This chapter reviews the evolution of dielectric resonator antenna (DRA) technology over the past 24 years from the first cylindrical DRA to the latest magneto DRA. An account of the existing design aspects for achieving wideband operation, multiband operation, conical radiation patterns, circular polarisation and compactness for DRAs has been presented. Finally, a survey of the FDTD analysis of DRAs has been carried out.

2.1 DIELECTRIC RESONATOR ANTENNA - THE BEGINNING

Dielectric resonator (DR) is a ceramic puck characterised by a definite volume, shape, high dielectric constant and low loss. Radiation from open DRs was realized by Richtmyer in 1939 [1]. But the first theoretical and experimental analysis of a cylindrical DR antenna was carried out by Long et al. in 1983 [2]. Since then, DRAs transformed into a fast growing focus among the antenna researchers so that new DR geometries like rectangle, hemispherical, triangular, ring etc. were evolved and studied extensively [3-7], [9].

Kishk et al. presented a detailed numerical analysis of a dielectric disk antenna placed on a conducting surface based on surface integral equations to compute the resonant frequency and Q-factor [8]. Later, Mongia et al. published a comprehensive review of the modes and radiation properties of various DRs [10]. Accurate closed-form expressions for the resonant frequency, radiation Q-factors and the inside fields of a cylindrical DR were also described in the above work.
A detailed study of the fabrication imperfections of probe fed cylindrical DRAs was reported in [12]. It described that even thin air gaps between the DRA and the ground plane backing or between the probe and the DRA can notably modify its input impedance. An account of the various technological aspects of DRA research at the Communications Research Centre, Ottawa, Canada till year 1998 was published in [13]. This included novel DRA elements and arrays designed for wide bandwidth, compactness, circular polarisation, high gain and active antenna applications. All the existing feed mechanisms such as coaxial probe [2, 8], microstrip [5, 14, 15], coplanar waveguide [16, 17], slot-line [6, 11, 18], waveguide [19-21] etc are compatible with DRAs also.

2.2 WIDEBAND DRAs

In the early 90s when Junker et al. noted that the presence of an air gap between a cylindrical DRA and the ground plane, a kind of fabrication imperfection can cause broadening of the resonant curve of the DRA [12, 22]. This was the effect of reduced unloaded or radiation Q-factor (Q_u or Q_r) of the DRA due to an increased effective radiating area. Later, Ittipiboon et al. introduced an aperture fed rectangular DRA, with its centre portion removed. This DRA and its image formed a rectangular ring DRA to acquire a 28 % bandwidth [23]. This was motivated by the work of Verplanken et al. [24] which reported that the Q_r of certain modes of a cylindrical ring DR is lower than those of the corresponding cylindrical DR.
Use of multiple DRAs as part of the radiator provided an easy and straightforward way of exciting multiple radiating modes, which facilitated multi-band DRA design. By properly choosing the \( \varepsilon_r \) and dimension of individual DRAs, the resonant frequencies corresponding to the modes can be brought closer so as to enhance the bandwidth. Kishk et al. showed that a low \( \varepsilon_r \) DRA stacked on top of a high \( \varepsilon_r \) DRA could provide a bandwidth of 25 % [25]. Further studies on stacked DRA designs were carried out both experimentally and numerically [26-28]. Two rectangular DRAs separated by a metallic plate yielded a much broader bandwidth of 76.8 % [29]. Keeping the separate DR elements as a single entity in the above cases was tiresome and was avoided by fabricating single stacked DRA structures in the form of flipped stairled pyramid [30], L and T shaped equilateral triangular [31, 32] which offered a maximum bandwidth in excess of 60%.

Special DRA shapes like split-cylinder [33] and conical [34] were also reported to have wide bandwidths. Such geometries however suffered from an increased antenna dimension, especially the DRA height, compared to an individual element. Embedding one DRA within another, in the form of an annular ring solved the above problem where the antenna dimensions are the same as that of the parent DRA [35, 36]. Later, a stacked-embedded DRA design improved the bandwidth to 68 % [37]. A detailed comparative study of the stacked and embedded wideband DRAs with the homogeneous DRA was also carried out [38].
Modification of the feed geometry proved to be a successful method for improving the impedance matching and bandwidth. Luk et al. used a vertical metallic stub extended from a microstripline [39] or a coaxial probe [40] enhanced the bandwidth to 19 % and 43 % respectively for cylindrical and rectangular DRAs. In addition, this was also shown to improve the impedance matching. A fork-like tuning stub [41] coupling energy from a microstrip through a circular aperture to the DRA also improved the bandwidth. Feeding techniques like L-shaped [42] and T shaped [43] microstrip also improved the impedance bandwidth. To be suitable with low-Qr, DRA shapes like cylindrical cup, novel feeds like L, hook and J shaped probes [44, 45] were also found suitable in addition to the probe or slot feed. An aperture feed which excites the DRA in addition to radiating itself [46, 47] was capable of producing two merged-resonances causing wide bandwidth operation.

Designs using a simple DRA is also presented for bandwidth enhancement [48, 49], where an aspect ratio greater that unity allowed excitation and merging of dual modes of similar radiation properties.

2.3 MULTI-BAND DRAs

A dual-band antenna can replace two single band antennas of suitable operating bands. The work [25] on stacked wideband DRA was an implication to the design of dual-band DRAs by choosing two DRAs of different dimensions, excited by a single feed.
A wideband antenna unless is operating over a useful application band, is useless. This suggests the design of independent application bands where the antenna radiates only over those bands. Z. Fan et al. introduced a slot excited double element rectangular DRA for dual or wideband application [50]. Stacking of two cylindrical DRAs excited by an annular ring excited by a probe has shown a three-band behavior [51]. In [52] dual frequency operation was achieved by incorporating additional DRA in a parent DRA, both cylindrical in shape, so that the volume of the structure remains unchanged. A cylindrical ring DRA is fed with two orthogonal microstrip feeds is reported [53] for dual resonance. This also has the effect of producing orthogonally polarised bands but with similar broadside radiation patterns. Special eye-shaped DRA is also shown to be effective in producing dual radiating modes [54].

By adding an additional radiator to the DRA also, dual-frequency operation can be achieved. This principle is implemented in [55] where a cylindrical DRA and a ring-slot are fed together by a circular slot thereby allowing radiation from the two at respective resonances. If the feed to the DRA is also radiating at a particular frequency, it will be advantageous in this context. This technique is explained in [56] where the rectangular slot-feed to the DRA is made radiating by adjusting its dimensions. The same team introduced another design [57] by using a T-shaped microstrip feed that radiates in addition to exciting the DRA. A ceramic loaded annular ring monopole antenna is found to resonate in the dual WLAN bands [58]. The principle is nothing but the inherent size reduction property of high $\varepsilon_r$ DRs to be explained in the next chapter.
2.4 MONOPOLE/CONICAL BEAM DRAs

Most of the DRA designs discussed above produce broadside radiation where the pattern maximum occurs at the broadside or zenith ($\theta = 90^\circ$). This is achieved by properly exciting the magnetic dipole mode of the DRA [10]. But certain other applications like high performance radio local area network (HIPERLAN) [59] and vehicular communications need monopole-like or conical radiation patterns with the maximum radiation located at the elevation, most commonly in the range $30^\circ < \theta < 60^\circ$ and a null at the zenith. This is done in most cases by exciting the monopole-like modes of the DR with a center-fed coaxial probe.

In 1993, Kishk et al. noted that in the case of a probe fed cylindrical DRA, when the probe is positioned close to the centre of the antenna, a monopole $TM_{0m\delta}$ mode is also excited with the same strength as the broadside $HEM_{1m\delta}$ [8]. Mongia et al. demonstrated that a cylindrical ring DRA excited in the $TM_{018}$ mode can produce near monopole-like radiation [9] over a small bandwidth. Later, this design was modified for size reduction and good mode separation by incorporating a metallic cylinder concentrically inside the ring DRA [61].

A combination of microstrip line and probe was used for exciting monopole mode of a cylindrical ring DRA [62]. Conical beam operation is also realized by the use of two cylindrical DRAs fed by a single probe [63]. This has the effect of a 35 % increase in antenna gain but a 0.7 % decrease in bandwidth compared to a single element.
Recently, Guha et al. showed that by using an array of four cylindrical DRAs surrounding a coaxial probe [64] a wider impedance bandwidth of 29% can be achieved. Special geometries like stacked triangular DRA [32] or half-hemispherical DRAs [65] have also been reported to provide wideband conical-beam operation. Ultra wideband (UWB) monopole mode DRA was employed [66] by combining a quarter wave monopole and a ring DRA. The design details of the above antenna were given by Guha et al. [67]. In this, three resonances, resulted from the bare monopole, the ring DRA and the DR loaded effective monopole, combine to provide the UWB response.

2.5 CIRCULARLY POLARISED DRAs

Generally a DRA produce linearly polarised radiation when operated on any of the fundamental modes. The ability of DRAs to support multiple radiating modes simultaneously is well exploited in the design of circularly polarised (CP) antennas.

CP antenna design using DRAs started with [68] that propose a rectangular DR with two diagonally opposite corners truncated similar to the design implemented with rectangular patch antennas to produce CP. Later, Mongia et al. [69] produced CP by exciting the two orthogonal HE_{11s} modes of a cylindrical ring DRA using a 3dB quadrature coupler. In [70] the orthogonal HE_{11s} modes of a cylindrical dielectric resonator are excited by two probes fed in phase quadrature by a microstrip line. In [71] a slot-coupled rectangular DRA is used where the DRA position is adjusted 45° with respect to the slot to produce
CP from a cylindrical DRA over a bandwidth of 3.4 % and beam width of 110°. A cross-slot of unequal slot lengths in the ground plane of a microstrip line has been used [72] to produce CP from a cylindrical DRA over 3.91 % of bandwidth. A design with dual conformal strip feed [73] can also produce CP but over a wide bandwidth of 20 %. A cylindrical DRA is fed by a perturbed annular ring slot [74] to achieve an axial ratio bandwidth of 3.4 %. In this design, a backing cavity of hemispherical shape was used to block the back lobe radiation. Effect of parasitic conducting strip loading on the impedance characteristics of a cylindrical DRA has been studied [75] where CP is achieved by varying the angular position of the parasitic strip relative to the conformal feed.

A design similar to [71] is reported [76] where a parasitic strip is diagonally attached on top of a rectangular DRA and is fed through an aperture. The design is also shown suitable for a four element sequentially rotation DRA array. CP from a hemispherical DRA [77] has been produced by using an approach discussed in [75]. In the design, a slot aperture is used for coupling and the dual orthogonal modes for CP are generated by using a grounded parasitic strip attached to the DRA surface. A new geometry DRA in the form of a stair has been fed by a slot is also reported [78] for generating CP over a 10.6 % bandwidth. In [79] a 4.7 % axial ratio bandwidth has been achieved by using a cross-slot of unequal slot lengths for coupling to a cylindrical DRA. A cylindrical DRA with longitudinal slots of limited depth has been shown to produce CP over a 4 % bandwidth [80]. Compact CP design [88] is also reported using a half-split cylindrical DRA.
2.6 COMPACT DRAs

Design of compact DRAs has always been a challenging issue among antenna researchers. By using a high dielectric constant material, a small volume of DR can resonate at a lower resonant frequency as per Eq. (3.8) in Chapter 3. But this will increase the Q-factor and hence a lower bandwidth with the resonant frequency becoming highly temperature dependent [81].

Mongia et al. noted the existence of one or more planes of symmetry for isolated DR shapes. While this plane of symmetry serves as an electric wall for certain modes, it behaves as a magnetic wall for the other modes. This was the motivation for the work [82] where a half-split cylindrical DR was paced over a metallic ground plane, which was at the plane of symmetry \( \Phi = 0 \). The particular antenna configuration was excited in \( \text{TE}_{015} \) (magnetic dipole) mode with a low Q, thereby facilitating more than 8% bandwidth. A similar split-DR with a slot feed was used for allowing integration with MICs [83]. Numerical analysis of a half-split cylindrical DRA on a ground plane excited in the low Q modes -\( \text{TE}_{015} \) and \( \text{HEM}_{125} \) is presented [84] using a method of moment approach for the coupling between a body of revolution (BOR) geometry and a non-BOR geometry.

M. T. K. Tam et al. reported a half-volume design [85] for the broadside modes of a cylindrical (\( \text{HEM}_{115} \)) and rectangular (\( \text{TE}_{115} \)) DRAs based on the aforesaid approach. But they used an additional metallic plate attached to the plane of symmetry of the DR which was oriented in the orthogonal plane of that in [82]. In the same paper, the above team put forward the thread for further size
reduction of the DRA by using a metallic post instead of the metallic plate. The FDTD analysis of the above design was carried out by Steven G. O'Keefe [86] additionally demonstrating a higher directivity for the half-volume DRA.

But a revolutionizing low-volume design was presented by Tam et al. in 1999 using circular and annular sector DRAs [87] where a 75% reduction in volume is demonstrated. The design used different inner to outer radius ratios, sector angles and boundary conditions (metallic, open or mixed) for the sector DRA. A modification of the structure in [85] was used to produce circular polarisation [88]. Kishk et al. exhaustively studied the bandwidth enhancement property of split-cylinder DRAs numerically and experimentally [89]. Use of partial vertical and horizontal metallizations on a rectangular DRA has been proposed to reduce the overall dimensions of the DRA to be used at WLAN applications [90]. A thorough analysis of a reduced volume rectangular DRA based on the above principle has been presented [98] using FDTD and measurements.

For the enhanced miniaturization and a simultaneous increase in bandwidth, the new DRA trend was introduced by K. Sarabandi et al. utilising magneto-dielectric materials having both relative permittivity and permeability greater than unity [91]. The dimensions of the DR is thus proportional to the square root of the product of \( \varepsilon_r \) and \( \mu_r \). Recently, the experimental and theoretical aspects of a probe fed cylindrical DRA based on a magnetodielectric material have been studied [92].
2.7 FDTD ANALYSIS OF DRAs

Modeling of DR based structures using the FDTD method has been a major research area during the past few years. In 1991, Navarro et al. [93] theoretically obtained the resonant frequencies of a cylindrical DR enclosed in a metallic cavity, using FDTD combined with discrete Fourier transform (DFT). Kaneda et al. presented a modified contour-path integral FDTD [94] to analyze a shielded cylindrical DR, while maintaining the rectangular cells. In [95] Dey et al. discuss a conformal FDTD approach for cylindrical DR modeling based on weighted volume effective dielectric constant. An alternate and easier method was proposed by Yu et al. [96] based on a linear average effective dielectric constant concept. A fast and more accurate computation of resonant properties of axisymmetric DRs using FDTD was presented by Shi et al., by using the Pade'-DFT technique [97].

Much works on the modeling and analysis of DRAs using FDTD are not available in the literature. In 1994, Shum et al. studied the effect of an air gap between the DRA and the ground plane on the resonant frequency of a coaxial fed cylindrical ring DRA using FDTD [98]. The FDTD coordinate system used was cylindrical (r, Φ and z) because of the axial symmetry of the structure. An absorbing boundary condition (ABC) based on a parabolic interpolation was used to terminate the boundary and was placed at distances three times the dimensions of the DRA. A Gaussian-modulated sinusoidal pulse was used for excitation. The same team also calculated the resonant frequency of an aperture coupled rectangular DRA using FDTD [99].
Later, Esselle [100] obtained the radiation patterns of an aperture coupled low-profile rectangular DRA using FDTD. Mur's ABC was used to terminate the volume. The patterns were obtained by using the equivalence principle over a fictitious surface enclosing the DRA.

But the fundamental probe fed cylindrical DRA structure of [2] was analyzed by S. M. Shum et al in 1995 [101] and in detail in 1998 [102]. Since their DRA is offset-fed, unlike the approach in [98], the rectangular coordinate system was used with the second order Liao's ABC at the boundary. Various feed models like Voltage gap, Jenson and Magnetic-frill for the coaxial probe have been compared. A simple Gaussian pulse excited the system. The equivalent sources just above the DRA are calculated by using the Goertzel algorithm and the far-fields are computed by using the fundamental integral equations. The effect of fabrication imperfections of the DRA on its performance has also been simulated.

The effect of ground plane thickness and coupling slot geometries on the field coupling to a cylindrical DRA has been studied using FDTD by Guo et al. [103]. Four layer perfectly matched layer (PML) ABC has been used. In 2002, O'Keefe et al. studied the radiation characteristics of reduced-size DRAs [86] using FDTD. A four layer PML ABC with parabolic conductivity profile and Gaussian pulse excitation were used. In the work, they also computed the return loss, in-field and radiation patterns of HEM_{118}, TE_{118} and TE_{018} modes.

Conformal FDTD was used by Farahat et al. [104] to analyze a circularly polarised cross-shaped DRA. It is shown that the conformal mapping offers a 2:1
advantage over staircase mapping, without compromising accuracy. FDTD was used to design the dimensions of a rectangular DRA, feed and parasitic elements for the design of a CP DRA [88]. Sernouchkina et al. presented a detailed analysis of the modes in a rectangular DRA fed by a microstrip line [105]. Additionally, the influence of DR dimensions, feed location and surface metallization on the modes was also presented. In [106], Lan et al. used FDTD to design both the radiator and feed sections a combination antenna using a rectangular DRA and an inverted L-plate. A complemented dispersive boundary condition has been implemented in order to reduce the computational domain.

CONCLUSION

In this chapter, a detailed survey of the past works carried out in the field of dielectric resonator antennas was presented. Various aspects such as bandwidth enhancement, multi-band operation, circular polarisation, pattern modification and compact designs for DRAs were discussed. In view of the above, a new DRA design for wideband conical beam applications is proposed and studied in the forthcoming chapters.
REFERENCES


Literature Review


Literature Review


Literature Review


Literature Review


[92] H. H. B. Rocha F. N. A. Freire, R. C. S. Costa, R. S. T. M. Sohn, G. Orjubin, C. Junqueira , T. Cordaro , A. S. B. Sombra, Dielectric resonator Antenna: Operation of the magnetodielectric composites Cr0.75Fe1.25O3 (CRFO)/Fe0.5Cu0.75Ti0.75O3 (FCTO), Microwave and Opt. Tech. Letters., Vol. 49, pp. 409 - 413, December 2007


Chapter 2


