41] |
| 1 | Cylindrical | 5 - 6 | 9.8 | 2 | 1.30 | Strips | 20.0% | [166] |
| 1 | Hemisphere | 3.65 | 9.5 | 2 | 2.00 | Probes | 21.0% | [167] |
| 1 | Cylindrical | 1.9 | 9.5 | 4 | 2.00 | Probe | 25.9% | [168] |
| 4 | Cross | 11 | 10.8 | 1 | 3.17 | Slot | 16.0% | [56] |
| 4 | Cylindrical | 4.4 | 16 | 1 | 1.21 | Cross-Slot | >16.0% | [171] |
| 4 | Square | 14.2 | 9.9 | 1 | 2.10 | Slot | 18.0% | [172] |
| 4 | Elliptical | 8-12.5 | 10.2 | 1 | 1.77 | Probe | 26.0% | [173] |
| 16 | Chamfered Square | X-Band | 9.4 | 1 | 1.25 | Probe | 17.0% | [7] |
| 16 | Square | 7.6 | 6.9 | 1 | 2.18 | Cross-Slot | 20.0% | [69] |

15%. A wide range of these circularly polarized dielectric-resonator-antenna designs are listed in Table 5. For wider bandwidths, a dual-point (or multi-point) feed can be used, as discussed in the following section.

## 6.2 Dual-Point-Fed Dielectric Resonator Antennas

In order to radiate circular polarization, single-point-fed dielectric resonator antennas rely on the structure of the dielectric resonator antenna itself to generate the required spatial orthogonal modes in phase quadrature. (The cylindrical dielectric resonator antenna of Figure 6g is an exception, but the two arms of the cross-slot can actually be considered a dual-point feed.) By using a dual-point (or multi-point) feed to excite the dielectric resonator antenna, the generation of the orthogonal modes in phase quadrature is shifted to the feed. This is typically achieved by using dielectric resonator antennas that have either square or circular symmetry, and placing the two feed ports ($P_1$ and $P_2$) as shown in Figure 7. To achieve circular polarization, $P_1$ and $P_2$ are fed with equal-amplitude signals in phase quadrature. This is generally achieved using a microwave power-divider circuit, such as a hybrid coupler, or a Wilkinson or T-splitter (with the appropriate phase delays). Depending on the type of circuit, the required amplitudes and phases at the two ports can be maintained over a fairly wide bandwidth, which will translate into a wide axial-ratio bandwidth. Two-probe-fed dielectric resonator antennas have achieved 3 dB axial-ratio bandwidths of up to 20% [41, 166, 167], while a four-probe-fed cylindrical dielectric resonator antenna has demonstrated a 26% bandwidth [168]. Details of these designs are listed in Table 5.

## 6.3 Sequential Rotation and Dielectric-Resonator-Antenna Arrays

Although wide axial-ratio bandwidths can be achieved using dual-point or multi-point feeds, the additional area required for the power-divider network makes this an unattractive option for use in an array. Fortunately, a technique known as sequential rotation can be used to create a circularly polarized array that does not require a complicated feed network, and can still make use of a single-point-fed dielectric resonator antenna. The technique works with either linearly or circularly polarized elements [169, 170]. Examples of dielectric-resonator-antenna arrays that make use of sequential rotation are shown in Figure 8. The feed network is designed so that subarrays of four (or even two) elements are fed with a progressive 90° phase shift. The relative locations of the feed points of the elements are sequentially rotated by 90°, or else the elements themselves are rotated. Using the sequential-rotation technique, 3 dB axial-ratio bandwidths of up to 20% have been achieved [7, 56, 69, 171-173]. A list summarizing the performance of circularly polarized dielectric-resonator-antenna elements and arrays is given in Table 5.

## 7. Increased Directivity Designs

Dielectric resonator antennas operating in their lowest-order modes all radiate like short magnetic or electric dipoles. When mounted on moderate to large ground planes, they will generate patterns with a maximum directivity of about 5 dB. For applications requiring higher gain, arrays of dielectric resonator antennas can be used, as will be discussed in Section 9. For medium-gain applications, several techniques can be adopted to enhance the directivity of dielectric resonator antennas. One method for enhancing the dielectric resonator antenna's gain is to stack dielectric resonator antennas, similar to the technique used for enhancing the impedance bandwidth, as was seen in Section 4. Stacking dielectric resonator antennas may result in either increased bandwidth, enhanced gain, or both, depending on the design. Gains from 6.2 dBi to 7.7 dBi have been achieved using the stacking technique designed for enhanced gain [75, 99, 174, 175].

A second method for achieving increased directivity is to incorporate a metal cavity. Two examples of this technique are

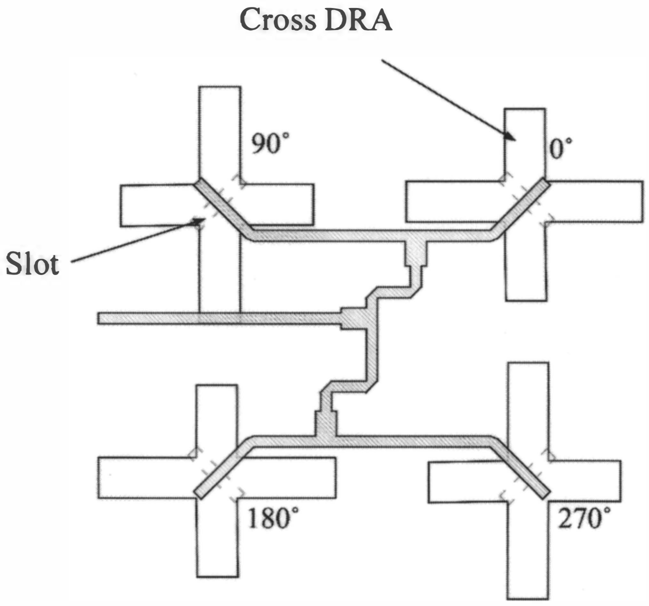


**Figure 8a. An example of a dielectric-resonator-antenna array with sequential rotation: $BW_{cp} = 16\%$ (from [56]).**

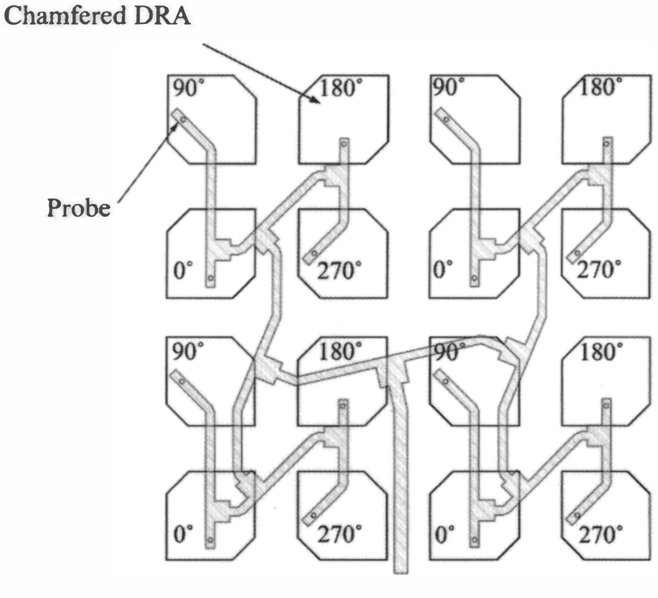


**Figure 8b. An example of a dielectric-resonator-antenna array with sequential rotation: $BW_{cp} = 17\%$ (from [7]).**

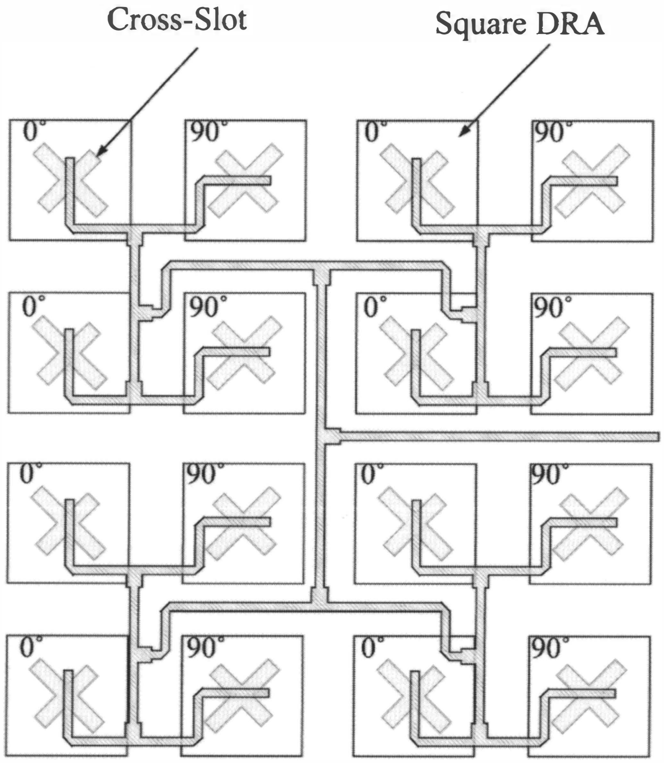


**Figure 8c. An example of a dielectric-resonator-antenna array with sequential rotation: $BW_{cp} = 20\%$ (from [69]).**

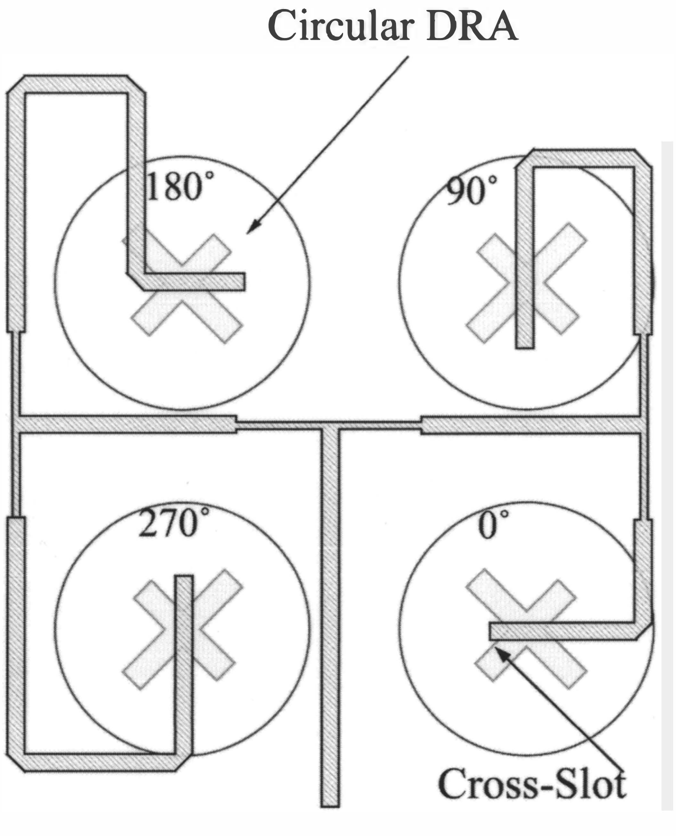


**Figure 8d. An example of a dielectric-resonator-antenna array with sequential rotation: $BW_{cp} > 16\%$ (from [17]).**

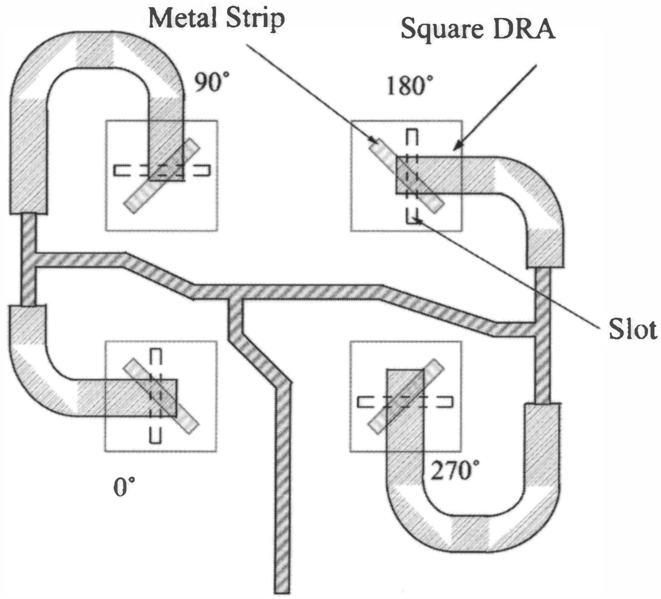


**Figure 8e. An example of a dielectric-resonator-antenna array with sequential rotation: $BW_{cp} = 18\%$ (from [172]).**

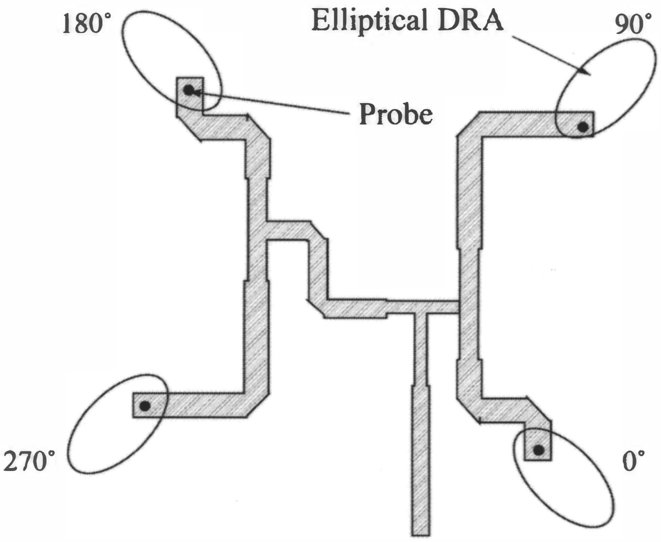


**Figure 8f. An example of a dielectric-resonator-antenna array with sequential rotation: $BW_{cp} = 26\%$ (from [173]).**

illustrated in Figure 9. Figure 9a shows a rectangular dielectric resonator antenna (linearly polarized) in a short rectangular horn-shaped cavity [176], while Figure 9b shows a cross dielectric resonator antenna (circularly polarized) within a cylindrical cavity [89]. The function of these cavities is to increase the effective radiation aperture of the dielectric resonator antenna, thus increasing the directivity of the antenna. The one- and two-wavelength cavities in Figure 9 result in measured gains of 10 dBi and 13.3 dBic, respectively. The use of an electromagnetic bandgap (EBG) structure along the ground plane has also been considered for improving gain, as shown in Figure 9c, where a gain of 8.5 dBi for a $1.2\lambda$-diameter ground plane was reported [177]. An alternative approach is to add a superstrate, as shown in Figure 9d. By selecting the thickness of the superstrate to be approximately a quarter of the guided wavelength, and by positioning it approximately a half free-space wavelength above the ground plane, a

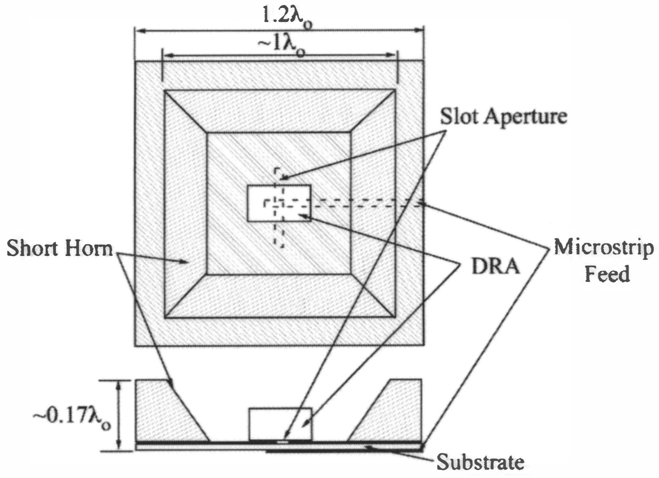


**Figure 9a. An example of a dielectric-resonator-antenna configuration with increased directivity: gain $\sim 10$ dBi (from [176]).**

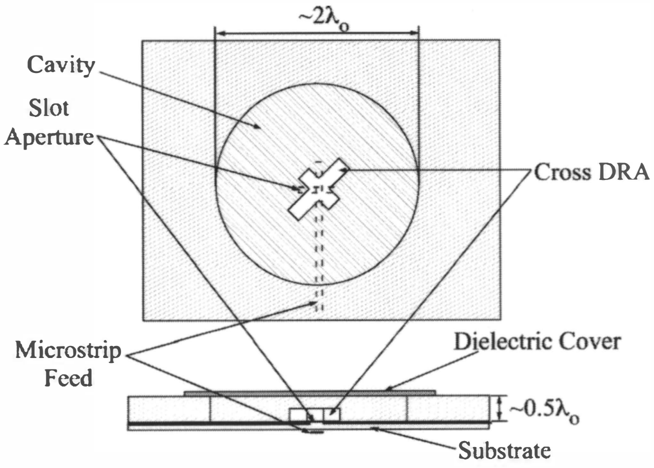
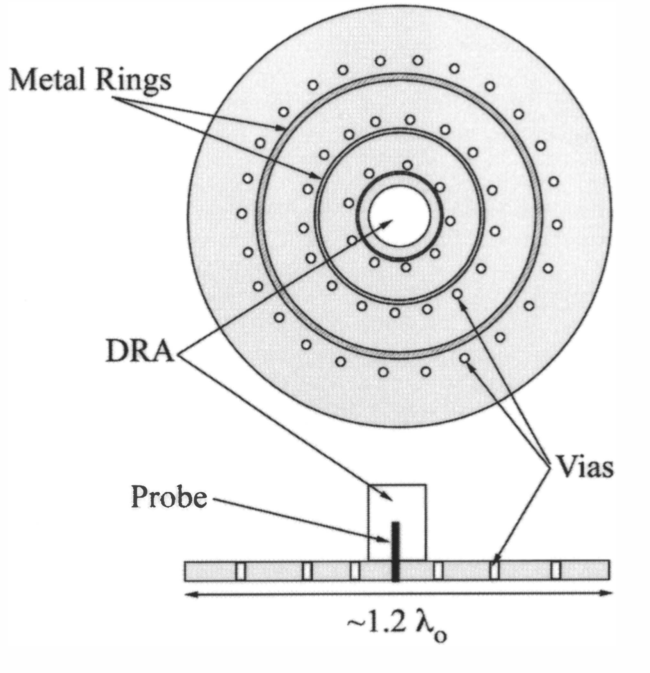


**Figure 9b. An example of a dielectric-resonator-antenna configuration with increased directivity: gain $\sim 13.3$ dBi (from [89]).**



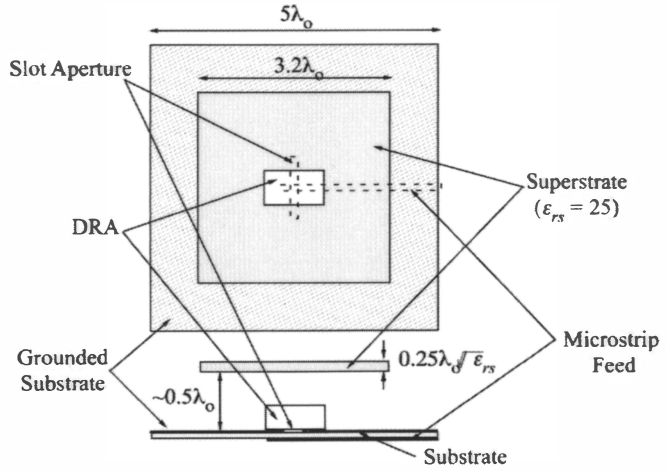


**Figure 9d. An example of a dielectric-resonator-antenna configuration with increased directivity: gain $\sim 16$ dBi (from [178]).**

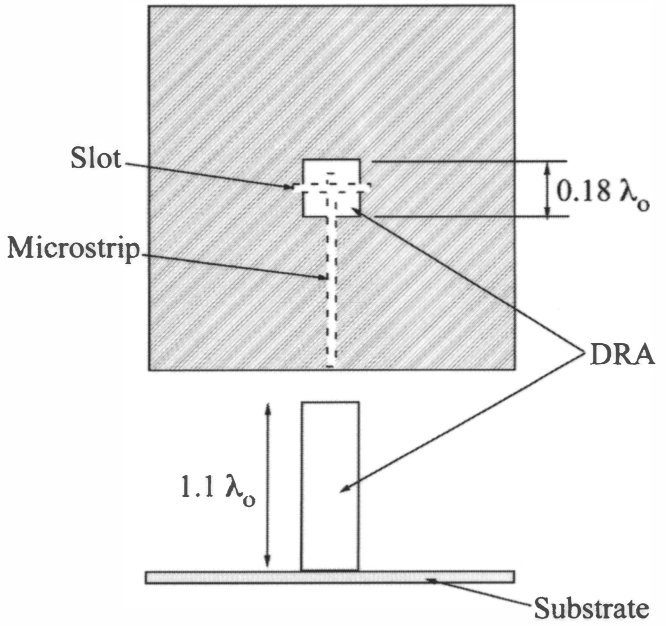


**Figure 9e. An example of a dielectric-resonator-antenna configuration with increased directivity: gain = 10.2 dBi (from [179]).**

**Figure 9c. An example of a dielectric-resonator-antenna configuration with increased directivity: gain $\sim 8.5$ dBi (from [177]).**

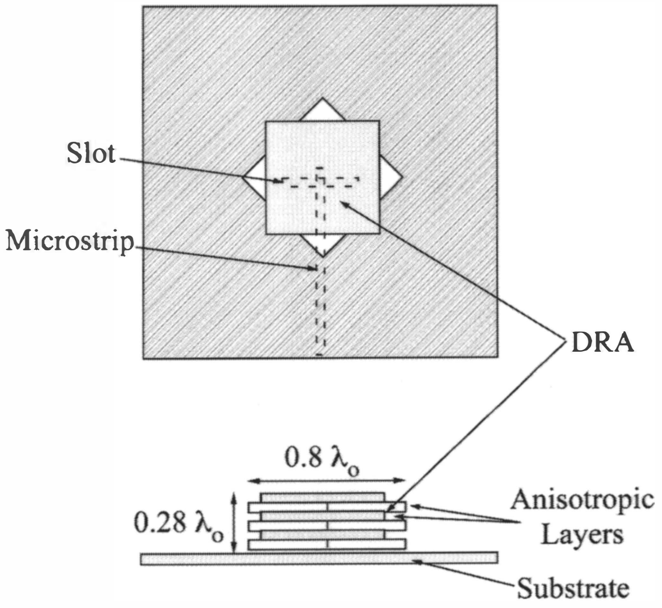


**Figure 9f. An example of a dielectric-resonator-antenna configuration with increased directivity: gain ~8.7 dBi (from [180]).**

leaky-wave mode is excited, and the area of the superstrate becomes the radiating aperture [178]. For the $3.2\lambda$ superstrate used in the example of Figure 9c, a maximum gain of 16 dBi was measured.

The use of cavities, EBG ground planes, or superstrates for enhancing the gain all require a relatively large area to achieve the improved gain performance. For applications where area is limited, these techniques may not be suitable. An alternative approach is to use dielectric resonator antennas operating in higher-order modes. An example of a higher-mode rectangular dielectric resonator antenna is shown in Figure 9e. The $1.1\lambda$ tall dielectric resonator antenna was designed to operate in the $TE_{15\delta}$ mode, and achieved a gain of 10.2 dBi [179]. A second example of a higher-order mode dielectric resonator antenna is shown in Figure 9f, consisting of alternate layers of two different anisotropic materials arranged in different orientations [180]. The example in Figure 9f achieved a gain of about 8.7 dBi, for a relatively compact structure.

Other improvements in gain have also been seen when parasitic elements were used, but this approach has focused on increasing the bandwidth, and the effects on enhancing directivity have not yet been thoroughly investigated.

## 8. Reconfigurable Designs

With increased spectrum usage due to greater consumer demand for high-speed wireless communications, the use of reconfigurable or adaptive antennas is being considered as one method for improving spectrum use. This section examines dielectric resonator antennas with capabilities for beam-steering, frequency tuning, or polarization agility.

### 8.1 Dielectric Resonator Antennas with Beam-Steering Capability

The ability to steer the peak of the beam of the radiation pattern finds many uses in various applications requiring tracking or interference mitigation. Beam patterns can be steered by either a physical movement of the antenna, or by electronic control of certain parameters within the antenna. An example of a dielectric resonator antenna with mechanical beam-steering ability is shown in Figure 10. The antenna consists of a probe-fed ring dielectric resonator antenna, which is composed of two sectors of different-dielectric-constant materials. For a ring dielectric resonator antenna made of homogeneous-dielectric-constant material, excitation using a center-fed probe results in an omnidirectional pattern. However, by introducing a sector of lower-dielectric-constant material within the ring, as shown in Figure 10, the gain in the direction of this sector increases, resulting in a directional pattern. By mechanically rotating the ring dielectric resonator antenna about its axis, the location of the beam peak can be scanned in azimuth. In [181], the prototype dielectric resonator antenna was fabricated by filling plastic tubes with liquids of different permittivity; however, more-practical designs would use solid ceramics.

The mechanically beam-scanned dielectric resonator antenna of [181] may be difficult to implement in practice, requiring a motor to rotate the dielectric resonator antenna. By using multiple feeds, the radiation patterns can be scanned using electronic switching. The advantages of electronic scanning include reduced mechanical complexity (improved reliability) and faster scanning speeds. Two examples are shown in Figure 11. Figure 11a is a single cylindrical dielectric resonator antenna having multiple probe feeds [109, 182-184]. By turning on or off different individual probes or combination of probes, the radiation pattern can be electronically steered in the azimuth direction. A second configuration, which uses the same technique for pattern steering, is shown in Figure 11b, consisting of an array of contiguous trapezoidal-shaped, probe-fed dielectric resonator antennas [185]. Such designs can find potential use in tracking or direction-finding applications [109].

### 8.2 Frequency-Tunable Dielectric Resonator Antennas

Antennas with electronic frequency tuning capabilities can find uses in applications requiring frequency hopping, for spectrum

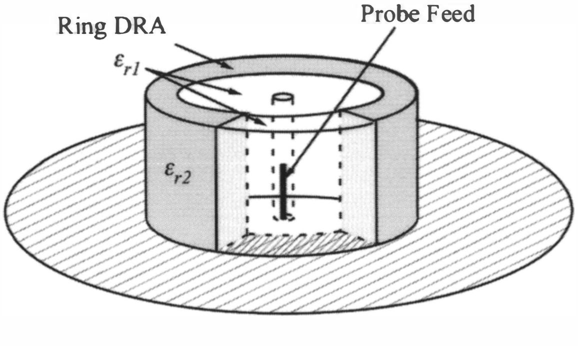


**Figure 10. A ring dielectric-resonator-antenna design for mechanically scanning the beam in azimuth (from [181]).**

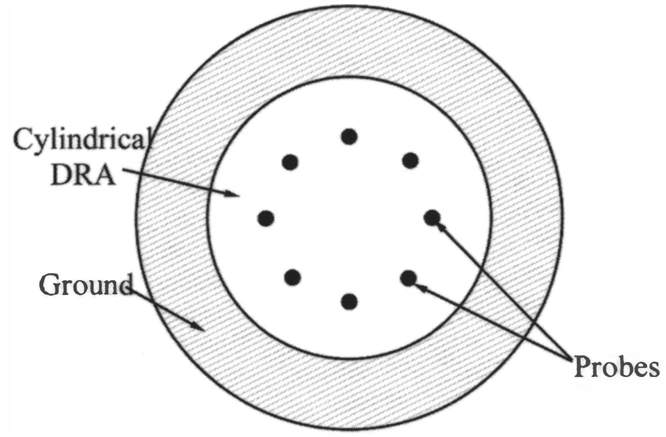


**Figure 11a. A dielectric resonator antenna with multiple probes for an electronically-switched beam in azimuth (from [182]).**

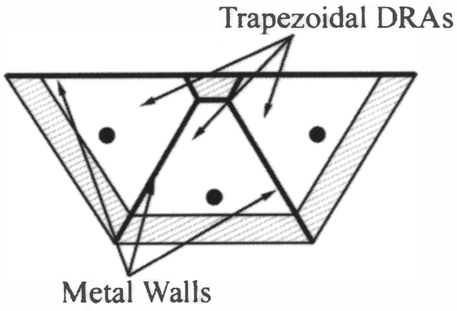


**Figure 11b. A dielectric resonator antenna with multiple probes for an electronically-switched beam in azimuth (from [185]).**

reuse, or for changing the frequency of operation from a remote site. Several publications have shown that the resonant frequency of dielectric resonator antennas can be tuned by properly loading them with slots, stubs, or metallic caps of varying dimensions. As with microstrip patches, by incorporating variable capacitors or diode switches, electronic frequency tuning should then be possible. Some preliminary research has examined the possibility of integrating PIN diodes with rectangular dielectric resonator antennas, and has shown that tuning ranges of greater than 50% are possible [186].

A second approach, which has also been used with microstrip antennas, is to incorporate microwave ferrite materials in the antenna's design. Applying a static magnetic field to a ferrite will alter its relative permeability. For resonant antennas designed with ferrite materials, this shift in relative permeability will lead to a shift in the resonant frequency. The resonant-frequency behavior of a rectangular dielectric resonator antenna fabricated from a ferrite material was documented in [103]. By applying a static magnetic field of varying intensity, it was experimentally demonstrated that the resonant frequency of the dielectric resonator antenna could be shifted from 9.35 GHz-11.45 GHz, corresponding to a 20% tuning range. An analysis published in [2, pp. 198-200] showed that maximum tuning ranges of between 40%-85% (depending on the frequency band) are theoretically possible using commercially available microwave ferrites.

Frequency tuning has also been demonstrated using a cylindrical dielectric resonator antenna consisting of a water-filled plastic tube [187]. By altering the height of the water in the tube, the resonant frequency can be tuned. A tuning range of 32% was demonstrated for a 50% change in height of the water level in [187].

## 8.3 Polarization Agility

Dielectric resonator antennas with polarization agility can be designed by using two or more feeds. For example, the dielectric resonator antennas shown in Figure 5 with the dual-point feeds can be made to radiate linear or circular polarization by proper amplitude and phase excitation of the two feeds. By incorporating electronic phase shifters and/or switches in the feed-network design, these dielectric resonator antennas can be made to exhibit polarization agility. An example using a two-probe-fed cylindrical dielectric resonator antenna was published in [106]. A diode was connected to each probe, and by the appropriate bias on the diodes, the dielectric resonator antenna could radiate two linear polarizations and one circular polarization. When operating in the circular-polarized mode, an axial ratio of 0.55 dB was measured at 4 GHz for this dielectric resonator antenna, with an overall radiation efficiency of 85%.

A second method for obtaining polarization agility is to exploit the tensor nature of microwave ferrites. It was shown in [104] that the polarization of a cylindrical dielectric resonator antenna fabricated of ferrite material could be switched from linear to circular when a static magnetic field was applied. Under an unbiased condition, the ferrite material behaved as a regular dielectric, and the aperture-fed dielectric resonator antenna operating in the $HE_{11\delta}$ mode radiated a linear-polarized pattern. However, when the magnetic bias was applied, the anisotropic permeability tensor of the ferrite resulted in the excitation of two orthogonal, quasi-degenerate $HE_{11\delta}$ modes, resulting in a circularly polarized pattern. For the dielectric resonator antenna designed in [104], the 3 dB axial ratio bandwidth was approximately 1.4%.

## 9. Dielectric-Resonator-Antenna Arrays

Dielectric resonator antennas are low-gain elements and, as with other low-gain elements, arrays of dielectric resonator antennas can be used to obtain higher directivity. This section highlights the developments in linear and planar dielectric-resonator-antenna arrays, and also considers some of the challenges involved in their fabrication.

### 9.1 Linear Arrays

Linear arrays are used for applications requiring fan-shaped radiation patterns (with a narrow beam in the plane parallel to the array axis, and a broad beam in the orthogonal plane). Some examples of linear dielectric-resonator-antenna arrays are shown in Figure 12. The arrays can be fed with either a series or a corporate power-divider network. Series feeds offer more-compact, lower-loss designs, but series-fed arrays have limited bandwidth, due to their inherent beam squint with frequency. Corporate feeds offer broader-band performance, but at the cost of higher insertion loss and the requirement for increased area. The selection of a series or a corporate feed for the linear array will thus depend on the requirements of the intended application.

Although several studies have been published analyzing the performance of various linear dielectric-resonator-antenna array configurations, the number of arrays actually fabricated has been quite small. Table 6 lists the key features of some of these arrays. One reason for the limited number of arrays is in the fabrication process. Dielectric resonator antennas have to be fabricated (usually machined from a block of ceramic), and then individually placed and bonded. This can be a labor-intensive and relatively expensive procedure. Some alternative fabrication techniques for dielectric-resonator-antenna array fabrication will be considered in the section on planar arrays.

## 9.2 Planar Arrays

Planar arrays are used to create pencil-beam radiation patterns with moderate to high directivity. Again, due to the added complexities involved in the use of dielectric resonator antennas in arrays, the number of fabricated planar dielectric resonator antennas that has been published is rather small. Table 7 lists several of these arrays, in order of increasing number of elements. As seen earlier, for circular-polarized operation, planar arrays can also be used to improve the axial-ratio performance of dielectric-resonator-antenna elements by adopting the sequential rotation technique. Several of the entries in Table 7 are examples of such arrays, many of which are shown in Figure 8.

A majority of these planar arrays consist of only a small number of dielectric-resonator-antenna elements. This underlines the fact that dielectric-resonator-antenna array technology is still in its infancy, and more research is required to overcome some of the challenges associated with fabricating large numbers of dielectric-resonator-antenna elements and assembling them into an array. One of the disadvantages of dielectric-resonator-antenna arrays compared to microstrip arrays is the added fabrication complexity involved in having to place and bond the individual elements. For high-volume applications, this process could be automated using robotic pick-and-place machines, but it is still not as attractive as the etching process used in printed technology.

Five of the dielectric-resonator-antenna arrays listed in Table 7 ([113, 200-203]) have been designed using alternative fabrication techniques. Figure 13 is a photograph of a planar array of

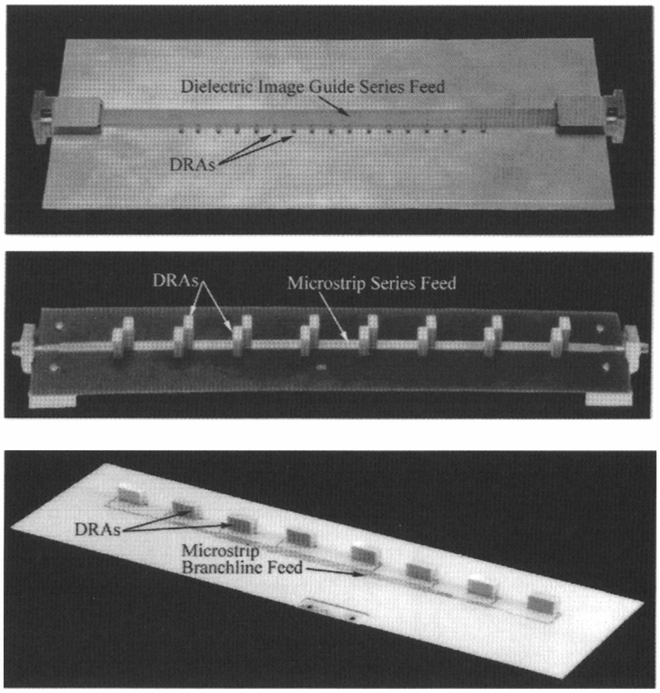


**Figure 12. Examples of linear arrays of dielectric resonator antennas.**

**Table 6. Linear arrays of DRAs.**

| Number of DRAs | DRA Shape | $f_0$ (GHz) | DRA Feed | Array Feed | Feed Structure | Ref. |
|---|---|---|---|---|---|---|
| 2 | Disk | 1.57 | Probe | Microstrip | Corporate | [68] |
| 2 | Disk | 5 | Aperture | Microstrip | Corporate | [49] |
| 2 | Disk | 6.7 | Probe | Microstrip | Corporate | [53] |
| 2 | Rectangular | 34-38 | Aperture | Surface Integrated Waveguide | Series | [188] |
| 3 | Rectangular | 18.5 | Aperture | Non-Radiating Dielectric Guide | Series | [54] |
| 4 | Disk | 4 | Probe | Microstrip | Corporate | [60] |
| 4 | Disk | 4 | Microstrip | Microstrip | Corporate | [61] |
| 4 | Rectangular | 41 | Aperture | Microstrip | Corporate | [63] |
| 4 | Stacked-Elliptical | 2 | Aperture | Microstrip | Corporate | [189] |
| 5 | Rectangular | 29 | EM Coupling | Dielectric Image Guide | Series | [190] |
| 10 | Rectangular | 19.9 | EM Coupling | Microstrip | Series | [50] |
| 10 | Rectangular | 8.2 | EM Coupling | Microstrip | Series | [51] |
| 10 | Multi-Segment Rectangular | 8 | Microstrip | Microstrip | Series | [191] |
| 12 | Rectangular | 8.5 | Microstrip | Microstrip | Series | [46] |
| 12 | Rectangular | 35.5 | EM Coupling | Dielectric Image Guide | Series | [6] |
| 16 | Rectangular | 5.75 | Aperture | Microstrip | Corporate | [192] |
| 16 | Rectangular | 7 | Microstrip | Microstrip | Series | [55] |
| 16 | Rectangular | 28.8 | EM Coupling | Microstrip | Series | [2] |
| 20 | Rectangular | 20.4 | EM Coupling | Dielectric Image Guide | Series | [50] |
| 30 | Disk | 11-12 | EM Coupling | Waveguide | Series | [193] |

**Table 7. Planar arrays of DRAs.**

| Elements | Element Type | $f_0$ (GHz) | Element Feed | Array Feed | Polarization | Ref. |
|---|---|---|---|---|---|---|
| 4 | Disk | 4 | Probe | Microstrip | Linear | [62] |
| 4 | Disk | 4.5 | Aperture | Microstrip | Linear | [64] |
| 4 | Disk | 4.4 | Aperture | Microstrip | Linear | [67] |
| 4 | Disk | 5 | Coplanar Waveguide | Coplanar Waveguide | Linear | [194] |
| 4 | Disk | 4.4 | Cross-Slot | Microstrip | Circular | [171] |
| 4 | Cross | 11 | Aperture | Microstrip | Circular | [56] |
| 4 | Rectangular | 7 | Aperture | Microstrip | Linear | [195] |
| 4 | Disk | 5.3 | Microstrip | Microstrip | Linear | [196] |
| 4 | Square | 14 | Aperture | Microstrip | Circular | [172] |
| 4 | Elliptical | 9-11 | Aperture | Microstrip | Circular | [197] |
| 7 | Cavity-Backed Cross | 30 | Aperture | Microstrip | Circular | [198] |
| 9 | Rectangular | X-Band | Probe | Waveguide Horn | Linear | [199] |
| 16 | Chamfered | X-Band | Probe | Microstrip | Circular | [7] |
| 16 | Square | X-Band | Cross-Slot | Microstrip | Circular | [69] |
| 16 | Rectangular | 09/11/09 | Slot | Microstrip | Linear | [200] |
| 64 | Square | 20 | H-Slot | Microstrip | Linear | [201] |
| 64 | MSDRA | X-Band | Microstrip | Microstrip | Linear | [57] |
| 64 | Perforated | 25 | Aperture | Microstrip | Linear | [202] |
| 128 | Square | 94 | Aperture | Microstrip | Linear | [113] |
| 320 | MSDRA | 8 | Microstrip | Microstrip | Linear | [58] |
| 529 | Rectangular | 30 | Space Fed | Waveguide Horn | Linear | [203] |

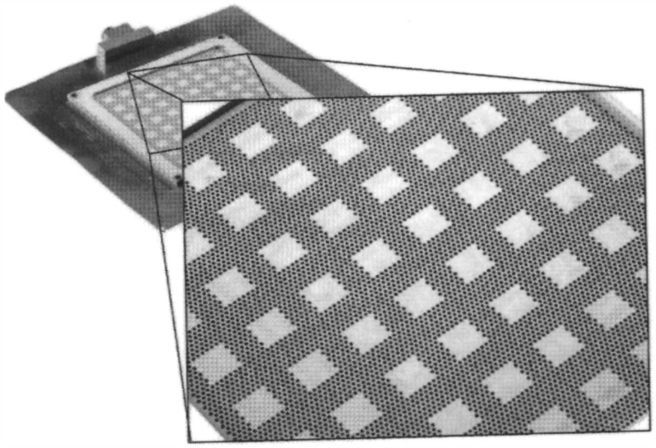


**Figure 13. A planar array of perforated dielectric resonator antennas.**

perforated dielectric resonator antennas designed at 25 GHz [202]. The technique of perforating a single dielectric sheet to form islands of solid material was used to overcome the fabrication challenge of placing and bonding individual dielectric-resonator-antenna elements in an array. Comparisons with a microstrip-patch array showed a 1 dB gain improvement and wider operating-band behavior for the dielectric-resonator-antenna array. A second technique for fabricating dielectric-resonator-antenna arrays uses ceramic stereolithography. In [201], this technique was used to fabricate an array of 64 rectangular dielectric resonator antennas designed at 20 GHz by assembling four monolithic subarrays, each consisting of 16 dielectric resonator antennas laid out in a square 4 × 4 lattice. The dielectric resonator antennas were locked into place by thin interconnecting ceramic beams. This technique thus avoids the need to individually place and bond each dielectric-resonator-antenna element, simplifying the fabrication process. At higher frequencies, silicon etching has been used for dielectric-resonator-antenna array fabrication. In [113], a planar array of 128 dielectric-resonator-antenna elements, designed at 94 GHz, was fabricated for use as a reflector feed. The square dielectric resonator antennas (1 mm × 1 mm × 0.16 mm high) were etched on the top side of a high-resistivity silicon wafer, while the feed network was processed on the underside of the wafer. Slot apertures were used to couple power from the feed network to the dielectric resonator antennas. The measured impedance bandwidth and radiation efficiency of this dielectric-resonator-antenna array were found to surpass those of a corresponding microstrip-patch array design. Finally, Figure 14 shows a 30 GHz reflectarray composed of rectangular dielectric resonator antennas [203]. Reflectarrays combine

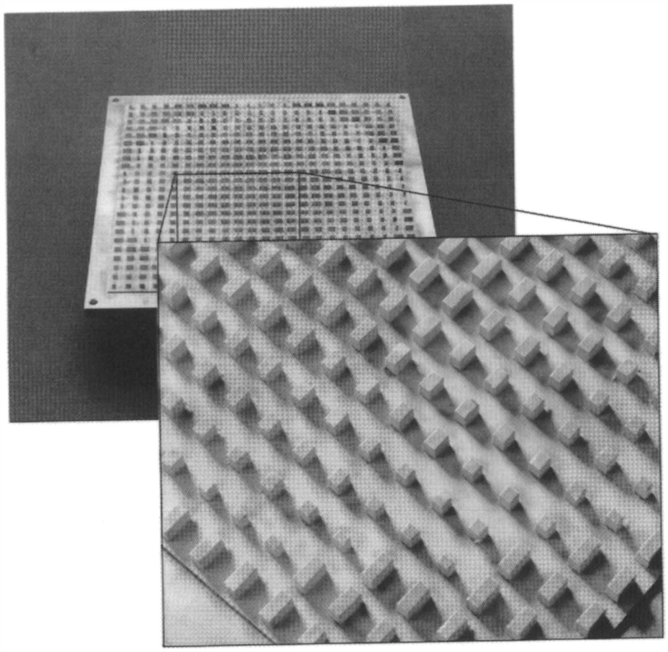


**Figure 14. A dielectric-resonator-antenna reflectarray.**

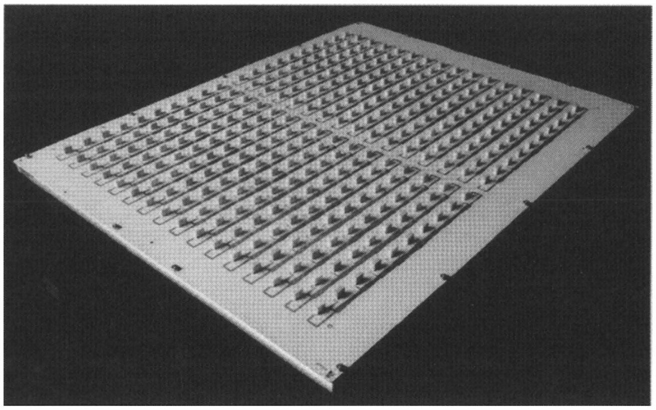


Figure 15. A planar phased array of multi-segment dielectric resonator antennas with electronic beam scanning.

the low-profile advantage of planar arrays with the low-loss performance of reflector antennas. The dielectric resonator antennas were machined from a single sheet of microwave dielectric substrate material, and then bonded to a rigid metallic flat plate. The dimensions of the dielectric resonator antennas were adjusted over the aperture's surface to produce the required reflected phase corresponding to a parabolic reflector. A small pyramidal horn was used to illuminate the dielectric-resonator-antenna reflectarray. With 529 elements, this represents the largest dielectric-resonator-antenna array in terms of element numbers.

Perhaps the most-complex dielectric-resonator-antenna array built to date is shown in Figure 15 [58]. The array consisted of 320 multi-segment dielectric resonator antennas, designed at 8 GHz, arranged in 16 columns of 20 elements each. On the back side of the antenna, a four-bit digital phase shifter was located behind each of the 16 columns, which were then combined using a corporate microstrip-feed network. The bits of the phase shifters were set using a computer-controlled interface in order to electronically steer the beam peak to the desired angle in the azimuth plane of the array.

## 10. Micro-Machined Dielectric Resonator Antennas and Dielectric Resonator Antenna Integration

One of the attractive advantages of dielectric resonator antennas is their relatively high radiation efficiency compared to microstrip antennas. This advantage comes from the lack of surface-wave losses and the reduced conductor losses of dielectric resonator antennas. The improved radiation-efficiency performance becomes more pronounced as the frequency is increased into the millimeter-wave region. One challenge facing millimeter-wave designs is to reliably fabricate dielectric resonator antennas with small physical dimensions (of 1 mm or less). Micro-machining and other fabrication techniques are starting to be used to construct dielectric resonator antennas for millimeter-wave applications, with designs of up to almost 100 GHz [113, 204-206]. Some of the details of these millimeter-wave dielectric resonator antennas are listed in Table 8. The use of micro-machining to fabricate dielectric resonator antennas can extend their frequency range well beyond 100 GHz. The challenge will then be in designing a feed structure to efficiently couple power to the dielectric resonator antenna.

Efforts are also starting to be made to integrate dielectric resonator antennas for system-in-package (SIP) applications. In [207, 208], a rectangular dielectric resonator antenna was used as both the radiating element and as a protective top cover of a housing for a radio-frequency chip package for 5 GHz communication applications. New techniques for attaching dielectric resonator antennas to microstrip lines are also being developed to facilitate dielectric resonator antenna integration [209]. Furthermore, the use of low-temperature co-fired ceramic (LTTC) techniques have successfully been adopted in the fabrication of dielectric resonator antennas for use in system-in-package applications. The example in [210] was of a rectangular dielectric resonator antenna designed at 24 GHz and fed by a metallic waveguide via a microstrip-to-waveguide transition. This demonstrated the ability of low-temperature co-fired ceramic technology to integrate dielectric and metal layers in a single process. Similar techniques could be used to integrated dielectric resonator antennas into handsets and other portable communication devices.

Some work is also being carried out to design dielectric resonator antennas that function as a circuit resonator as well as an antenna, which can facilitate system integration [211-214]. Finally, dielectric resonator antennas have also been integrated into all-dielectric wireless receivers, which are being designed to address the vulnerability of conventional wireless receivers to unwanted sources of intense microwave energy [215, 216].

## 11. Summary

The intent of this paper has been to provide a historical overview and a summary of the current state of the art of dielectric

Table 8. Micro-machined DRAs for millimeter-wave applications.

| DRA Shape | $f_0$ (GHz) | Dimensions (mm) | Dielectric Constant | Element Feed | Ref. |
|---|---|---|---|---|---|
| Rectangular | 92-98 | Length = 1.0<br>Width = 1.1<br>Height = 0.16 | ~11.7 | Slot | [113] |
| Rectangular | 54-71.5 | Length = 0.8<br>Width = 1.0<br>Height = 0.68 | 12.9 | Coplanar Waveguide-Fed Patch | [204] |
| Cylindrical | 59.5 | Radius = 0.33<br>Height = 0.3 | 48 | Coplanar Waveguide | [205] |
| Rectangular | 59.5 | Length = 1.0<br>Width = 0.5<br>Height = 0.3 | 48 | Coplanar Waveguide | [206] |

**Table 9. Summary of the state of the art of dielectric-resonator-antenna technology.**

| Description | State of the Art | Ref. |
|---|---|---|
| Smallest DRA (Physical) | Cylindrical DRA: radius = 0. 33 mm; height = 0.30 mm | [205] |
| Smallest DRA (Electrical) | Cylindrical DRA: radius = 0. 067 $\lambda_0$ ; height =0.052 $\lambda_0$ | [76] |
| Lowest Profile (Electrical) | Rectangular DRA: height = 0.026 $\lambda_0$ | [40] |
| Largest DRA | Cylindrical DRA: radius = 275 mm; height =200 mm | [109] |
| Lowest Frequency | 0.055 GHz | [109] |
| Highest Frequency | 94 GHz | [113] |
| Widest Impedance Bandwidth | 42% (for a simple rectangular DRA)<br>78% (2 stacked rectangular DRAs)<br>84% (2 embedded rectangular DRAs)<br>117% (hybrid monopole-conical DRA) | [127]<br>[142]<br>[152]<br>[158] |
| Widest Axial Ratio Bandwidth | 14.8% (single probe-fed hexagonal DRA)<br>20% (dual probe-fed)<br>26% (four-probe fed cylindrical DRA) | [161]<br>[41,167]<br>[168] |
| Largest Array | Linear Array: 30 DRAs<br>Planar Phased Array: 320 DRAs<br>Reflectarray: 529 DRAs | [193]<br>[58]<br>[203] |

resonator antennas, in order to highlight the high degree of flexibility and versatility that dielectric resonator antennas can offer. Dielectric resonator antennas can be designed to suit a wide range of physical or electrical requirements of varied communication applications, from VHF to EHF frequencies. Table 9 summarizes the current major achievements of dielectric resonator antennas and dielectric-resonator-antenna arrays. Many of these achievements can be improved upon, since they do not represent fundamental theoretical or practical limits. The cost of the versatility demonstrated by dielectric resonator antennas is the increased complexity associated with fabricating dielectric resonator antennas, compared to printed technology. However, as more research is carried out on dielectric resonator antennas, and existing or new fabrication techniques are adopted, many of the fabrication challenges will be resolved. This will make the dielectric resonator antenna an even more viable alternative to traditional low-gain resonating antennas.

## 12. Acknowledgments

The photographs in this article are courtesy of the Creative Visual Services Department of the Communications Research Centre Canada.

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