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RESEARCH PAPER

Conical dielectric resonator antenna with improved gain and bandwidth for X-band applications

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In this paper, a simple conical-shaped dielectric resonator antenna operating in $HEM_{11\delta}$ mode is presented for X-band wireless applications. A rectangular slot with a running microstrip line is used for excitation purpose. By placing a FR-4 based superstrate at 7 mm height from the ground FR-4 substrate and incorporating a set of modified ground plane on either side of the feed line, gain is improved by 42.85% and bandwidth by 68.92%, simultaneously. A prototype of designed antenna is fabricated and characterized. The measured results are found to be good in matching with the simulated ones.

Keywords: Antenna design, Modeling and measurements, RF front ends, Dielectric resonator antenna, Superstrate

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I. INTRODUCTION

Dielectric resonator antenna (DRA) is considered to be one of the front-line antenna model now-a-days. From the day of its invention [1], it has brought keen attention in antenna researchers' community. This is only because of its several performance specifics such as wide bandwidth, high radiation efficiency, and low loss as well as geometrical specifics such as more design flexibility than the conventional printed antennas [2, 3]. It has been extensively used for different applications in microwave engineering domain [4]. Out of these, the usability of X-band is quite prevalent in civil as well as in military domain [5]. In general, it requires compact, wideband, high-gain, low-loss, and high-efficiency characteristics [3]. In reference to [6], DRA satisfies the desired requisites except for high gain as it deals with an average gain of ~5 dB. Different techniques such as stack [6, 7], electromagnetic band gap (EBG) [8], surface-mounted horn [9], mode [10, 11], reflector [12], and array [13], etc. have been proposed for improvement of the gain. However, improving the gain of compact size DRA without disturbing the bandwidth is quite challenging.

In view of gain improvement with a compact structure and null effect on other performances superstrate loading concept can be considered as an ultimate alternative. This technique has been widely used for the gain improvement of microstrip antennas [14, 15]. In case of DRAs, the superstrate-loading concept is very much limited [16–21], such as frequency selective surface (FSS) superstrate [16, 17], metamaterials superstrate [18], metal superstrate [19], transparent non-metallic superstrate [20], and stacked dielectric superstrate [21]. Generally, FSS and metamaterials structures are electrically complex as they are made in the form of array and nanometers scale [22]. Hence, they need high precision during fabrication [23]. In this context [16–18], also deal with the same issues. In [19], the authors have introduced a metal sheet as a superstrate for improving the gain. Though the approach is good, the overall size of designed superstrate, i.e. $96 \times 96 \times 0.3$ mm^3, may create application restraint. The overall larger superstrate size, i.e. $34 \times 34 \times 4.5$ mm^3, is the main constraint of the stacked superstrate in [21] too.

Here, in this proposed work, the authors have developed a simple conical DRA covered by a narrow transparent lightweight dielectric superstrate (no FSS/EBG/patch) for 42.85% gain improvement and tapered ground plane for 68.92% bandwidth improvement. The uniqueness of the proposed work can be considered as: (i) incorporation of lighter weight narrow dielectric superstrate for gain improvement, which is rarely proposed in the existing open literature; (ii) integration of tapered ground plane for bandwidth enhancement; (iii) overall compact geometry (not array, as in [13]); (iv) economic and ease of fabrication; and (v) high co-to-cross-polarization ratio. This paper is organized as follows: the proposed antenna geometry is described in Section II, followed by geometry optimization and analysis in Section III. Prototype fabrication and result validation are discussed in Section IV. Finally, the conclusion followed by references is discussed in Section V.

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II. PROPOSED ANTENNA GEOMETRY

Figure 1 depicts the proposed antenna geometry. It has three main parts: a conical dielectric resonator ($\varepsilon_{rd} = 10$), a

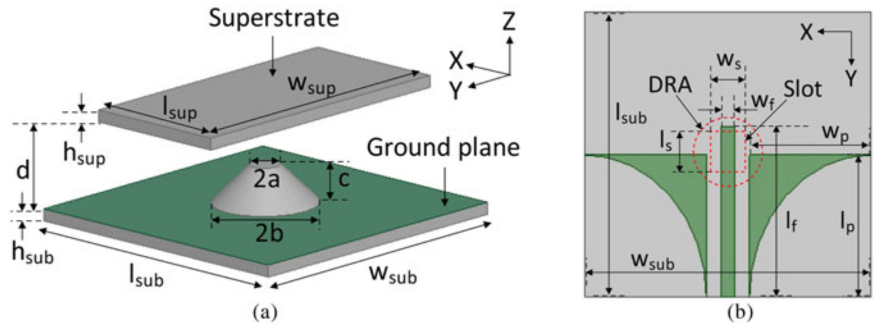

Fig. 1. Schematic diagram of the proposed dielectric resonator antenna, (a) 3D view, (b) bottom view of ground plane substrate (the dotted lines indicating DRA and slot are made on top side of the ground plane. Here $l_{sub} = w_{sup} = 40$, $l_{sup} = 40$, $w_{sup} = 20$, $h_{sub} = h_{sub} = 1.6$, $l_f = 24$, $w_f = 2$, $l_s = 7$, $w_s = 5$, $l_p = 20$, $w_p = 17$, $a = 2$, $b = 7$, $c = 5$, $d = 7$. Further all dimensions are in millimeter).

dielectric ground plane substrate ($\varepsilon_{rsub} = 4.4$, $\tan\delta = 0.02$), and a dielectric superstrate substrate ($\varepsilon_{rsup} = 4.4$, $\tan\delta = 0.02$). The conical dielectric resonator has upper radius $a = 2$ mm, lower radius $b = 7$ mm, and height $c = 5$ mm. The dielectric ground plane substrate has length $l_{sub} = 40$ mm, width $w_{sub} = 40$ mm, and thickness $h_{sub} = 1.6$ mm. The dielectric superstrate has length $l_{sup} = 40$ mm, width $w_{sup} = 20$ mm, and thickness $h_{sup} = 1.6$ mm. The substrate is placed at an air gap $d = 7$ mm from the ground plane substrate. For coupling purpose, a rectangular slot ($l_s \times w_s = 7 \times 5$ mm^2) is made on the upper side of the ground plane substrate with a 50 Ω microstrip feed line ($l_f \times w_f = 24 \times 2$ mm^2) on the other side of the substrate. A set of tapered patch is used on either side of the microstrip feed line for performance improvement. This proposed antenna geometry is designed and simulated using HFSS v13.0 [24].

III. GEOMETRY OPTIMIZATION AND ANALYSIS

The proposed DRA geometry is optimized in two steps: step 1 deals with optimization of the DR dimensions and coupling-slot dimensions. The superstrate and ground plane are then optimized in steps 2 and 3, respectively.

A) Step 1: DR dimensions and coupling-slot dimensions optimization

As per [2], a cylindrical DR has one degree of freedom (two controlling parameters, i.e. radius and height). On the other hand, in cone, the number of controlling parameters increased to three (i.e., upper radius, lower radius, and height), which is another advantage from modeling point of view. Hence, in order to find out the optimized cone dimension, upper and lower radius as well as height (as these parameters generally affect the *Q*-factor [2]) of the cone are taken into consideration, and their effects on antenna performance in terms of bandwidth and gain are observed carefully (Fig. 2).

The effect of varying the upper radius (a) of the cone on resonance frequency shift as well as on gain is shown in Fig. 2(a). It is clear that the resonance matching is improving from −18 to −28 dB by varying the upper radius ($0.03\lambda_o \leq a \leq 0.13\lambda_o$). For the same variations in the radius, the resonance frequency is also shifting (from 9.3 to 8.0 GHz) in lower side indicating the frequency reconfigurability. In comparison to resonance variation, the gain value does not vary much (Fig. 2(a)). Thus, the upper radius is optimized here as $a = 0.06\lambda_o$ to achieve the impedance bandwidth of 6.79% with a peak gain of 4.88 dBi. Similarly, the lower radius of the cone (i.e., b) is varied between $0.16\lambda_o \leq b \leq 0.26\lambda_o$, and finally, it is optimized as $b = 0.23\lambda_o$ for achieving the impedance bandwidth of 7.91% with a peak gain of 5.32 dBi as described in Fig. 2(b). In this optimization, the upper radius remains constant at $a = 0.06\lambda_o$. Finally, the height of the cone (i.e., c) is varied between $0.13\lambda_o \leq c \leq 0.23\lambda_o$ (Fig. 2(c)) and found to be better at $c = 0.16\lambda_o$, i.e. the initial value taken during optimization of a and b. Hence, the results are similar as of previous optimization (of radius b).

For coupling of the DR, a rectangular slot of size $l_s \times w_s$ was inserted at the center of top side of the ground plane. Therefore, post DR optimization, to observe the effect of the slot, both the slot length (l_s) and slot width (w_s) are varied

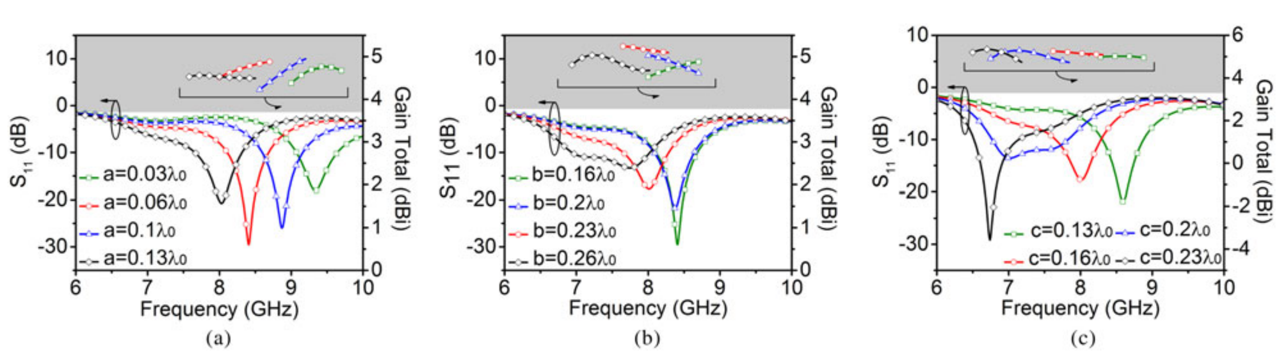

Fig. 2. Effect on S_{11} and gain (a) variation due to DR-upper radius at fixed $b = 5$ mm and $c = 5$ mm, (b) variations due to DR-lower radius at fixed $a = 2$ mm and $c = 5$ mm, and (c) variations due to DR-thickness at fixed $a = 2$ mm and $b = 7$ mm.

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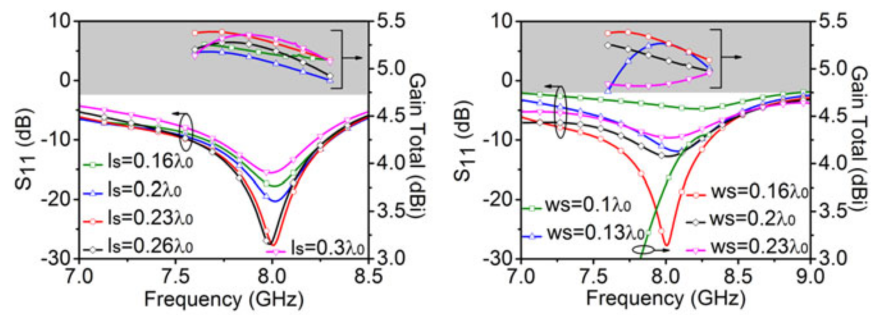
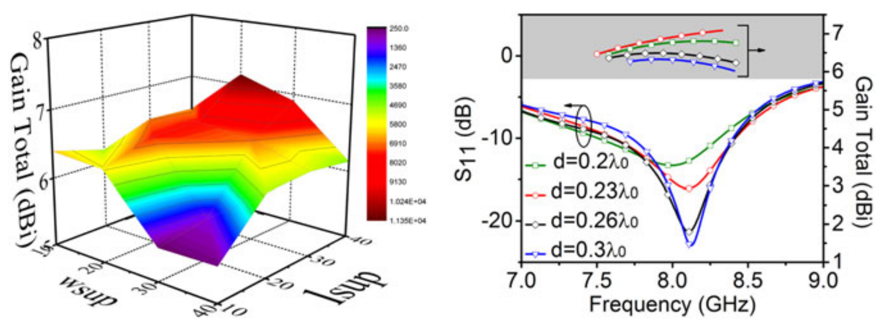


(a) (b)

Fig. 3. Effect on S_{11} and gain (a) variation due to slot-length (l_s) at fixed $w_s = 0.16\lambda_o$ (b) variation due to slot-width (w_s) at fixed $l_s = 0.23\lambda_o$.



(a) (b)

Fig. 4. (a) Gain total variation of the antenna for different combinations of lsup and wsup (at $d = 7$ mm and $\theta = 0°$, $\varphi = 0°$), (b) effect of air-gap height on bandwidth and gain.

in between $0.16\lambda_o \le l_s \le 0.3\lambda_o$ and $0.1\lambda_o \le w_s \le 0.23\lambda_o$, respectively. These variations are plotted in Figs 3(a) and 3(b), respectively. The resonance frequency of the antenna is not varying here in both the cases as plotted in Figs 3(a) and 3(b). It may be because of the fact that in general, the mode of operation of the DR depends upon its dimensions, but not upon the ground plane/slot dimension [2, 3]. Thus, the slot length (l_s) and slot width (w_s) are optimized as: $l_s = 0.23\lambda_o$ and $w_s = 0.16\lambda_o$ to achieve an impedance bandwidth of 9.46% with a peak gain of 5.32 dBi. The antenna having conventional microstrip feed, optimized in this section, is denoted as DRA #1.

B) Step 2: Superstrate optimization

The distinctive surface current distribution required to achieve desired performance characteristics can be accompolished by using a superstare [16, 19]. There are several types of superstrates such as: semi-transparent non-metallic superstrate [16–18], non-transparent metallic superstrate [19], and transparent non-metallic superstrate [20]. For the proposed work, authors have considered a solid transparent non-metallic superstrate. Its optimization is being discussed in this section.

An FR-4 ($\varepsilon_{rsup} = 4.4$) substrate sheet of 1.6 mm thickness is placed as a superstrate at height d from the ground plane substrate. Thus, the superstrate–substrate length (i.e., l_{sup}) and width (i.e., w_{sup}) are varied between 10 mm $\le l_{sup} \le$ 40 mm and 10 mm $\le w_{sup} \le$ 40 mm, respectively. The gap between the superstrate–substrate and the ground plane substrate (i.e., d) is also varied between 6 mm $\le d \le$ 9 mm (i.e., $0.2\lambda_o \le d \le 0.3\lambda_o$). The variations in gain total for different values of l_{sup} and w_{sup} are depicted in Fig. 4(a), whereas the variations in S_{11} and gain total for different values of d are plotted in Fig. 4(b). The three-dimensional view shown in Fig. 4(a) indicates that the gain of the antenna remains almost constant for different $l_{sup} = w_{sup}$ (i.e., ~6.2 dBi at $\theta = 0°$, $\varphi = 0°$), whereas it increases almost linearly with increase of different $l_{sup} \neq w_{sup}$. It can be concluded that the gain increases when the length of the superstrate is oriented in the direction of antenna polarization. Thus, $l_{sup} = 40$ mm, $w_{sup} = 20$ mm, and $d = 7$ mm are optimized to achieve a peak gain of 6.65 dBi with 10.73% impedance bandwidth. The antenna with superstrate, optimized in this section, is considered as DRA #2.

C) Step 3: Ground plane optimization

The dimensions of DR as well as coupling slot are optimized in step 1 with a conventional microstrip feed line on the bottom side of the ground plane substrate. The superstrate dimensions are then optimized in step 2. In this step, the microstrip feed line structure (Fig. 5(a)) is further modified in twofold: one is based on microstrip feed line with two parasitic conducting patches (Fig. 5(b)), and another is based on microstrip feed line with two parasitic conducting tapered patches (Fig. 5(c)). For making it convenient for comparison, the ground planes shown in Figs 5(a)–5(c) are denoted as ground plane 1, ground plane 2, and ground plane 3, respectively. The antenna with superstrate and ground plane 3 is considered as DRA #3. The E-field

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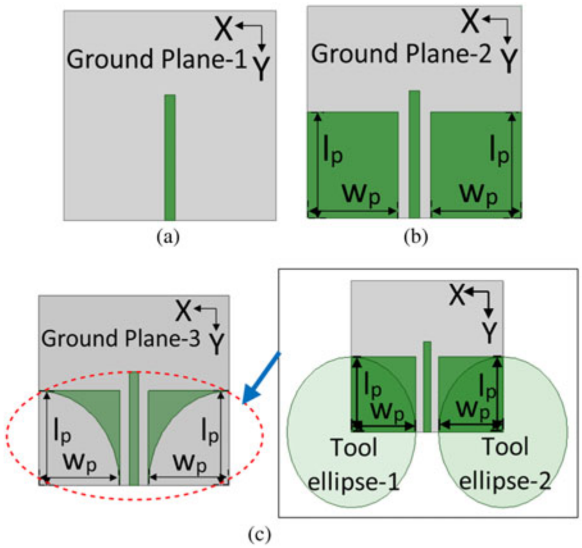

Fig. 5. Different modified ground planes, (a) with only feed, (b) with feed and rectangular parasitic patch (c) with feed and tapered parasitic patch.

distributions for these three ground planes are shown in Figs 6(a)–6(c), respectively.

The proposed DRA with ground plane 1 gives an impedance bandwidth of 10.73% with 6.65 dBi peak gain (Fig. 7(a)). To impose the parasitic coupling, a set of rectangular patches (each of $l_p \times w_p = 0.66\lambda_o \times 0.56\lambda_o$) is suspended on either side of the feed line (Fig. 5(b)). The *E*-field becomes comparatively stronger (Fig. 6(b)) than without patch (ground plane 1) (Fig. 6(a)). The *E*-field near to the edge of the substrate could not couple the DR actively. Thus, the bandwidth decreased to 8.8%. However, the gain of the antenna remains almost same (~6.68 dBi) as of previous case. This indicates further refinement of these parasitic patches for performance improvement.

For further improvement, the suspended parasitic patches are made tapered (Fig. 5(c)) by considering two ellipses – each of major axis $(l_p) = 0.66\lambda_o$ and minor axis $(w_p) = 0.56\lambda_o$ (i.e., Tool ellipse-1/Tool ellipse-2 (Fig. 5(c))) are taken and kept centering at the bottom edge corner of the rectangular patch, so that 1/4th of each ellipse covers some part of the rectangular patch (Fig. 5(c)). Finally, using HFSS v13.0 [24] subtract tool, these elliptical shapes are subtracted from respective rectangular patches, which resulted a tapered patch. This modification further strengthens the *E*-field on the top side ground plane along the feed line as well as the tapered patch (Fig. 6(c)). This configuration creates additional resonance in the lower frequency and abruptly enhances the bandwidth up to 15.48%, with an improved peak gain of 7.25 dBi. This superstrate and ground plane 3-based antenna is considered as DRA #3. The S_{11} and gain variations for DRA #3 as well as two already described DRAs (DRA #1 and DRA #2) are depicted in Fig. 7(b). The performance comparison of DRA with these three ground planes are compared and summarized in Table 1, which is self-explanatory. Post optimization of DRA #3, the *E*-field distribution inside the DR is shown in Fig. 8(a), which signifies the $HEM_{11\delta}$ mode [3]. The *E*- and *H*-fields on the superstrate are shown in Figs 8(b) and 8(c), respectively.

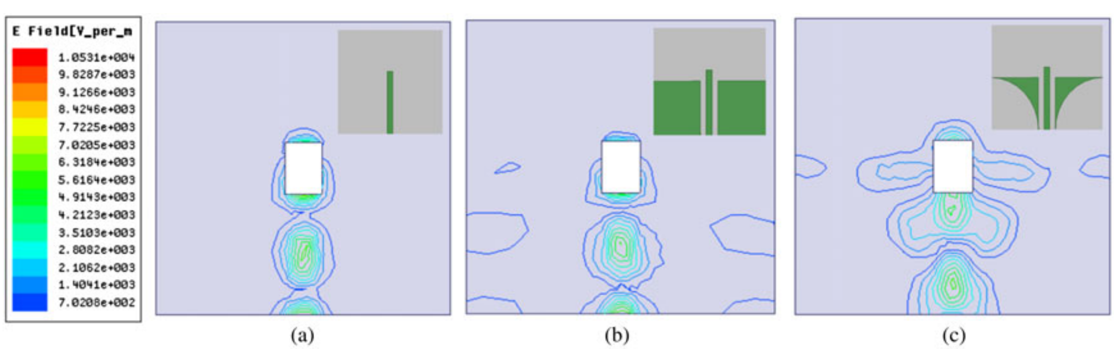

Fig. 6. E-filed distribution in the top side of ground planes, (a) Ground Plane-1, (b) Ground Plane-2, (c) Ground Plane-3.

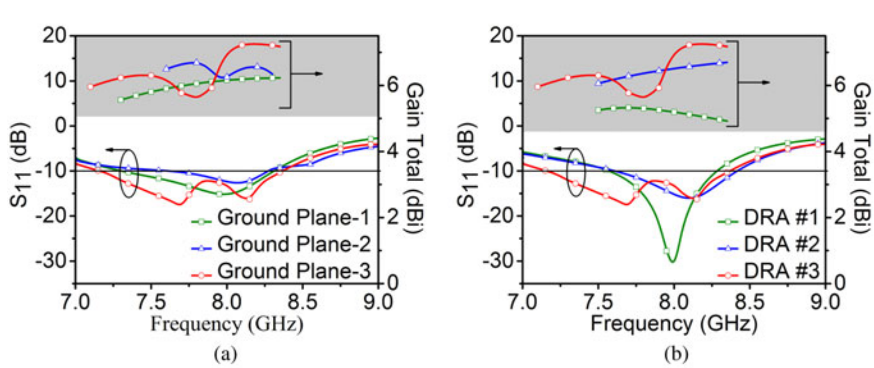

Fig. 7. Variation of S_{11} and gain total, (a) for three different ground planes, (b) for three different stages of DR-antennas.

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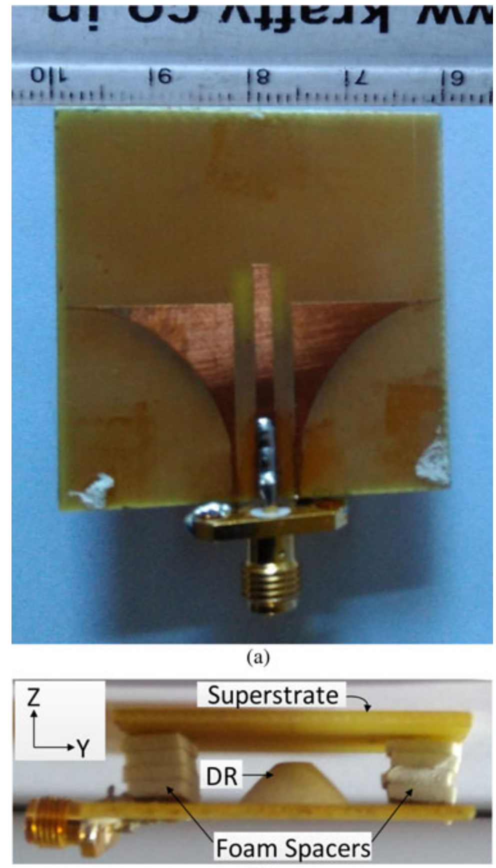
Table 1. Comparison of effect of conducting sheets on DRAs' performance.

DRA #3 (simulated)			
Parameters	**Ground plane 1**	**Ground plane 2**	**Ground plane 3**
Bandwidth (GHz)	(7.5–8.35) 10.73%	(7.6–8.3) 8.8%	(7.15–8.35) 15.48%
Gain (dBi)	6.65	6.68	7.25

IV. PROTOTYPE FABRICATION AND RESULT VALIDATION

The proposed work is validated by fabricating an antenna prototype based on DRA #3, and the snapshot of the same is depicted in Fig. 9. Dielectric FR-4 sheet ($\varepsilon_r = 4.4$) is used here for the ground plane substrate as well as superstrate. The photo lithography etching process is used for making the two PCBs – one for ground plane and another for superstrate. Automatic CNC machining is applied to make a dielectric cone of $a = 2$ mm, $b = 7$ mm, and $c = 5$ mm from Eccostock HiK rod ($\varepsilon_r = 10$). With the help of adhesive glue, the dielectric resonator is made fix on the ground plane. The superstrate is kept above the ground plane at an air gap $d = 7$ mm with the help of some non-conducting material (foam spacers) of $\varepsilon_r \sim 1$. Then, the structure is characterized by using vector network analyzer.

The measured parameters (both S_{11} and gain total) of the fabricated DRA #3 are compared with their simulated counterparts in Figs 10(a) and 10(b), respectively. Though the measured one's resonance shifts from lower to higher frequency, there is still very good matching in the trend. The variation in the resonance is because of the invisible air gap between the ground plane and dielectric resonator, and the unconsidered soldering materials. The measured gain reaches peak 7.6 dBi (Fig. 10(b)) with average 0.5 dBi gain variation with the simulated one, which is negligible. In addition to this, the simulated radiation efficiency of the optimized antenna (i.e., DRA #3) is depicted in Fig. 10(b). It shows that the efficiency varies between 0.76 and 0.88 over the matching bandwidth with an average value of 0.82. Though DRA gives better efficiency than other antennas, i.e. >95% [2, 3], the variation and comparatively less efficiency of the proposed antenna can be attributed to the lossy dielectric sheet (FR-4) taken as a ground plane substrate.



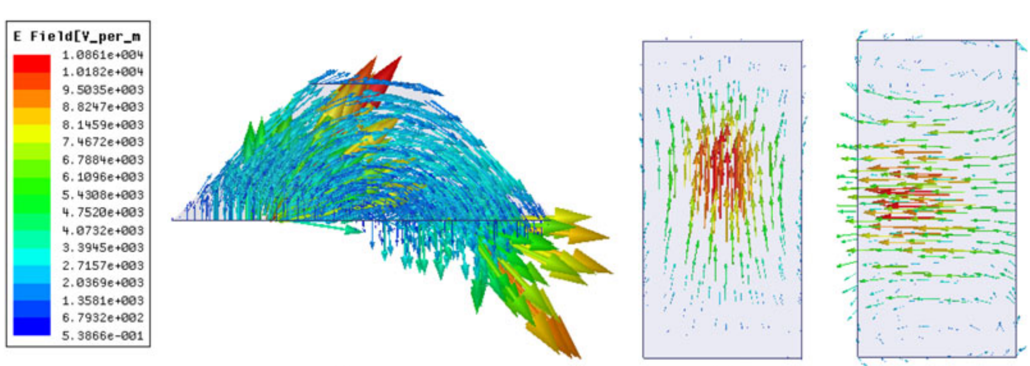
(a)

(b)

Fig. 9. Fabricated prototypes, (a) bottom-view, (b) side-view.

The overall performance comparison of three DRAs is depicted in Table 2, which is self-explanatory. The general outcome of this superstrate and tapered patch/ground plane-based DRA (DRA #3) can be summarized as: (i) 68.92% improvement in the percentage bandwidth, i.e. 1.2 GHz; (ii) 42.85% improvement of the gain total with a peak value of 7.6 dBi; (iii) operating in hybrid $HEM_{11\delta}$ mode; (iv) introduction of much compact and lightweight dielectric superstrate in comparison to [16] and [19]; and (iv) no complicated patch or geometry (FSS/metamaterial) as in [16–18], which reduces the simulation time and improves fabrication feasibility.

The radiation patterns are measured for two resonating frequencies, i.e. at 7.7 GHz (Figs 11(a) and 11(b)) and 8.15 GHz



(a) (b) (c)

Fig. 8. Field distribution, (a) E-field in cone indicates $HEM_{11\delta}$ mode, (b) E-field in superstrate, (c) H-Field in superstrate.

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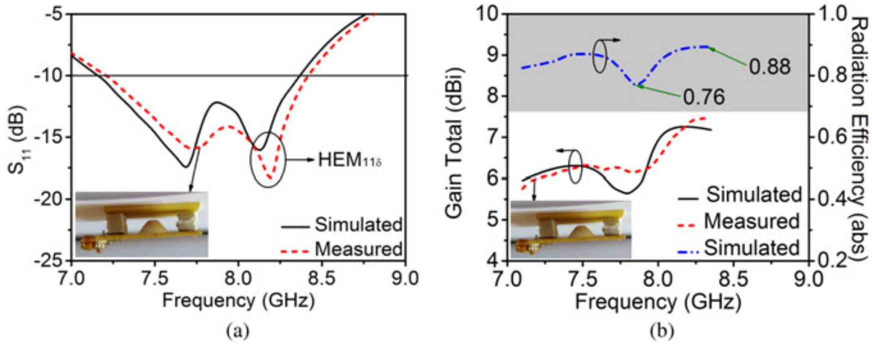

Fig. 10. Measured and simulated results, (a) S_{11} variations, (b) gain total variation.

Table 2. Comparison of three different DRAs.

Parameters	DRA #1	DRA #2	DRA #3	
			Simulated	Measured
Bandwidth (GHz)	(7.55–8.3) 9.46%	(7.5–8.35) 10.73%	(7.15–8.35) 15.48%	(7.2–8.45) 16%
Gain (dBi)	5.32	6.65	7.25	7.60

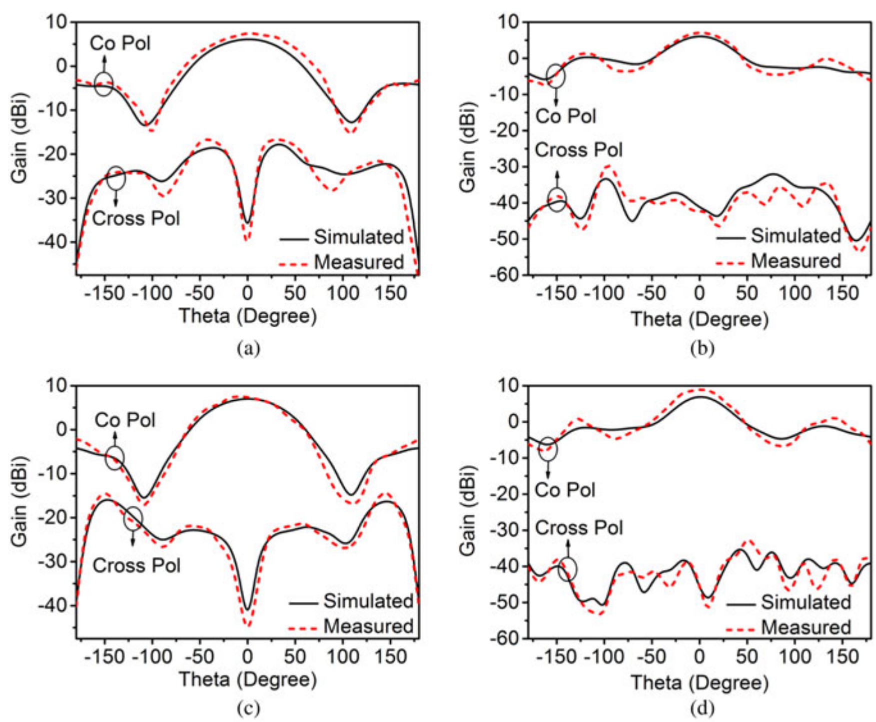

Fig. 11. Measured and simulated gain radiation patterns, (a) E-plane at 7.70 GHz, (b) H-plane at 7.70 GHz, (c) E-plane at 8.15 GHz, (d) H-plane at 8.15 GHz.

Table 3. Comparison of proposed models with some existing models.

Techniques	Working freq. (GHz)	ε_r value	DR volume (mm^3)	Bandwidth (%)	Gain (dBi)	Ref.
Dual segment	10.0	2.1, 2.2	r = NA, h = 4.2	11.6%	6.39	[5]
Multiple stacked DR	1.8	38, 80	7143.75	2.7%	6.2	[6]
Excitation of $TE_{\delta 15}$ mode	11.0	10	490	NA	5.5	[10]
Metal plate reflector	5.4/5.5	55	307.88	1.8%	~5.5*	[12]
Dielectric superstrate	7.6/8.15	10	350.81	16%	7.25	This one

r, radius; *h*, height of the cylindrical dielectric resonator.
*Directivity.

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(Figs 11(c) and 11(d)). Despite the presence of unconsidered foam spacers, the measured gain radiation patterns seem to be more accurate like simulated one in *E*-plane as well as in *H*-plane (Fig. 11). The observed co-to-cross-polarization ratios were as follows: 50.48:1 (*H*-plane) and 2:1 (*E*-plane) at 7.6 GHz, and 44.52:1 (*H*-plane) and 1.31:1 (*E*-plane) at 8.15 GHz. Post characterization, the proposed model is compared with some existing literatures [5, 6, 10, 12] in Table 3. This comparison is purely based on different techniques, physical compactness, and performances, which shows its advantages over those exiting ones.

V. CONCLUSION

In this communication, the bandwidth and gain improvement of a conical DRA with a narrow dielectric superstrate have been proposed. It has been demonstrated that by reducing the superstrate dimension opposite to the direction of antenna polarization possesses low profile, compact size, and high gain without much altering the other performance of the antenna. In addition to this, a set of tapered patch (ground plane 3) has been placed on either side of the microstrip feed line for bandwidth and reasonable gain improvement. The gain and the impedance bandwidth in the demonstrated antenna (DRA #3) have been improved by 42.85% and 68.92%, respectively. High co-to-cross-polarization ratio (50.48:1) has been found in the *H*-plane at 7.6 GHz, while 44.52:1 in the *H*-plane at 8.15 GHz, respectively. The proposed antenna geometry can be a suitable candidate for X-band applications. Thus, proper scope should be arranged for the suitable utilization of this proposed idea. However, further miniaturization of this geometry would be much valuable.

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