Dielectric Resonator Antennas: Applications and developments in multiple-input, multiple-output technology

Dielectric Resonator Antennas: Application and Development in Multiple Input Multiple Output Technology

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***Abstract*—This article presents a comprehensive review of multiple-input multiple-output (MIMO) dielectric resonator antennas (DRAs) evolved in the past decade. Besides the major challenges faced during designing a MIMO DRA, this article also discusses research gap required to be filled in the future. Exploring the advantages of DRAs, numerous novel designs have been proposed in the last few years. Major contributions of this article are: i) highlighting and comparing different MIMO DRAs on the basis of performances and applications; ii) elaborating the challenges, issues and research gaps in the emerging field of MIMO DRAs. To compare the performance of MIMO DRAs, published articles concerning MIMO DRAs are divided into five segments; the first segment covers Ultra Wide-Band solutions; circularly polarised solutions are discussed in the second segment; in the third one single element compact MIMO DRAs are taken over; multi-band MIMO DRAs are covered in the fourth segment and in the last segment, remaining articles of MIMO DRAs are discussed. A comprehensive review of all the latest trends of MIMO DRAs has been presented along with seven research gaps/challenges which needs to address in the future.**

***Index Terms*—dielectric resonator antenna (DRA), multiple input multiple output (MIMO).**

I. Introduction

In the past decade, exponential growth of communication standards has been evident around the globe. Following the principle of demand-supply of economics, speed of wireless data transfer and compactness of wireless devices have made substantial impact on the present world. Increased growth of wireless communication system resulted in the development of the Multiple-Input Multiple-Output (MIMO) antennas. These antenna systems with the ability to suppress fading, provide increased coverage and connectivity, high throughput and low latency playing a crucial role in the development of various RF and microwave communication systems [1], [2]. The 4^{th} generation (4G) and 5^{th} generation (5G) wireless broadband standards depend heavily on MIMO technology. On the other hand, Dielectric Resonator Antennas (DRAs) have several attractive characteristics such as no surface wave losses, high radiation efficiency, compact size, nearly constant gain, high impedance bandwidth (IBW) and ease of excitation. Hence, they are good candidates for various applications across the spectrum, from microwave toward to the optical frequency bands. The current state of the arts of DRAs in the microwave regime includes filtering DRAs [3], [4], compact DRAs with omnidirectional radiation patterns [5], wideband circularly polarized (CP) DRAs [6], [7], anisotropic DRAs [8], [9], RF energy harvesting [10], microwave image sensing [11], characteristic mode analysis of DRAs [12], frequency tunable DRAs [13], [14], active DRAs [15], [16] and DRA arrays [17]–[19]. A Substrate Integrated Waveguide (SIW) fed DRA array is shown in Fig. 1 with parasitic DRAs. DRA arrays are different from MIMO DRA for example: i)usually single feed used in array and multiple feeds used in MIMO; ii) power divider circuitry used in array to feed each element whereas the same is used in MIMO to achieve polarization diversity; iii) arrays are generally used to achieve high gain whereas MIMO antennas are preferred to achieve diversity.

One of the prominent features that draw attention to DRAs is their high radiation efficiency, which arises from their radiation mechanism being mostly based on displacement currents. Metallic antennas such as patch and printed dipole antennas suffer from high conductor losses at millimeter-wave range, where the skin effect gets more pronounced. Hence, their radiation efficiency starts to noticeably worsen as the frequency increases in the millimeter-wave band. In contrast, as reported in [19]–[22], DRAs indicate higher radiation efficiency, typically above 90%, at millimeter-wave band, which demonstrates their potential for applications in this band. Due to the high efficiency of the DRAs in the millimeter-wave band, it is highly desirable to extend their application range in the Terahertz regime. This has received growing attention from researchers in the field of Terahertz antennas. For example, in [23] a low loss on-chip Terahertz DRA has been reported, which has a radiation efficiency of 74% at 341 GHz. Also, to mitigate the size issue at Terahertz frequencies, Li et al. [24] studied designs of CMOS DRAs operating at their higher order modes. At optical frequencies, the electric field penetrates into the metal and couples with the surface plasmons, which results

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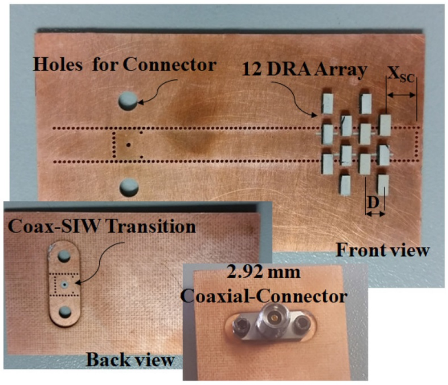

Fig. 1: SIW fed DRA Array [17]

in high dissipation losses. Due to the resilience of DRAs to losses in their ground (GND) plane, acceptable radiation efficiencies still could be obtained in the optical bands. This feature has inspired huge interest in the optics community [25]–[27].

In 2008, Ishmiya et. al. [28] proposed DRA based MIMO antenna which have more degrees of freedom for designing and low loss due to absence of metal in the DRA. Advantages of MIMO technology, combine with benefits of DRA, forms a new technological advance antenna system called DRA based MIMO antenna. DRA has also been operating in multi-mode and radiating power effectively in one direction. Also, circular polarization can be realized in DRA by using orthogonal modes. Exciting multi-mode or orthogonal modes in the DRA can be used to create multiple decoupled antenna ports, which can be considered as a basic building block of the MIMO system.

This article is organized into three sections. An overview of DRA based MIMO antennas operating at different frequency bands is first discussed. This is followed by a critical review of the recent publications on MIMO DRA over the last decade. In this section, published MIMO DRAs are divided into five segments: A) Ultra Wide Band (UWB) MIMO DRAs, B) CP MIMO DRAs, C) Single element MIMO DRAs, D) Multi-band MIMO DRAs and E) Remaining articles of MIMO DRAs which does not fall into (A)-(D). From this review, current research issues, challenges and research gaps are identified and discussed in detail. The concluding remarks presented at the end of this work include future strategies to fill the research gaps and elevation of research in proper direction.

II. Classification of MIMO DRAs

In the last decade, studies on DRA based MIMO antennas increased significantly for diverse wireless applications. To review this emerging domain of technology based on performance and characteristics, published articles concerning MIMO DRAs have been grouped into the following segments:

A. Ultra Wide Band MIMO DRA

In line with the definition for UWB transmitters given by the US Federal Communications Commission [29], UWB antenna should have a fractional BW equal to or larger than 0.20 or has an UWB BW equal to or larger than 500 MHz. In [30], a dual port half Cylindrical DRA (CDRA) based MIMO antenna has been discussed; frequency agility has been achieved by addition of re-configurable parasitic slot loading. PIN diode has been used as switching element. Two orthogonal GND planes were used for generating two modes (TE and HE) in the half CDRA and three MIMO configurations with three different frequencies (622 MHz, 700 MHz and 780 MHz) have been proven by varying switching state of PIN diode and value of capacitance. In [31], a simple Rectangular DRA (RDRA) with two ports has been proposed for LTE applications. A Coplanar Waveguide (CPW) feed with inductive slot and a coaxial probe feed have been applied on RDRA to excite $TE^x_{\delta 21}$ and $TE^y_{2\delta 1}$ modes, respectively. A metallic strip has been used to connect DRA to the coaxial probe in order to make the antenna operate at 2.6 GHz. Dimensions of metallic strip have been found by parametric analysis. In [32], four $HE_{11\delta}$ modes have been excited within the DRA by slots which were etched out of the GND plane of the FR4 substrate onto which the DRA has been mounted. Each of these slots has been excited by two 50-Ω Micro-Strip (MS) transmission lines; 7 dB IBW has been reported which may be useful in some low power requirement applications.

In [33], two F-shaped DRAs have been proposed for MIMO DRA with multiple GND planes. The use of multiple GND planes instead of the connected GND plane does not fall under the definition of MIMO antennas. The use of multiple GND plane is not a practical choice since, in a real system, the signals should have a common reference plane, i.e. a single common GND plane, so that all signal levels within the system can be interpreted properly based on that reference level (i.e., zero volts or GND level). If separate GND planes are used, one cannot guarantee that the system will work since the assumption of having all GND planes with the same voltage level is invalid [34]. In [35], two mushroom shaped DRAs, made up of RT/Duroid 6010 (ϵ_r=10.2, tanδ=0.002), have been excited by a conformal trapezoidal patch which form a MIMO antenna for wide-band applications. DRAs have been placed orthogonal to each other to achieve polarization diversity. Peak gain has been achieved from 3.34 to 7.4 dBi throughout the IBW. The mushroom shaped DRA has been formed by adding a rectangular DRA and half split cylindrical DRA on the top of it. This DRA resonates at three different frequencies (5.37, 6.95 and 9.58 GHz) corresponding to three modes TE_{111}, TE_{113} and TE_{115}. Here, matching and excitation of different modes that merge to offer wider BW have been provided by conformal patch. In [36], a single cross shaped DRA based dual band MIMO antenna for Global Positioning System (GPS) and LTE bands applications has been proposed. A cross-shaped DRA with carved corners and a cylindrical slot in

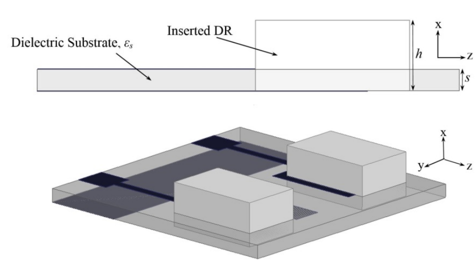

Fig. 2: UWB MIMO DRA with 106% fractional BW [37]

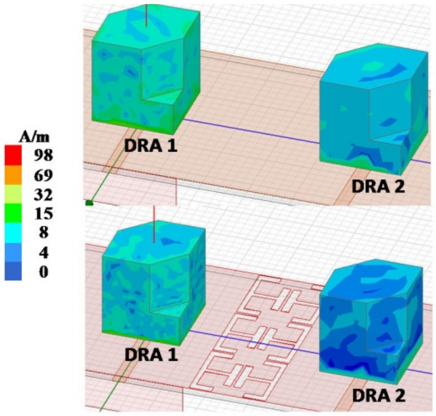

Fig. 3: Surface current distribution comparison of MIMO DRA with and without EBG [49]

between the DRA resulted BW enhancement. A slot on the GND plane between two feed points altered the current path and reduced mutual coupling. To add frequency agility in the design, PIN diodes were used in the GND plane.

In [37], an UWB MIMO DRA with WLAN band rejection has been proposed as shown in Fig. 2. Two RDRAs have been excited using MS feed lines and a stub connected to the GND plane helps to achieve wider BW with acceptable isolation throughout the BW. One more structure in the form of L-shaped parasitic strip connected to RDRAs on the top of the substrate is said to claim band rejection in WLAN band from 4.98 to 6.08 GHz, by providing strong disturbance of the DRA modes leading to a strong impedance mismatch near the notch frequency. However, realised gain varies from 1.1 to 5.3 dBi throughout the band except band rejection where gain drops to -1.64 dBi. In this work, RDRA has been inserted into Taconic RF-35 substrate with thickness 1.524 mm, such that it touches GND as well as MS line feed above substrate. In [38], the authors proposed a dual element, fractal T- shaped DRA based MIMO antenna for wide-band applications. Here, a C-shaped periodic Defective Ground Structure (DGS) has been applied to achieve isolation between ports. In [39], a triangular shaped DRA excited by three probe feeds has been proposed for switch beam operation. It focused on beam steering operation in WLAN applications; radiation pattern is tuned by switching the angular excitation port. In [40], the authors have used the conformal rectangular strip for excitation whereas in [35] a conformal trapezoidal-shaped strip is used to excite the mushroom-shaped DRA. Though, A-shaped DRA design has been taken from equilateral triangular DRA having dimension corresponding to fundamental TM_{101} mode. The DRA was made up of RT/Duroid 6010 with eight stack layers to achieve the desired height. 20 dB isolation has been realized by introducing sufficient inter-element spacing between two elements.

In [41], two RDRAs have been used to built a dual port MIMO antenna for LTE applications. A T-type matching circuitry has been used to match the antenna on the serial resonance of the first resonant mode at 800 MHz. Probe fed RDRAs have been placed diagonally for higher isolation. In [42], a self complementary hybrid Ring DRA (RiDRA) based MIMO antenna has been proposed. Two RiDRAs, made up of alumina ceramic (ϵ_r=9.8, tanδ=0.002), are excited by using stepped slot based GND and MS line above the FR4 substrate (ϵ_r=4.4, tanδ=0.02). The slot behaves as a resonating structure whose frequency is associated with dimensions of slot, mainly its length. Here wide-band IBW is achieved by merging dual bands developed due to stepped slots and two bands corresponding to $HE_{11\delta}$ and $TE_{01\delta}$ modes. In [43], a two element MIMO antenna with dual band capability has been proposed. It included two CDRAs placed on annular ring printed line which acted as a magnetic dipole and responsible for $HEM_{11\delta}$ and $TE_{01\delta}$ in CDRAs. A slit in the GND plane has been used to reduce mutual coupling in the lower operating frequency band. To improve isolation in the upper band, two radiators have been arranged orthogonally. In [44], the authors have proposed a two CDRAs based triple band MIMO antenna with a Y-shaped MS line feed. To increase isolation between ports, two metallic strips and a slot on the GND plane have been used. It was dictated that Y-shaped feed act as a short magnetic dipole to excite $HEM_{11\delta}$ mode in the CDRA. Moreover, it has been shown that lower band response is produced due to metallic reflector placed on the GND plane, mid band response is produced due to $HEM_{11\delta}$ mode in CDRA and upper band response is produced due to Y-shaped printed line. In addition to triple band, this antenna also exhibits circular polarization in the upper band which was due to Y-shaped line's ability to produce orthogonal modes.

In [45], a tri-band DRA based MIMO antenna has been proposed for WLAN/WiMAX applications. Interestingly, it fulfilled criteria for UWB given by [29] in all the three bands with fractional BW corresponding to 0.51, 0.21 and 0.26 in their respective bands. It was claimed that $HEM_{11\delta}$ and $HEM_{12\delta}$ modes have been generated due to Cylindrical DRA (CDRA) and T-shaped printed line, which acts as an electric dipole. Additionally, a circular ring shaped printed patch of the size of CDRA base, was found accountable for TM_{11} mode. To enhance isolation between ports, the concept of slitted GND plane has been used in the antenna. In [46], two element DRA based MIMO antenna has been proposed. Here, DRA was constructed using stacking of three rectangular DRAs. It exhibited around 46% fractional BW but only simulated results were discussed. In [47], two RiDRAs excited using U-shaped printed line has been proposed for MIMO applications in ultra wide range of BW (3-7 GHz). To improve isolation between ports, dual L-shaped DGS and a rectangular DGS are carved

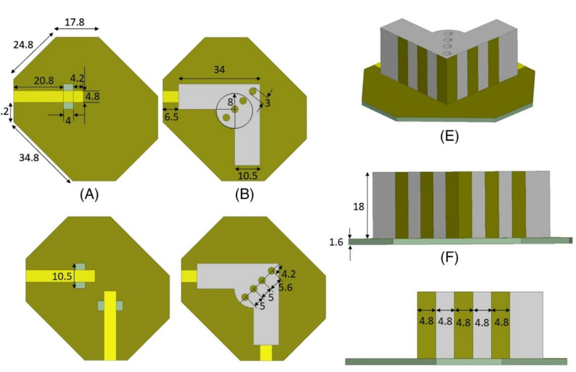

Fig. 4: Geometry of MIMO DRA with copper strips for gain enhancement [50]

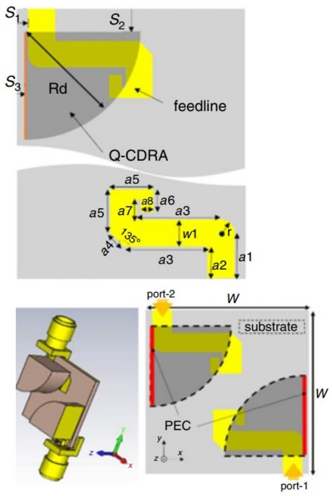

Fig. 5: Compact wideband Q-CDRA based MIMO antenna[56]

from the GND plane.

In [48], a wideband CP MIMO antenna with two RDRAs made up of Eccostock Hik bar (ϵ_r=10, tanδ=0.002) is presented. The diagonal placement of RDRAs give rise to high isolation. Each RDRA has been excited by E-shaped conformal copper strip which in turn was excited using probe feed. It shows a wide Axial Ratio BW (ARBW) along with wide IBW. Wide ARBW has been achieved by optimization of conformal patch and diagonal position of both the RDRAs. It was claimed that degenerate mode pair $TE^{x}_{\delta 13}$ and $TE^{y}_{1\delta 3}$ has been excited to generate circularly polarized radiated wave. In [49], Chen et. al. used Electromagnetic Band-Gap (EBG) surface along with DRA to obtain CP MIMO radiator for 5G applications. Here, a two diagonal edges truncated DRA was excited by a cross-ring slot to generate CP fields. In this work, for the first time a EBG surface has been used in DRA based MIMO antenna. Small triangular stands at the edges of DR have been utilized to hold it, avoiding any glue which can deteriorate its performance. The optimized planar EBG structure has been used to reduce mutual coupling between two truncated DR elements. Surface current distribution comparison of MIMO DRA with and without EBG is shown in Fig. 3. In [50], authors proposed a single element dual port MIMO antenna for WLAN applications. Geometry of the antenna is shown in Fig. 4. The shape of DRA has been obtained by merging L-shaped DRA and CDRA at its center. This compact antenna exhibited high gain but moderate isolation between ports. Gain enhancement and IBW broadening have been achieved by etching vertical copper strips on the surface of DRA. For better impedance matching and tuning four air gaps with optimized radii have been utilized in the antenna.

In [51], a dual band two element MIMO DRA has been proposed with circular polarization in the upper band. Two RiDRAs are excited using plus shaped aperture feed and a DGS in the GND is used to achieve high isolation. In [52], two I-shaped DRAs has been excited by circular aperture coupled feeds and high isolation is achieved by utilizing meander lines in between ports. In [53], stacked CDRA based dual band antenna has been proposed for WLAN applications. Here, broadside radiation patterns are achieved by exciting $HEM_{11\delta}$ and $HEM_{12\delta}$ in two stacked CDRAs of different dimensions. Isolation between ports has been achieved by utilizing spatial diversity. In [54], authors proposed the concept of circular polarized adaptability in DRA based MIMO antenna for sub-6 GHz applications. Two CDRAs have been excited using conformal probe and L-type feed network which resulted CP fields. RiDRAs have also been used to show concept of changing CP BW with varying inner shells of DRA. In [55], authors reported a dual port CP MIMO DRA for C band applications. Single DR element has been formed by combining a RDRA and a half cylindrical DRA, whereas two elements are joined together with no space in between them to achieve compactness. This resembles elliptical shape DRA. Each single DR element of antenna operates with $TM_{11\delta}$ and $TM_{21\delta}$ modes. In [56], a two-port compact wideband quarter cylindrical DRA (Q-CDRA) with CP has been proposed for MIMO applications. Geometry of the antenna is shown in Fig. 5. It consists of two-quarter CDRs facing each other; both excited by a quasi-spiral micro-strip transmission line to achieve CP. The image theory is applied, by placing electrical and magnetic walls to reduce the size of the CDR. In [10], a dual-port dual-CP DRA with wide ARBW (43.5%) is reported for electromagnetic energy harvesting. A series feeding structure that consists of four crossing slots and one MS line is used to excite the DRA. However, since the reported antenna is used for receiving energy, the performance of the antenna is not affected by the relatively low port isolation of 10 dB.

B. *Circularly Polarized MIMO DRA*

CP antennas are preferred over their linearly polarized counterparts because of advantages such as ease of reception and higher reliability of signal. For MIMO antenna system CP antennas are preferred to increase its diversity performance. UWB CP MIMO DRAs [32], [44], [48], [49], [51], [54]–[56] have already been discussed in preceding subsection.

In [57], a cross shaped DRA with broadside CP and vertically polarized omnidirectional radiation patterns has been proposed by exciting two different modes within DR as shown in Fig. 6. The size of the DR is reduced by using thin plates of high-permittivity material (ϵ_r=50). Sequential rotation feed technique is utilized to increase the symmetry of the modes and reduce coupling between the two ports. In [58], authors presented a simulated antenna without being verified with fabricated prototype's measured results. In this work, a corner truncated V-shaped DRA has been excited by two MS line feeds to generate CP fields in the antenna. In [59], Sahu et. al. proposed a L-shaped based CP MIMO DRA for WLAN applications. Two L-shaped DRAs have been placed self complementary and excited using coaxial probe feed arrangement. Two self complementary C like shaped DGS have been applied to achieve desired isolation between ports. Two degenerate orthogonal modes ($TE^{x}_{\delta 11}$ and $TE^{y}_{1\delta 1}$) have been excited in

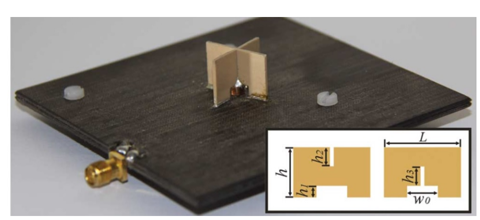

Fig. 6: High permittivity (ϵ_r=50) cross shaped antenna [57]

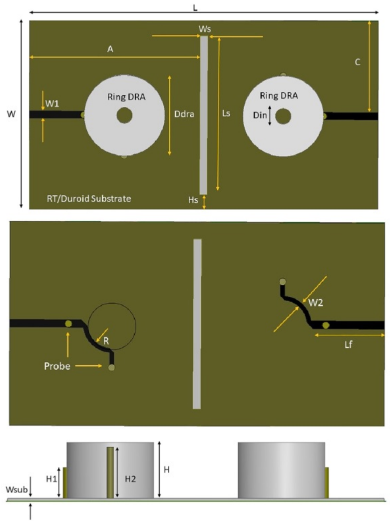

Fig. 7: Geometry of MIMO DRA with CP BW in both the operating bands [61]

DRA, using optimized position of coaxial probe. In [60], Das et. al. proposed a dual port, dual CDRA based CP MIMO antenna for WLAN applications. Circular polarization has been generated by using modified circular shaped aperture slot. To achieve isolation between ports, number of DGS slits have been applied in the GND plane. Due to perturb circular shaped aperture, two degenerate orthogonal modes ($HE^{x}_{11\delta}$ and $HE^{y}_{11\delta}$) have been generated in the CDRA to produce CP fields. In [61] a dual band MIMO DRA with ARBW in both the operating bands has been proposed. Geometry of the antenna is shown in Fig. 7. An arc shaped line feed network is used to achieve CP and impedance matching whereas slit in the GND plane is used to achieve isolation between ports. Low correlation has been achieved by polarization diversity and spatial diversity.

C. Single Element MIMO DRA

Compactness of antenna is one of the desirable property in applications such as satellite and mobile communication. Compactness is one of major attraction in multi-port MIMO antennas. A small size can be chosen using high permittivity DR material, as permittivity of the DR is inversely related to its dimensions. But high permittivity DR lack the property of field leakage which affect its radiation properties as antenna. In view of this, single element MIMO DRA is one of the thrust area which requires attention. In previous subsections some single element MIMO DRAs have already been discussed [30]–[32], [36], [50], [57], [58]. Figure 8 shows geometry of dual band cross shaped compact MIMO DRA [36]. Some other geometries are discussed in this subsection.

In [62], a half-split cylindrical DRA with two orthogonal GND planes have been chosen with two feeds. A mode degeneration method derived from perturbation theory has been proposed to make the TE and HE modes of the split-cylindrical DRA resonate at the same frequency. In addition, very low mutual coupling between two ports has been observed due to the presence of orthogonal GND planes. In [63], a CDRA excited by two orthogonal probe feeds for MIMO applications has been discussed. Here, a simple frequency-domain channel capacity analysis method has been derived for the DRA-based MIMO systems, which directly used complex S-parameters for calculating the normalized correlation matrix eigenvalues. In [64], a dual-mode DRA with a magnetic-monopole-like and electric-monopole-like radiation patterns has been proposed by exciting the ($TE_{01\delta}$ and $TM_{01\delta}$) modes in a single annular cylindrical DR. Two groups of four radially arranged MS feeding lines with two different lengths are utilized to increase the BW of the TE mode and suppress the influence of higher-order modes.

In [65], a dual band and dual-polarized cylindrical DRA made up of lower permittivity material (K9-Glass ϵ_r=6.85) has been investigated. The fundamental mode (HEM_{111}) and higher-order mode (HEM_{113}) of the cylindrical DRA have been excited by the strip- and slot-fed excitation methods. To achieve impedance matching, a pair of unequal arc-shaped slots are used for one port, whereas an impedance transformer is inserted in the MS feedline for second port. In [66], a RDRA has been fed with two MS line feeds with conformal patch. The top face of the DR has been covered with a square copper patch. Two orthogonal modes ($TE_{\delta 11}$ and $TE_{1\delta 1}$) have been excited inside the DR to achieve high isolation. The vertical metal strips have been connected with MS line, to improve impedance matching. In [67], discussed the design formulae for three port CDRA based MIMO antenna. The $TM_{01\delta}$ mode of the DRA is excited using an axial coaxial probe, whereas each of the orthogonal $HEM^{x}_{12\delta+1}$ and $HEM^{y}_{12\delta+1}$ modes is excited by a pair of balanced slots. These balanced slots of both the ports are fed by using two Wilkinson power divider printed on the substrate. In [68], two annular RDRAs stacked on each other have been excited by two probe feeds. Here, only simulated results were discussed which have acceptable values for MIMO operations.

In [69], a single RDRA element has been housed in a thin FR4 substrate and fed by two MS feed lines. Both the feeding lines excited $TE^{x}_{\delta 11}$ mode in DR. Two slits in the GND plane has been introduced to decrease the mutual coupling between the ports. In [70], a L-shaped DR element with cylindrical air gap has been excited using two slot coupled feed lines. The cylindrical air gap has been introduced to provide isolation between both the ports. To improve impedance matching, two copper strips have been etched at back of DR element. In [71], a compact dual-band MIMO stacked DRA has been proposed for WiMAX/WLAN applications. Stacking is used to make

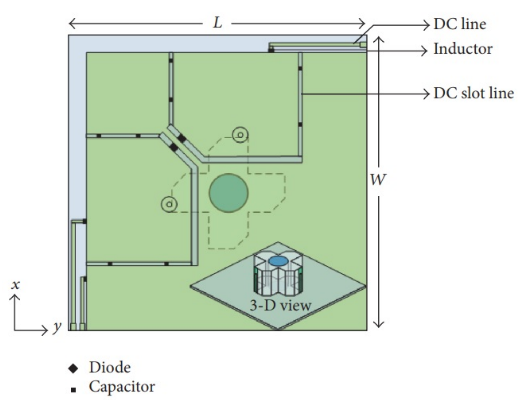

Fig. 8: Dual band cross shaped compact MIMO DRA [36]

the design compact and the DGS technique has been applied to achieve high isolation between antenna ports. For both the ports, excited modes radiate like a short magnetic dipole. Two coaxial probes of equal heights are used to excite two different modes in the DR that radiate like a short magnetic dipole. In [72], a RDRA has been excited using two feeds which were probe feed and aperture coupled feed, resulting in dual band antenna for LTE applications. However, in this work multiple GND were taken for two RDRAs. In [73], a cross shaped DRA has been excited using probe feed and aperture coupled feed. A rectangular aperture coupled feed has been used to excite $TE^x_{\delta 11}$ and $TE^x_{\delta 13}$ modes whereas probe port feed has been used to excite $TE^y_{1\delta 1}$ and $TE^y_{1\delta 3}$ modes at 3.5 GHz and 5.25 GHz, respectively. A metallic strip was also etched on surface of DRA to achieve better impedance matching.

In [74], a RDRA excited using three ports has been proposed for X-band applications. Here, method to generate three mutually decoupled modes has been discussed where the decoupling between two of the modes ($TE^x_{\delta np}$) was achieved by minimizing the spatial overlapping of field magnitudes, instead of exciting mutually perpendicular field components. The third mode $TE^y_{m\delta p}$ has been excited using probe feed. where the field components of that $TE^y_{m\delta p}$ mode were perpendicular to the ones of $TE^x_{\delta np}$ mode, which was needed to excite the three mutually decoupled modes. In [75], a differential dual-band dual-polarization DRA has been investigated and realized using the cross-shaped DR fed by two same pairs of differential schemes. TE_{111} and TE_{113} modes are utilized to obtain two resonant frequencies for dual-band response. In [76], a CDRA has been excited using two aperture coupled feeds. During port-1 excitation, a power divider has been used to excite the DR through two narrow annular shaped slots in the GND plane. These slots behaved like a magnetic dipole which resulted $HE^y_{11\delta}$ mode generation in the DRA. During port-2 excitation a simple MS line has been used with annular shaped aperture in the GND. In [77], a L-shaped DRA excited using two probe feeds has been proposed for dual band LTE applications. A DGS slot between ports has been applied to increase isolation. Proposed MIMO antenna also demonstrated high throughput for different modulation schemes. In [78], an equilateral triangular DR element has been excited by two parallel MS line feeds with conformal strips on the DRA. To achieve higher isolation between feeds, front edge of DR element was perturbed in the form of semi-cylindrical geometry as shown in Fig. 9.

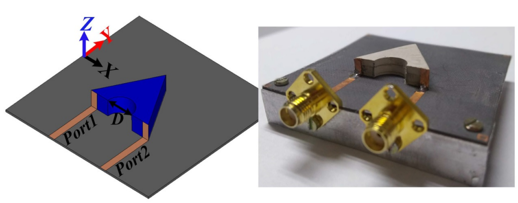

Fig. 9: Stacked and perturbed equilateral triangular shaped MIMO DRA [78]

In [79], a wideband dual-polarized metal loop dielectric resonator magneto-electric (MLDR-ME) dipole antenna with low backward radiation and symmetrical E- and H-plane radiation patterns for a broadside array has been proposed. It comprised of two perpendicular metal semi-loop radiators and a cross-shaped dielectric resonator. The metal semi-loops serve as the feeding structure to the two orthogonal modes in the dielectric resonator as well as two magnetic dipole antennas whereas each of the resonant modes in the dielectric resonator creates an electric dipole.

In [80], a differential dual-polarized filtering DRA using a four-leaf-clover shaped DR as the radiator has been proposed. Two pairs of orthogonal modes with out-of-phase field distributions in the DR are excited by T-shaped feeding strips. The T-shaped feeding strips also facilitate integration applications by offering flexible input impedance for the radiation part. After integrating a pair of high performance filtering baluns on the back of the reflecting GND, the proposed DRA also shows high frequency selectivity for each polarization, without increasing the antenna size.

D. Multiband MIMO DRA

Multiband antennas always attracted researchers due to their diverse commercial applications in different bands simultaneously. Features of multiband geometries [41], [43]–[45], [51]–[53], [61], [65], [68], [70]–[73], [77] have already been discussed in previous sections, so remaining publications are reviewed here. Figure 10 shows geometry of triple band CDRA based MIMO antenna [45].

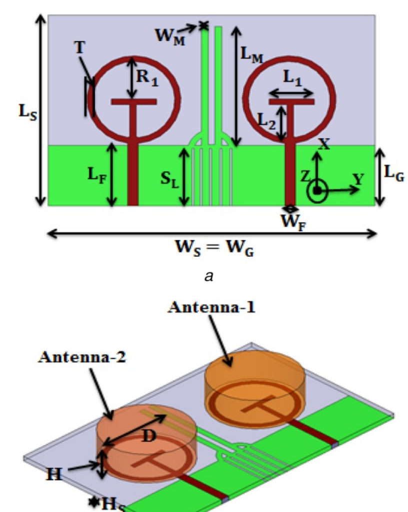

Fig. 10: Geometry of triple band MIMO antenna [45]

In [81], eight CDRAs have been excited by eight feeds to make a dual band MIMO antenna. One group of four CDRAs covered the 2.45 GHz band whereas other group of four CDRAs covered 5.8 GHz band. Isolation between lower band elements and upper band element was better than 15 dB. At lower band and higher band, $HEM_{11\delta}$ and $TE_{01\delta}$ modes have been excited, respectively. A centre metallic reflector element to reduce the correlation coefficients via tilting the fields and thus improving the system operation has also been introduced. In [82], four half-split CDRA based dual band MIMO antenna has been proposed for LTE and WLAN applications. The dual band operation has been achieved by simultaneously exciting $TE_{01\delta}$ and $TE_{02\delta}$ modes in an aperture coupled half-split

CDRA. Four elements have been arranged in 2x2 format and also orthogonally to each other to achieve better radiation characteristics. In [83], two RDRAs have been excited using MS line feed followed by meander lines. However, in this work multiple GND were taken for two feeds which contradicts the MIMO definition given in [34]. In [84], authors proposed a partial reflector surface structure with varying circular patches on it, to improve isolation between CDRAs for multiband MIMO applications. Geometry of the antenna is shown in Fig. 11. In [85], a MIMO antenna is proposed with four RiDRAs excited by aperture coupled feed. Due to the use of polarization and space diversity, the isolation value is more than 20 dB for all the ports. Pentagon ring shaped aperture excited dual modes $HE_{11\delta}$ and $HE_{12\delta}$ in the ring ceramic resonator.

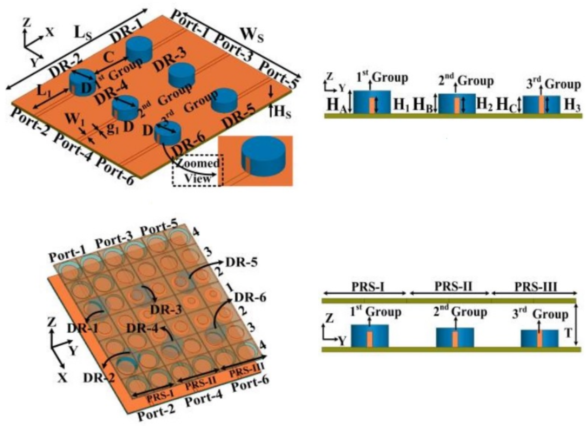

Fig. 11: Geometry of triple band MIMO DRA with partial reflector surface [84]

E. Other MIMO DRA

This subsection is dedicated to those published articles relating to MIMO DRAs which does not fall into any of the categories discussed in subsections (A)-(D) above. In [86], a dual port eight CDRA based MIMO antenna has been proposed for handheld devices. There were two arrays of four CDRAs each which were excited by aperture coupled feed. A passive MS line based feed network has been used to excite the array elements from two ports. In [87], four arrays with four elements each has been excited by four ports. However, only simulated results were discussed without fabrication of design in [86] and [87]. In [88], a dual port MIMO antenna has been proposed with technique to improve the isolation between two adjacent DRAs operating at 60 GHz. Improved isolation is achieved by using a metasurface shield constructed of a unique split-ring resonator that is designed to provide band-stop functionality over the operating frequency range centered at 60 GHz. By integrating the array of SRR cell structure between the H-plane DRs along the E-plane results in a substantial reduction in the mutual coupling between the adjacent radiators. In [89], an eight-element MIMO antenna system has been proposed for 4G and 5G mobile communication. It consists of two arrays with four elements that are closely spaced which are selected to compensate for the free-space path losses that can be observed at mm-wave frequencies and provide beam steering capability to reduce channel correlation.

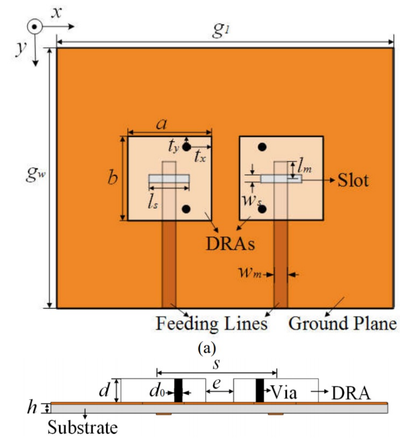

Fig. 12: Geometry of MIMO DRA with metallic vias based decoupling [95]

In [90], a metamaterial polarization-rotator wall has been used to reduce the mutual coupling due to spatial electromagnetic fields between two CDRAs in a MIMO system. In [91], a beam-tilting MIMO antenna loaded with the metamaterial unit-cells has been investigated. Authors proposed metamaterial unit-cells which are used to create a negative refractive index medium, which is responsible for beam-tilting mechanism. The proposed beam-tilting antenna consists of a double-feed DRA and 1×4 NRIM array fixed by nylon studs over the DRA. In [92], a three port, two CDRA based MIMO antenna has been discussed. Two CDRAs were excited by two probe coupled feeds and one MS line feed with an array mode. The isolation between ports has been improved by etching two C-shaped defected GND slits. Due to coaxial probe port and MS line fed port, orthogonal modes $HE_{11\delta}^{x}$ and $HE_{11\delta}^{y}$ are generated on the CDRAs, respectively. In [93], Das et. al. proposed a compact back-to-back two element CDRA based four port MIMO antenna. These CDRAs are glued on opposite sides of FR4 substrate with top two ports are fed using CPW conformal MS line and bottom two ports are excited using MS line fed conformal strip lines. Isolation between ports has been improved by generating orthogonal modes in CDRAs and use of opposite excitation. In [94], a four element eight port MIMO antenna with pattern diversity has been proposed. Due to cross configuration of four CDRAs and eight feeds, GND could not made common with all the ports.

In [95], a simple decoupling method using metallic vias has been investigated in a two RDRA based MIMO antenna. Geometry of the antenna is shown in Fig. 12. It has been found that by placing the vias vertically inside the DRA elements at appropriate positions, the mutual coupling can be substantially reduced, without increasing either the footprint or height of the antenna. At the same time, the decoupling vias affect slightly the field distributions of the excited antenna, and therefore the radiation patterns are not deformed and kept almost the same as the single DRA. In addition, since the DR is still the main radiator and the additional vias do not resonate in the operating band, the loss caused by the vias is desirably negligible. In [96], a four port MIMO antenna has been proposed where antenna beams are separated spatially to achieve high isolation and low correlation. Authors used two phase gradient FSS and placed both sides of the substrate as a superstrate. Two CDRAs are positioned at top of the substrate and another two are placed at its bottom. With this special technique, the antenna achieves more than 20 dB of isolation and excellent Envelope Correlation Coefficient (ECC) values (less than 0.1). In [97], a method to improve the isolation between two adjacent RDRA elements has been proposed by introducing a metal strip printed on the upper surface of each RDRA. The strongest part of the coupling field moves away from the adjacent exciting slot of the DRA so that a maximum improvement of 12 dB on the isolation over 27.5 - 28.35 GHz is achieved. In [98], a CDRA has been split into four quad CDRA and these four elements has been excited using four MS line feeds. Exploiting image theory, copper strip has been etched on the sides of quad CDRA elements so that each element characterized as full CDRA. In [99], eight elements, sixteen ports based MIMO DRA is proposed. Here, four CDRA are placed back to back on substrate and excited using CPW feeds and MS line feeds. In [100], two CDRAs fed by printed ridge gap waveguide (PRGW) for the beam-switching antenna system based on FSS has been investigated at 28GHz. In the MIMO antenna, each CDRA is fed by a rectangular slot etched on the top plate of the PRGW. Additionally, two FSS layers, each one includes a 3x3 FSS unit cell, working in the reflection mode, are fixed in the middle of a double-feed DRA by inserting inside the rectangular cuts which are etched in the two vertical walls on two sides of the antenna, to tilt the antenna beam at the Ka-band. In depth statistical and comparative analysis has been given in the supplementary for interested readers. References [101]-[106] are cited in the supplementary material.

III. Future Challenges

MIMO technology uses multiple radiators at transmitter and receiver ends to increase data rates for a given BW and power requirement. To realize this, one can use antenna elements like a dipole, patch, DRA, etc. It is argued that once a single element DRA is designed, the multiple elements can be arranged in the proper configuration to achieve diversity (spatial, polarization, angle). But there are challenges that one can encounter in designing compact MIMO systems with DRAs having closely spaced elements or a single element with multiple ports for next-generation 5G communication systems and beyond. Major challenges in DRA based MIMO antennas can be classified as follows:

1) Single element compact CP MIMO DRA;
2) Multiband CP MIMO DRA;
3) Isolation mechanism such as DGS, Meander line, FSS, Meta-material, inserting vias and others;
4) Feeding mechanisms to excite desired modes in non-conventional shapes of DRA in MIMO configuration;
5) Detailed theoretical mode analysis in multi-element non-conventional shaped DRA based MIMO antenna;
6) Low dielectric constant material of DRA element;
7) Effect of casing on DRA based MIMO antenna.

IV. Conclusions

In this dissemination, a comprehensive review of recently published MIMO DRAs has been presented. A detailed comparison of MIMO DRAs has been done on the basis of various performance parameters and radiation characteristics. The aim of the review is the identification of major research gaps/ challenges for future investigators. The results of this study indicate that there is immense scope in the emerging domain of DRA based MIMO antennas. Due to various advantages of DRA and MIMO technology, challenges revealed by this work will prove a milestone in the future. The future challenges to be concurred by researchers are: fabricating and testing lower dielectric constant material MIMO DRAs; analyzing modes of unconventional shaped MIMO DRAs; compact single DRA based MIMO antennas with high isolation between multiple ports design or designing hybrid feeds to generate desired modes in unconventional shaped DRA based MIMO antennas.

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