Research Article

Wideband Cylindrical Dielectric Resonator Antenna Operating in $HEM_{11\delta}$ Mode with Improved Gain: A Study of Superstrate and Reflector Plane

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A wideband and high gain dielectric resonator antenna (DRA) operating in hybrid $HEM_{11\delta}$ mode is proposed. The investigated geometry employs one cylindrical dielectric resonator partially covered with a transparent dielectric superstrate and backed up by a single side metal coated dielectric reflector plane. The reflector is dedicated for gain enhancement while the superstrate is employed for merging of two resonant bands resulting in a single wide band. The dielectric resonator is excited by simple microstrip feed slot coupling technique and operates over X-band, ranging from 7.12 GHz to 8.29 GHz, that is, of 15.18% impedance matching bandwidth with 11.34 dBi peak gain. The different development stages like standalone DRA, DRA with superstrate, DRA with reflector, and DRA with both superstrate and reflector plane with respect to bandwidth and gain performances are analyzed properly. To the best of authors' knowledge, this is the first time this type of combination of both superstrate and reflector plane is demonstrated in DRA engineering. An antenna prototype was fabricated and characterized and a very good agreement is achieved between the simulated and measured results.

1. Introduction

In recent years, the dielectric resonator antenna (DRA) has got broad consideration in the field of microwave and millimeter wave engineering. The cutting edge advancements are broadly covered in some books and review articles [1–4]. Though the dielectric resonators have been used as the high Q-factor element in oscillator and microwave filter since 1939 [5], its radiation characteristics were studied in 1983 [6]. That day onward, DRA has received tremendous attention from the researchers and industries because of its remarkable advantages like wideband, high efficiency, low loss, and 3-dimensional design flexibility compared to those traditional antennas. In course of time, several developments have been done on DRA in terms of performance improvement as well as geometrical optimization.

The research on wide bandwidth and gain improvement of DRA is being considered frequently in last few decades.

However, obtaining high gain with wide bandwidth is quite challenging because of their mathematical relation. It can be noted that sometimes DRA becomes application restraint because of average gain ~ 6 dBi [7]. Hence, several efforts have been done for gain improvement with wide bandwidth. For example, in 1997, Hwang et al. [8] and, in 2016, Pan and Zheng [9] have used the stacking of different materials to enhance the gain up to 6.2 dBi and 9 dBi, respectively. Some researchers have also actualized electromagnetic band gaps (EBG) on the ground plane, which reduces the surface wave propagation and improves the gain up to 8 dBi [10]. Nasimuddin and Esselle [11, 12] have experimented peak gain of >8 dBi by placing a surface mounted horn around a rectangular and modified rectangular DRA, respectively. According to Guha et al. in [13], the exploration of higher order mode ($HEM_{12\delta}$) also gives high gain of 8.5 dBi. Further, the use of superstrate with DRA has been deeply analyzed by research groups led by Coulibaly et al. [7], Dutta et al. [14],

FIGURE 1: It illustrates the schematic diagram of the proposed dielectric resonator antenna.

and Dong et al. [15]. Briefly, the use of periodic frequency selective surfaces (FSS) on superstrate has enhanced the gain up to 11 dBi [7], while the use of loaded patches has been used to enhance the gain up to 12.2 dBi and 7.54 dBi in [14] and [15], respectively, without affecting the mode of operation. Ali et al. [16–18] and Nikkhah et al. [19] have proposed the concept of reflector to improve the directivity and gain by means of reducing the back radiation which are quite valuable for researchers. Though these techniques [8–12] improves the gain, some issues cannot be ignored, like disturbance of Q-factor during stacking of different dielectric layers [8, 9], costlier and high precession fabrication/tailoring of complex EBG structures [10], and comparatively large size and weight [11, 12]. However, in comparison to these approaches, the use of superstrate and reflector seems to be simple as it affects neither resonator shape nor feed network.

In this proposed structure, the authors have demonstrated a DRA with both superstrate and reflector plane. A theoretical analysis is done to study the back radiation reduction mechanism in context to reflector plane. The authors also show the effect of superstrate and reflector separately with standalone DRA. The optimized DRA with both superstrate and reflector can be considered as a better alternative to some existing models, because of the following advantages: (i) wideband of 15.18% and gain enhancement up to 11.34 dBi, (ii) use of dielectric reflector plane as well as combination of superstrate and reflector plane which is first time realized in DRA literature, (iv) overall compact geometry, (v) ease of fabrication, (vi) good radiation pattern with high co-pol to cross-pol ratio, and (vii) comparatively good matching over entire band. This paper is organized as follows: the geometrical construction and parameters of the proposed antenna are discussed in Section 2, followed by design flow, simulation results, and discussion in Section 3. The characterization and conclusion are shown in Sections 4 and 5, respectively.

2. Proposed Antenna Structure

The proposed cylindrical DRA is shown in Figure 1. It is comprised of one cylindrical DR ($h_d = r_d = 0.135\lambda_0$) and

permittivity of $\epsilon_{rd} = 10$ with loss tangent ($\tan \delta$) = 0.003. For the ground plane, a double sided perfect electric conductor (PEC) coated FR4 of $\epsilon_{rsub} = 4.4$ with loss tangent ($\tan \delta$) = 0.02 sheet ($l_{sub} \times w_{sub} \times h_{sub} = 1.08\lambda_0 \times 1.08\lambda_0 \times 0.043\lambda_0$) is taken. Photolithography etching process is applied to design feed ($l_f \times w_f = 0.648\lambda_0 \times 0.054\lambda_0$) and slot ($l_s \times w_s = 0.135\lambda_0 \times 0.135\lambda_0$) in appropriate place of the ground plane substrate as shown in Figure 1. Another FR4 sheet of $\epsilon_{rsub} = 4.4$ and $\tan \delta = 0.02$ (both side etched) $l_{sup} \times w_{sup} \times h_{sup} = 1.08\lambda_0 \times 0.54\lambda_0 \times 0.043\lambda_0$ is kept above the DRA with an air-gap ($a_1 = 0.216\lambda_0$) and known as superstrate. Then, the third FR4 sheet ($l_{ref} \times w_{ref} \times h_{ref} = 1.35\lambda_0 \times 1.35\lambda_0 \times 0.043\lambda_0$) of $\epsilon_{rref} = 4.4$ and $\tan \delta = 0.02$ which is single side etched is kept below the ground plane substrate (conducting side fetches towards the -Z direction) at an air-gap ($a_2 = 0.108\lambda_0$). This third one is used as reflector plane in order to reduce the back-front radiation and improving gain. The proposed structure is modelled with finite element solver Ansys HFSS v13.0 [20]. The design flow with different developing stages of this optimized antenna geometry is further illustrated in Section 3.

3. Design Flow and Result Discussion

The different development stages of the proposed antenna are depicted in Figure 2. This design starts by placing a cylindrical dielectric resonator (DR) of $h_d = r_d = 0.135\lambda_0$ and $\epsilon_{rd} = 10$ on a slot of $l_s = w_s = 0.135\lambda_0$, with a 50Ω feed line network. Figure 3 shows the impedance matching curve, where resistance line crosses the 50Ω and reactance line crosses 0Ω near 7.9 GHz which indicates proper matching of the 50Ω feed line. The mode of operation and resonant frequency of the dielectric resonator (DR) can be calculated using (1) [1], which shows resonant frequency ~ 7.9 GHz and also signifies excitation of $HEM_{11\delta}$ hybrid mode. This mode is later cross verified with the simulated E-field distribution inside the DRA as shown in Figure 4:

$$f_{r(HEM_{11\delta})} = \frac{c}{2\pi r_d} \times \frac{6.324}{\sqrt{\epsilon_{rd} + 2}} \times \left[0.27 + 0.36 \left(\frac{r_d}{2h_d} \right) + 0.02 \left(\frac{r_d}{2h_d} \right)^2 \right]. \quad (1)$$

FIGURE 2: It illustrates the cross-sectional views of four different development stages of the proposed dielectric resonator antenna (antenna design dimensions: $h_d = r_d = 0.135\lambda_0$, $l_{sub} = w_{sub} = 1.08\lambda_0$, $l_{sup} = 1.08\lambda_0$, $w_{sup} = 0.54\lambda_0$, $l_{ref} = w_{ref} = 1.35\lambda_0$, $h_{sub} = h_{sup} = h_{ref} = 0.043\lambda_0$, $l_f = 0.648\lambda_0$, $w_f = 0.054\lambda_0$, $l_s = w_s = 0.135\lambda_0$, $a_1 = 0.216\lambda_0$, and $a_2 = 0.108\lambda_0$). All dimensions are in millimeter.

FIGURE 3: It illustrates the input impedance of the DR-antenna.

Next, the different development stages of the antenna design are discussed in respective subsections.

FIGURE 4: Electric field distribution in the DR (cross-sectional view) indicating $HEM_{11\delta}$ mode.

FIGURE 5: It illustrates S_{11} versus frequency.

3.1. Design and Optimization of Antenna #1. It is a well-known fact that the performance of cylindrical DRA depends upon its controlling parameters, that is, radius (r_d) and height (h_d) [1–3], which can be cross checked from (1). Hence, in this context, with the ground plane and other arrangements being the same, the radius (r_d) and height (h_d) are taken as the tuning parameters in order to find the optimum performance (Figure 5). The resonant frequency was found to be shifting significantly with the variation of r_d and h_d , which interprets (1). Hence, after multiple observations, these parameters were optimized as $r_d = h_d = 0.135\lambda_0$ resulting in a dual band (6.9 GHz–7.28 GHz) and (7.72 GHz–8.26 GHz) with 5.38 dBi and 3.11 dBi gain, respectively. Here, this standalone DRA is considered as Antenna #1. As per the performance characteristics, this antenna can be suitable for (i) dual band operation and (ii) medium gain operation. The subsequent performance improvement of this Antenna #1 is discussed in next subsection.

3.2. Design and Optimization of Antenna #2. Generally superstrate improves the gain and radiation characteristics without affecting the standard of operation of DRA [14]. So in view of this, the authors started analyzing the performance of the antenna by introducing a transparent dielectric superstrate. Initially, a FR-4 sheet of $l_{\text{sup}} \times w_{\text{sup}} \times h_{\text{sup}} = 1.08\lambda_0 \times 1.08\lambda_0 \times 0.043\lambda_0$ was placed above the ground plane at a random height of $a_1 = 0.189\lambda_0$, that is, 7 mm. Then, to study its characteristics, the dimensions (l_{sup} and w_{sup}) are varied between $10 \text{ mm} \leq l_{\text{sup}} = w_{\text{sup}} \leq 20 \text{ mm}$, that is, $0.27\lambda_0 \leq l_{\text{sup}} = w_{\text{sup}} \leq 1.08\lambda_0$ with a step size of 10 mm (i.e., $0.27\lambda_0$). The respective gain variations for different combinations of l_{sup} and w_{sup} are plotted in Figure 6. It can be observed that the antenna possesses more gain while the superstrate larger side (l_{sup}) is oriented in the direction of antenna polarization. Finally a peak gain of 6.39 dBi with

FIGURE 6: Gain total variation of Antenna #2 for different combinations of l_{sup} and w_{sup} (at $a_1 = 0.189\lambda_0$).

17.12% impedance bandwidth is obtained for $l_{\text{sup}} = 1.08\lambda_0$ and $w_{\text{sup}} = 0.54\lambda_0$. It can be noted that, at particular air-gap height (a_1), the variation of superstrate dimension (i.e., l_{sup} and w_{sup}) has very less impact on S_{11} response; hence, these results are not included here for brevity.

Next to this, the effect of air-gap (a_1) between the ground plane and superstrate at optimized superstrate length ($l_{\text{sup}} = 1.08\lambda_0$) and width ($w_{\text{sup}} = 0.54\lambda_0$), on bandwidth and gain, is observed in Figure 7. After observation, a_1 is fixed at $0.216\lambda_0$, that is, 8 mm for 16.84% bandwidth with 6.6 dBi peak gain. The E-field and H-field distribution on the superstrate depicted in Figure 8 clearly indicate that the field is strong at the center and decreases towards the edge. It can be concluded that the field trapped in between the cylindrical DR and the dielectric superstrate causes a wide impedance band by shifting the first resonance above (Figure 7). This superstrate based DRA is considered as Antenna #2 and its

FIGURE 7: It illustrates the effect of air-gap (a_1).

FIGURE 8: Field distribution in superstrate of Antenna #2 (top view).

outcomes can be summarized as (i) improvement of 22.67% peak gain, that is, up to 6.6 dBi, (ii) formation of single wide band by merging two resonant bands, (iii) being operated in the same HEM_{118} mode, and (iv) introduction of light weight, simple, and compact dielectric superstrate in comparison to [14]. Though this antenna deals with quite improved performance compared to Antenna #1, further performance enhancement study is presented in next subsection.

3.3. Design and Optimization of Antenna #3. It is a known fact that every antenna deals with some back radiation, which affects gain as well as directivity. Avoidance of these back radiations can act as a thrust for gain/directivity improvement, and this is possible by redirecting/checking the back directed electromagnetic (EM) waves. Moreover, as per the literature [21, 22], when an EM wave travels from one permittivity medium to another permittivity medium, reflection takes place. With this concept, the authors have placed a non-transparent one side metal coated FR4 sheet of size $1.35\lambda_0 \times 1.35\lambda_0 \times 0.043\lambda_0$ below the ground plane as a reflector. The

FIGURE 9: Plane wave incident and reflection in context to reflector.

reflection mechanism is sketched in Figure 9 considering five different regions as follows: region-P/R/T is filled with air ($\epsilon_p = \epsilon_r = \epsilon_t = 1$) with loss factor $\tan \delta_p = \tan \delta_r = \tan \delta_t = 0$ and region-Q/S is dielectric sheet ($\epsilon_q = \epsilon_s = 4.4$) with loss factor $\tan \delta_p = \tan \delta_s = 0.02$. When input is given through microstrip feed line, some energy couples into the cylindrical DR through the slot and some other energies (say E_r) are released into region-R, then move in $-Z$ direction, and face multiple reflections at Interface-RS and Interface-ST.

The reflection and transmission of EM energy at each interface can be justified by the standard theorem [21, 22]. When EM wave moves from region-R to region-S (Figure 9), the ratio of reflected to incident wave can be expressed as [21, 22]

$$\left| \frac{E_{r(\text{ref})}}{E_r} \right| = \left| \frac{\sqrt{(\epsilon_r - j \tan \delta_r) / (\epsilon_s - j \tan \delta_s)} - 1}{\sqrt{(\epsilon_r - j \tan \delta_r) / (\epsilon_s - j \tan \delta_s)} + 1} \right|. \quad (2)$$

From (2) it is clear that there is a chance of reflection if $\epsilon_r \neq \epsilon_s$. It can be noted that once $\epsilon_s \sim \infty$, then the total wave will be reflected and this is known as “short-circuit situation” [23]. However, in the investigated case, reflection as well as transmission must occur because of two different finite permittivities. This transmitting energy again is incident on Interface-ST (Figure 9), where the reflection mechanism is alike previous case.

$$\left| \frac{E_{s(\text{ref})}}{E_s} \right| = \left| \frac{\sqrt{(\epsilon_s - j \tan \delta_s) / (\epsilon_t - j \tan \delta_t)} - 1}{\sqrt{(\epsilon_s - j \tan \delta_s) / (\epsilon_t - j \tan \delta_t)} + 1} \right|. \quad (3)$$

As per (3), when $\epsilon_s \neq \epsilon_t$, some of the little amount reflects to region-S and some amount propagates into region-T. It can be noted that if $\epsilon_s \rightarrow \infty$, then Interface-RS takes over the situation as per (2) and at the same time Interface-ST becomes “dielectric open” [23]. Finally, the transmitted

energy to region-T can be calculated by taking the ratio of transmitted wave to the incident wave [23] as

$$\left| \frac{E_s}{E_r} \right| = \left| \frac{2}{\sqrt{(\epsilon_r - j \tan \delta_r) / (\epsilon_s - j \tan \delta_s) + 1}} \right|, \quad (4)$$

$$\left| \frac{E_t}{E_s} \right| = \left| \frac{2}{\sqrt{(\epsilon_s - j \tan \delta_s) / (\epsilon_t - j \tan \delta_t) + 1}} \right|. \quad (5)$$

Moreover, the validation of the reflector efficiency can be done by calculating the ratio of power in region-T and region-R. The power in each region can be calculated by using Poynting's theorem. For a plane wave, Poynting's vector can be stated as [21, 22]

$$P_r = \frac{E_r^2}{\eta_r}, \quad (6)$$

$$P_t = \frac{E_t^2}{\eta_t},$$

where

$$\eta_r = \sqrt{\frac{\mu_0}{\epsilon_0 (\epsilon_r - j \tan \delta_r)}}, \quad (7)$$

$$\eta_t = \sqrt{\frac{\mu_0}{\epsilon_0 (\epsilon_t - j \tan \delta_t)}}.$$

Furthermore the desired $P_t : P_r$ can be written as

$$\frac{P_t}{P_r} = \left(\frac{4}{T_1 T_2} \right)^2 \cdot \sqrt{\frac{(\epsilon_t - j \tan \delta_t)}{(\epsilon_r - j \tan \delta_r)}}, \quad (8)$$

where

$$T_1 = \sqrt{\left(\frac{\epsilon_r - j \tan \delta_r}{\epsilon_s - j \tan \delta_s} \right) + 1}, \quad (9)$$

$$T_2 = \sqrt{\left(\frac{\epsilon_s - j \tan \delta_s}{\epsilon_t - j \tan \delta_t} \right) + 1}.$$

Case 1 (without loss factor). For a lossless dielectric reflector, the loss factor $\tan \delta$ tends to zero. Hence substituting appropriate values of ϵ_r , ϵ_s , and ϵ_t (as per the investigated structure) in (2) and (3), the incident to transmit ratio shows that ~40% and ~35% amount of energy are reflected at Interface-RS and Interface-ST, respectively. Subsequently, by substituting the values of ϵ_r , ϵ_s , and ϵ_t (as per the investigated structure) in (6) and (8), the transmitted power to reflected power ratio becomes ~0.77. This indicates that the proposed reflector is efficient in terms of checking the reasonable amount of back directed EM waves.

Case 2 (with loss factor). The loss factor of the dielectric reflector ($\tan \delta_s = 0.02$) and air medium ($\tan \delta_r = \tan \delta_t = 0$)

FIGURE 10: It illustrates the effect of air-gap (a_2) on bandwidth and gain.

is included in respective equations. Finally the outcome of (8) comes out to be 0.7645, that is, almost the same as Case 1. Means, the lossy reflector of $\tan \delta = 0.02$, has less impact on performance of the designed geometry. Moreover, it can be concluded that the proposed dielectric reflector is kind of partial reflector as the power ratio is ~0.77. This indicates that the proposed reflector is efficient in terms of checking the reasonable amount of back directed EM waves.

After theoretical analysis of reflector plane, certain tuning of air-gap (a_2) was done to resonate the DRA with reasonable bandwidth and gain (Figure 10). It can be noted here that, by placing reflector plane, dual band is generated. The air-gap (a_2) was fixed at $0.108\lambda_0$ for dual band operation over 6.95–7.43 GHz and 7.85–8.22 GHz with a peak gain of 10 dBi and 10.02 dBi, respectively, as shown in Figure 10. The total gain radiation pattern is depicted in Figure 11. The presence of reflector increases the antenna gain in broadside (between $\theta = 330^\circ$ to 30°) by redirecting the back directional wave (between $\theta = 150^\circ$ to 300°). This reflector based antenna is considered as Antenna #3 and its outcomes are as follows: (i) 86.24% (4.64 dBi) improvement of gain, that is, up to 10.02 dBi with dual band characteristics, (ii) introduction of dielectric reflector plane (light weight and small size) which is quite first time in DRA literature, and (iii) operating in $\text{HEM}_{11\delta}$ hybrid mode.

3.4. Design and Analysis of Antenna #4. In the above three subsections, the authors have examined the performance improvement of standalone cylindrical DRA (CDRA), that is, Antenna #1, CDRA with superstrate, that is, Antenna #2, and CDRA with reflector, that is, Antenna #3, separately with individual advancements. It can be concluded that cavity resonator concept [21] was helpful in improvement of bandwidth and gain up to 16.84% and 6.6 dBi, respectively, in Antenna #2, while for Antenna #3, the reflector plane

FIGURE 11: Gain total radiation pattern of Antenna #1 (without reflector) and Antenna #3 (reflector).

FIGURE 12: Performance comparison of all antennas.

concept [16–18], helped in significant improvement of gain up to 10.02 dBi. Therefore, the prediction of improved gain and wide bandwidth by the combination of superstrate and reflector, that is, Antenna #2 and Antenna #3, cannot be ignored. Hence, this hybrid combination is considered as Antenna #4 (Figures 1 and 2(d)) and results in wideband of 14.34% (7.06 GHz–8.15 GHz) with 10.66 dBi peak gain. It can be noted that the use of superstrate combines two resonant bands of Antenna #3 and forms a single wideband, with little gain improvement. Moreover, the qualitative performance comparison of all antennas is done in Figure 12 and Table 1, from which Antenna #4 is found to be the best geometry. This clearly shows improvement of gain without much deteriorating the bandwidth, which is rarely available in the referenced

works. Antenna #4 performance is concluded as follows: (i) ability of combining two resonant bands into a single wideband (Figure 12), (ii) improvement of gain around 1 dBi, (iii) excitation of $HEM_{11\delta}$ hybrid mode, and (iv) introduction of a novel concept, that is, combination of superstrate and reflector.

4. Prototype Characterization and Validation

A prototype of the optimized antenna (Antenna #4) was fabricated and characterized for validation purpose (Figure 13). Three FR4 sheets ($\epsilon_r = 4.4$ and $\tan \delta = 0.02$) of respective dimensions are taken and photolithography etching process was applied to create feed, slot, and removal of copper from

TABLE 1: Simulated performance comparison of developed antenna geometries.

Results	Antenna #1	Antenna #2	Antenna #3	Antenna #4
Bandwidth (GHz)	(6.9–7.28), (7.72–8.26)	(6.96–8.24)	(6.95–7.43), (7.85–8.22)	(7.06–8.15)
Gain (dBi)	5.38, 3.11	6.6	10, 10.02	10.66
Techniques	Stand alone	Superstrate	Reflector	Sup.+ ref.
Scope of applications	Dual band, low gain	Wideband, medium gain	Dual band, high gain	Single band, high gain

FIGURE 13: It illustrates the fabricated prototype of Antenna #4.

FIGURE 14: Comparison of simulated and measured results of Antenna #4.

required portions. The realized cylindrical DR ($r_d = h_d = 0.135\lambda_0$) was shaped out from Eccostock HiK dielectric rod of $\epsilon_r = 10$ and $\tan \delta = 0.003$ and placed above the slot by using an adhesive glue. Some nonconducting spacers having $\epsilon_r \sim 1$ have been used to place the superstrate and reflector at proper positions.

Vector network analyzer was used for the physical characterization of different parameters. Figure 14(a) shows an excellent matching between the simulated and measured S_{11} . The measured total gain (Figure 14(b)) seems to be little improved (11.34 dBi) than the simulated value (10.66 dBi). The far-field radiation patterns are measured in an echo free automatic Anechoic Chamber by the use of Analog signal

generator and spectrum analyzer (Figure 13(c)). Spherical scanning surface technique, which generally gives much accurate results is adopted for measuring the radiation pattern at both the resonating frequencies (7.4 GHz and 7.9 GHz) (Figure 15). During measurement, with the reference horn antenna alignment and position being fixed, the test antenna is kept one meter away from the reference antenna. It is rotated along either of planes ($\phi = 0^\circ$ and $\phi = 90^\circ$) to record the measure receive power in dBm. Later gain value (in dBi) has been extracted by using Friis transmission formula. The calculated values have been converted into normalized value and then compared with the simulated ones in Figure 15. These variations can be attributed to the positive interference

FIGURE 15: Measured and simulated gain radiation patterns.

of some practical unavoidable objects, say soldering, foam spacers, and so on. The simulated radiation efficiency is incorporated in Figure 14(b), which shows $\sim 90\%$ efficiency over the entire operating range. Table 2 shows the comparison of all simulated and measured results. From Table 2 and Figure 15, it is clear that this proposed Antenna #4 possesses high co-pol to cross-pol ratio in both principal planes, except little disturbance near E -plane 260° while operating at around 7.9 GHz. Though this conjecture is well verified during demonstration, this geometry needs to be fabricated by professional manufactures for real on field applications, like naval mobile satellite, land mobile satellite and military requirements for NATO fixed systems in some countries, and so on. After measurement of the prototype, detailed comparison of some previous noted works related to gain improvement is compared with this newly proposed one (Antenna #4) in Table 3. The outcome of this comparison

stands with the following conclusion: (i) comparatively compact antenna structure, (ii) probably a new technique which is not yet introduced so far, and (iii) wide impedance matching over 15.18% bandwidth by maintaining a peak gain of ~ 11.34 dBi.

5. Conclusion

This study has investigated a cylindrical DRA for improvement of performance in terms of bandwidth and gain by maintaining high co-pol to cross-pol ratio. Four sets of antennas (as shown in Table 1) have been studied and compared. Among those, the concept of dielectric reflector as well as the combination of superstrate and reflector for cylindrical single DRA has been realized for the first time. Finally a wide bandwidth of $>15\%$ (7.12–8.29) GHz with nearly 11.34 dBi peak gain and broadside radiation pattern with a

TABLE 2: Comparison of measured and simulated results of Antenna #4.

Parameters	Simulated	Measured
Bandwidth	(7.06–8.15) GHz	(7.12–8.29) GHz
Gain	10.66 dBi	11.34 dBi
Co : Cross		
At 7.4 GHz		
Max.	48.93 : 1 ($\phi = 0^0$) 48.93 : 1 ($\phi = 90^0$)	54.96 : 1 ($\phi = 0^0$) 46.35 : 1 ($\phi = 90^0$)
Min.	11.27 : 1 ($\phi = 0^0$) 29.33 : 1 ($\phi = 90^0$)	9.4 : 1 ($\phi = 0^0$) 20.12 : 1 ($\phi = 90^0$)
At 7.9 GHz		
Max.	40.77 : 1 ($\phi = 0^0$) 40.77 : 1 ($\phi = 90^0$)	54.63 : 1 ($\phi = 0^0$) 50.87 : 1 ($\phi = 90^0$)
Min.	3.47 : 1 ($\phi = 0^0$) 3.32 : 1 ($\phi = 90^0$)	1 : 1.99 ($\phi = 0^0$) 1 : 3.98 ($\phi = 90^0$)

TABLE 3: Comparison of proposed work with available literature.

Ref.	Antenna vol. (mm ³) (Avg.)	Technique	Operating at GHz	BW	Peak gain (dBi)
[7]	358.1	FSS superstrate	61.34	13.56%	11
[8]	19384.75	Stacking	1.8	2.7%	6.2
[9]	31423.7	Stacking	4.35/5.4	40%	~9
[10]	111000	EBG	2.28	6%	~8
[11]	32788.8	Surface mounted horn	6.25/7.75	25%	8.5
[12]	~32788.8	Surface mounted horn	6.25/7.75	21.3%	8
[13]	7759.73	Higher mode	6/7.4	—	8.5
[14]	1780000	Loaded metal sheet	3.7	23%	12.2
[15]	153000	Loaded patches	2	25.6%	7.54
[16]	~32874	Parabolic conductor	5	1.8%	NA
[17]	30874.47	Flat conductor	5	1.8%	NA
[18]	30874.47	Box conductor	5	1.8%	NA
[19]	*446000	Conductor strip	2.2	Multiple	#
<i>Present</i>	30000	<i>Superstrate + reflector</i>	7.4/7.9	15.18%	11.34

* Volume with respect to single element, # 10.2 dBi → 4 element (E-plane array), 12.5 dBi → 4 element (H-plane array), and 17.6 dBi → 16 element (planar arrays).

high co-pol to cross-pol ratio of 54.96 : 1 has been achieved by the combination of superstrate and reflector with DRA. As per measured results, this compact antenna can be a suitable candidate for different real field X-band applications and in view of this, suitable scope should be created for the effective utilization of the same. This proposed concept can be utilized for any antennas including all types of DRAs for abrupt gain enhancement. However, further improvement of performance with geometrical optimization could be a favorable concentration as well as a valuable contribution to antenna engineering society. Proposed antenna is useful for wideband applications.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

- [1] K. M. Luk and K. W. Leung, *Dielectric Resonator Antennas*, Research Studies, Hertford-Shire, U.K., 2002.
- [2] A. Petosa, *Dielectric Resonator Antenna Handbook*, Artech Publication House, Norwood, MA, USA, 2007.
- [3] S. K. K. Dash, T. Khan, and A. De, "Modelling of dielectric resonator antennas using numerical methods: a review," *Journal of Microwave Power and Electromagnetic Energy*, vol. 50, no. 4, pp. 269–293, 2016.
- [4] S. K. K. Dash, T. Khan, and A. De, "Dielectric resonator antennas: an application oriented survey," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 27, no. 3, 2016.
- [5] R. D. Richtmyer, "Dielectric resonators," *Journal of Applied Physics*, vol. 10, no. 6, pp. 391–398, 1939.

- [6] S. A. Long, M. W. McAllister, and L. C. Shen, "The resonant cylindrical dielectric cavity antenna," *IEEE Transactions on Antennas and Propagation*, vol. 31, no. 3, pp. 406–412, 1983.
- [7] Y. Coulibaly, M. Nedil, L. Talbi, and T. A. Denidni, "Design of high gain and broadband antennas at 60 GHz for underground communications systems," *International Journal of Antennas and Propagation*, vol. 2012, Article ID 386846, 7 pages, 2012.
- [8] Y. Hwang, Y. P. Zhang, K. M. Luk, and E. K. N. Yung, "Gain-enhanced miniaturised rectangular dielectric resonator antenna," *Electronics Letters*, vol. 33, no. 5, pp. 350–352, 1997.
- [9] Y. M. Pan and S. Y. Zheng, "A Low-Profile Stacked Dielectric Resonator Antenna with High-Gain and Wide Bandwidth," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 68–71, 2016.
- [10] T. A. Denidni, Y. Coulibaly, and H. Boutayeb, "Hybrid dielectric resonator antenna with circular mushroom-like structure for gain improvement," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 1043–1049, 2009.
- [11] Nasimuddin and K. P. Esselle, "Antennas with dielectric resonators and surface mounted short horns for high gain and large bandwidth," *IET Microwaves, Antennas and Propagation*, vol. 1, no. 3, pp. 723–728, 2007.
- [12] Nasimuddin and K. P. Esselle, "A low-profile compact microwave antenna with high gain and wide bandwidth," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 6, pp. 1880–1883, 2007.
- [13] D. Guha, A. Banerjee, C. Kumar, and Y. M. M. Antar, "Higher order mode excitation for high-gain broadside radiation from cylindrical dielectric resonator antennas," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 1, pp. 71–77, 2012.
- [14] K. Dutta, D. Guha, C. Kumar, and Y. M. M. Antar, "New approach in designing resonance cavity high-gain antenna using non-transparent conducting sheet as the superstrate," *Institute of Electrical and Electronics Engineers. Transactions on Antennas and Propagation*, vol. 63, no. 6, pp. 2807–2813, 2015.
- [15] F. Dong, L. Xu, W. Lin, and T. Zhang, "A Compact Wide-Band Hybrid Dielectric Resonator Antenna with Enhanced Gain and Low Cross-Polarization," *International Journal of Antennas and Propagation*, vol. 2017, pp. 1–8, 2017.
- [16] S. M. Ali, M. A. Zakariya, Z. Baharudin, and J. J. Adz, "Parabolic reflector fed by Cylindrical Dielectric Resonator Antenna with high gain," in *Proceedings of the 2014 5th International Conference on Intelligent and Advanced Systems, ICIAS 2014*, IEEE, Kuala Lumpur, Malaysia, June 2014.
- [17] S. M. Ali, M. A. Zakariya, Z. Baharudin, M. H. M. Khir, A. A. Baba, and J. J. Adz, "Aperture coupled Dielectric Resonator Antenna design with flat reflector," in *Proceedings of the 2013 IEEE Business Engineering and Industrial Applications Colloquium, BEIAC 2013*, pp. 135–139, IEEE, Shah Alam Selangor, Malaysia, April 2013.
- [18] S. M. Ali, M. A. Zakariya, Z. Baharudin, M. H. M. Khir, A. A. Baba, and J. J. Adz, "Aperture coupled Cylindrical Dielectric Resonator Antenna design with box shaped reflector," in *Proceedings of the 2013 3rd IEEE Symposium on Wireless Technology and Applications, ISWTA 2013*, pp. 167–171, IEEE, Langkawi, Malaysia, September 2013.
- [19] M. R. Nikkhah, A. A. Kishk, and J. Rashed-Mohassel, "Wide-band DRA array placed on array of slot windows," *Institute of Electrical and Electronics Engineers. Transactions on Antennas and Propagation*, vol. 63, no. 12, pp. 5382–5390, 2015.
- [20] Ansoft, *High Frequency Structure Simulator (HFSS) v13.0*, 2013.
- [21] R. F. Harrington, *Field computation by moment methods*, Wiley-IEEE Press, 1993.
- [22] J. V. Bladel, *Electromagnetic Fields*, Hemishpere, New York, NY, USA, 1985.
- [23] Q. Rao, T. A. Denidni, and R. H. Johnston, "Dielectric reflector backed aperture-coupled antennas for reduced back radiation," *IEEE Transactions on Electromagnetic Compatibility*, vol. 48, no. 2, pp. 287–291, 2006.