A Simple Cylindrical Dielectric Resonator Antenna Based on High-Order Mode with Stable High Gain

Qihua Wu, Hongji Li, Sai-Wai Wong, *Senior Member, IEEE*, Zhonghe Zhang, and Yejun He, *Senior Member, IEEE*

***Abstract*—A stable high gain cylindrical dielectric resonator antenna (CDRA) based on high-order mode $HEM_{11\delta+2}$ is proposed. This design simplifies the complexity of the structure, combined with wideband feeding method, and exhibits a significant high gain performance over the operating band at the center frequency of 8 GHz. First, the high-order mode of CDRA is successfully excited through a wideband technique, achieving a 11.6% impedance bandwidth and a flat high gain of around 12.4 dBi. Then, a DRA array consisting of four elements is designed, with an impedance bandwidth of 13.7% and a stable realized gain as high as 17.8 dBi that is much higher than the gain of traditional DRA arrays.**

***Index Terms*—dielectric resonator antennas (DRAs), high-order mode, stable high gain.**

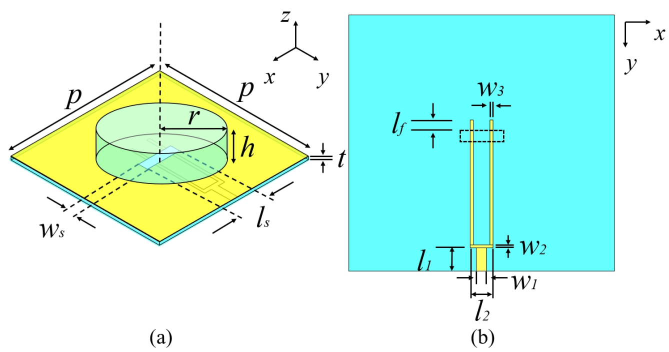

Fig. 1. Geometrical configuration of the proposed design. (a) 3-D view. (b) Bottom view. Design parameters: p = 71, t = 1, r = 17, h = 8, w_s = 3, l_s = 10, l_f = 4.9, l_1 = 6.5, w_1 = 2.7, l_2 = 6.1, w_2 = 0.8, w_3 = 0.8 (unit: mm).

I. Introduction

THE various devices and systems of modern wireless communication have made the Sub-6 GHz band increasingly crowded, so the next-generation wireless communication systems must seek and develop higher frequency bands to provide more spectrum resources. Dielectric resonator antennas (DRAs) have become promising choices for wireless communication [1], due to their significantly better radiation efficiency than conductive antennas at high frequencies. However, traditional DRA elements usually face limited gain issues with only 5-6 dBi, which means it is unfavorable for communication systems that require long-distance transmission and overcome path loss. In recent years, many technologies have been developed to enhance the gain of DRAs, which can be roughly divided into three categories.

The most used method is to design an antenna array with multiple DRA elements [2]-[8]. However, the realization of these high gain DRA arrays often rely on the use of power dividers, which inevitably increases the design complexity of the antenna feeding network and leads to unnecessary transmission losses in the power divider circuit. A grid dielectric resonator antenna planar array is proposed in [8], but its manufacturing and processing are relatively difficult.

In another approach, additional structures are used to increase the gain of DRA. In [9], the gain of DRA is increased by 3 dB by using a cylindrical EBG structure. Two or more layers of stacked DRA have been used to improve gain [10]-[11]. Besides, a peak gain of 11.3 dBi can be achieved by integrating a conical dielectric horn on the top of a CDRA [12]. Nevertheless, additional structures typically sacrifice the overall size of the antenna, and in some cases may increase manufacturing costs.

The third technique to consider is to excite the higher-order mode of antennas [13]-[18], which does not require any additional structure, but only the selection of appropriate excitation methods. In [13], by exciting the high-order mode TE_{115} of the rectangular DRA, a 10.2 dBi peak gain of 5 dB higher than the fundamental mode can be obtained. Similar methods for improving gain of DRAs using higher-order modes have also been applied in [14]-[18]. The newly reported work in [17], reasonable slot cuts are implemented on the surface of a rectangular DRA to enhance bandwidth and reconstruct the distribution of the electric field. Although achieving a stable gain of 12.3 dBi, the bandwidth is only 6.4% which is still too narrow for next-generation wireless communication applications.

As it can be seen, considering the energy loss of the feeding network, antenna size, processing complexity and costs, excitation of high-order modes becomes the best choice to improve DRA gain. However, current designs related to high-order modes and high gain in [13]-[18] still face the tremendous challenges of narrow bandwidth and intense gain fluctuations within the passband. Therefore, this letter focuses on the design of the high-order mode DRA, adopting wideband feeding method [19]. A stable high gain CDRA based on the high order mode $HEM_{11\delta+2}$ is proposed without the use of any additional gain enhancing structures. Finally, a 2 × 2 antenna array is constructed using four antenna elements, with much higher gain than traditional four element antenna arrays.

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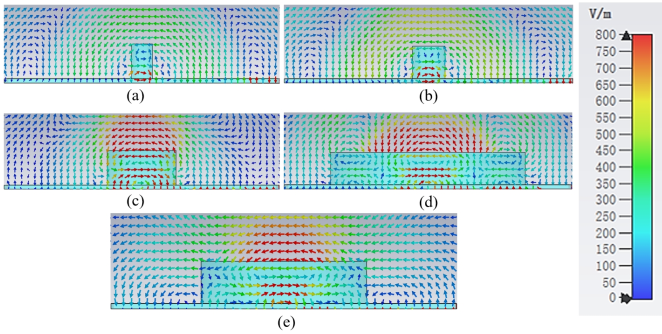

Fig. 2. Simulated electric field distribution of $HEM_{11\delta+2}$ mode under different r/h ratios at 8 GHz frequency. (a) r = 2.7 mm, h = 8 mm. (b) r = 4 mm, h = 8 mm. (c) r = h = 8.9 mm. (d) r = 24 mm, h = 8 mm. (e) r = 17 mm, h = 8 mm.

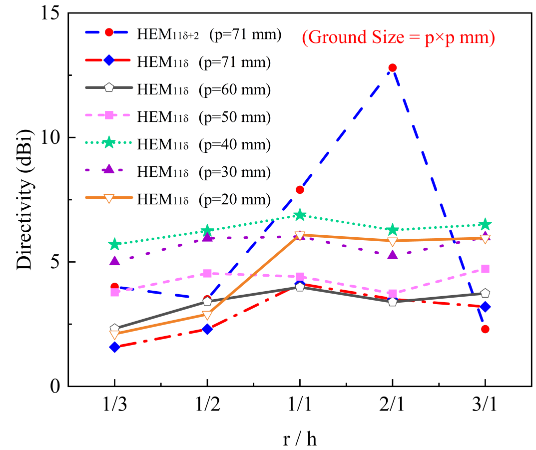

Fig. 3. The variation of antenna directivity with r/h operating in $HEM_{11\delta+2}$ mode and $HEM_{11\delta}$ mode at 8 GHz frequency. For the fundamental mode, the dimensions are as follows: (a) r = 1.1 mm, h = 3.3 mm. (b) r = 1.7 mm, h = 3.3 mm. (c) r = h = 3.3 mm. (d) r = 4.8 mm, h = 2.4 mm. (e) r = 9.9 mm, h = 3.3 mm.

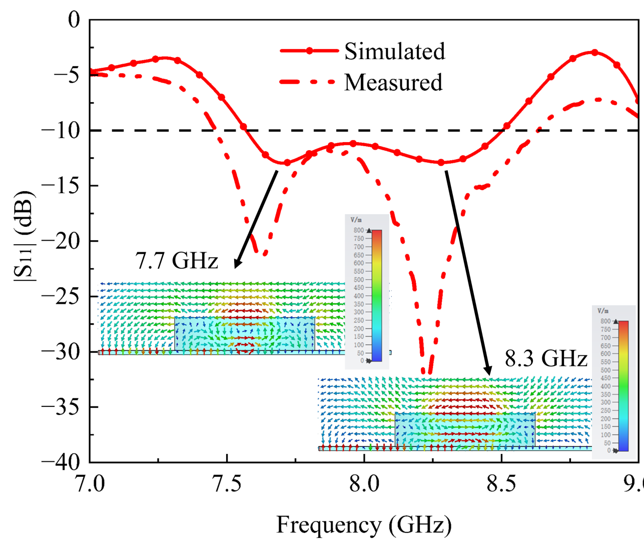

Fig. 4. Simulated and measured $|S_{11}|$ and the electric field distributions at the two resonance frequencies.

II. ANTENNA DESIGN

The primary design approach of CDRA proposed in this letter is based on the realization of cylindrical DRA radiating in its high-order mode $HEM_{11\delta+2}$. In our design, aperture coupling technology are used to excite the dielectric resonator to $HEM_{11\delta+2}$ mode, and the wideband technique is beneficial for better impedance matching. Specifically, by using dual-offset feedlines, a 50 Ω feedline is distributed into two 100 Ω feedlines, which are not affected by the spurious radiation introduced by a single offset feedline [19]. In addition, electromagnetic energy can be uniformly coupled to the CDRA through the path of dual-offset feedlines to the aperture to achieve the highest realized gain. Fig. 1 (a) and (b) shows the 3-D view and the bottom view, respectively, of the proposed CDRA. The dielectric resonator, as the radiator, is a cylindrical ceramic block with a relative permittivity of ε = 12 and a loss tangent of 0.0002. The feeding network is printed on an Arlon AD 255C substrate with a thickness of 1 mm, with a relative permittivity of 2.55 and a loss tangent of 0.0014. The other optimized parameters are also listed in Fig. 1.

Generally speaking, the in-phase electric fields tend to reinforce each other due to their overlapping nature, while the out-of-phase electric fields counteract one another, leading to the emergence of high-level sidelobes in the radiation pattern. Because of high sidelobes which can lead to radiation pattern cracks, some modes are typically not applicable. To ensure the directivity and stability of the radiation pattern, it should minimize the impact of the out-of-phase electric field as much as possible. Due to the absence of an out-of-phase electric field in $HEM_{11\delta+2}$, it is undeniable that it is an ideal choice for achieving high gain performance. For the proposed simple structure, the parameters of the cylindrical dielectric block determine the overall radiation performance of the antenna. In order to show that the effective radiating aperture is expanded with a suitable proportion, the $HEM_{11\delta+2}$ mode has been simultaneously excited at the same frequency (8 GHz) by taking different values of r/h while keeping all conditions the same. Specifically, as shown in the simulated electric field in Fig. 2, it can be seen that the $HEM_{11\delta+2}$ mode has been excited under different r/h values, but its field distribution effect varies. The obvious truth is that the larger the effective radiation area of the antenna, the higher the antenna gain. After comparing different r/h values, while maintaining the stability of the $HEM_{11\delta+2}$ operating mode, expanding the r/h ratio within a certain range will result in a larger antenna radiation aperture. After exceeding a certain range, this mode will be interfered by other chaotic higher-order modes (when the value of r/h reaches 3), resulting in some out-of-phase electric fields and ultimately weakening the effective radiation area of the antenna. Furthermore, we can plot the directivity of the antenna at 8 GHz frequency as a function of the r/h ratio through simulation results, as shown in Fig. 3, and it is clear that the optimal value should be around 2. After optimization, the maximum effective radiation aperture of the CDRA in the $HEM_{11\delta+2}$ operating mode was ultimately determined with the optimal proportion, thus achieving the maximum realized gain value. To facilitate the comparison, Fig. 3 also shows the directivity of the fundamental mode $HEM_{11\delta}$, which is still obtained by taking different r/h values at 8 GHz while keeping all conditions the same, but the ground size varies.

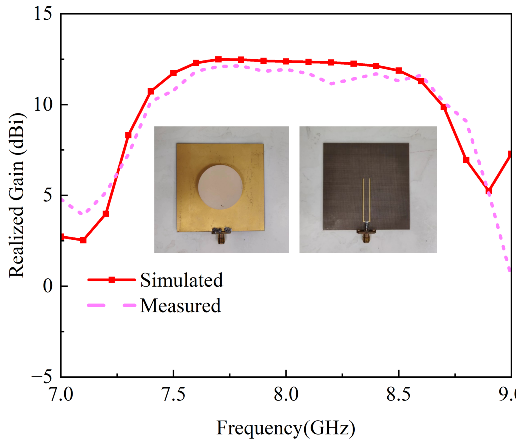

Fig. 5. Simulated and measured gain and photograph of the prototype.

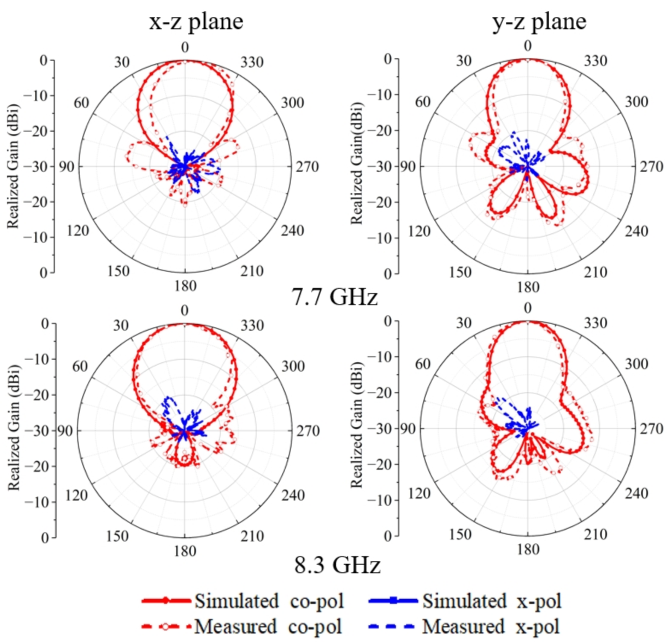

Fig. 6. Simulated and measured radiation patterns at 7.7 and 8.3 GHz.

The measured reflection coefficient performance of the proposed antenna is presented in Fig. 4 along with the simulated responses. It can be found that the simulated and measured impedance bandwidths are 11.6% (7.57–8.5 GHz) and 14.5% (7.46–8.63 GHz), respectively. Fig. 5 shows the measured and simulated realized gains of the proposed DRA in the boresight direction, where the gain response fluctuation achieved in the operating band does not exceed 0.6 dB, and the peak gain level is as high as 12.4 dBi. At last, the normalized radiation patterns of the proposed antenna in the x-z and y-z planes at 7.7 and 8.3 GHz are shown in Fig. 6 which fairly matches with the simulated ones.

In Table I, the performance of the proposed antenna is compared with other DRAs based on higher-order modes in [13], [14], [15] and [17], it can be seen that our proposed antenna is advantageous in impedance bandwidth, gain, and inband gain variation. Although the design using two-layer DRA in [16] achieved 21% enhanced bandwidth, its size is too large and the gain fluctuation is severe. Similarly, although the latest reported work in [18] has achieved a peak gain of over 16 dBi, the overall size of the antenna is very large and the in-band gain level has a considerable ripple of approximately 8 dB. However, our work not only has a more compact size but also avoids the problem of severe in-band gain fluctuations. Compared to the dielectric horn used in [12], our proposed antenna achieves similar gain while having a lower profile without the use of any additional structure. In addition, through normalized comparison, our proposed design has a much higher gain level per unit volume than other reported designs.

TABLE I

COMPARISON BETWEEN THE PROPOSED DRA AND THE PREVIOUSLY REPORTED LINEARLY-POLARIZED DESIGNS

Ref	Size/ Volume (λ_0)*	Imp. BW (%)	Max.gain (dBi)/ ΔGain (dB)**	Gain per unit volume
[12]	2×2×1.3/ 5.2	16.6	11.3/1	2.17
[13]	3.57×5.36×1.1/ 21.05	8.3	10.2/1.9	0.48
[14]	2.55×2.55×0.47/ 3.06	2.6	11.6/4	3.79
[15]	1.61×1.61×0.86/ 2.23	3.4	9.5/0.6	4.26
[16]	5.5×3.67×1.53/ 30.88	21	11.1/5	0.36
[17]	2.67×2.67×0.15/ 1.07	6.4	12.3/1.1	11.49
[18]	3.18×3.18×0.68/ 6.88	9.36	16/8	2.33
This work	**1.89×1.89×0.24/ 0.86**	**11.6**	**12.4/0.6**	**14.42**

*: λ_0 is the free-space wavelength at the center frequency.
**: ΔGain is the gain variation over the operating band.

III. DRA ARRAY

In order to validate the feasibility and practicality of employing multiple elements for an array configuration and further enhancing the gain, 4 elements are used to construct a 2 × 2 DRA array as shown in Fig. 7. Based on this view, an antenna array prototype is designed, fabricated, and measured. Fig. 8 displays both the simulated and measured antenna reflection coefficient, as well as the realized gain. The simulated and measured 10 dB return loss bandwidths are 13.7% (7.51-8.61 GHz) and 15.2% (7.56-8.8 GHz), respectively. From Fig. 8, it can be found that the proposed array achieves a peak gain level of up to 17.8 dBi at 7.6 GHz while achieving a gain response fluctuation of no more than 1.5 dB in the operating frequency band, demonstrating a good stable high gain characteristic. Despite a minor 1.5 dB discrepancy near 8.4 GHz due to processing or testing errors, the gain levels at other frequencies align closely with the simulation results, making the overall results acceptable. At last, the simulated and measured radiation patterns in the x-z and y-z planes of the proposed antenna array are shown in the Fig. 9, respectively obtained at 7.7 and 8.3 GHz.

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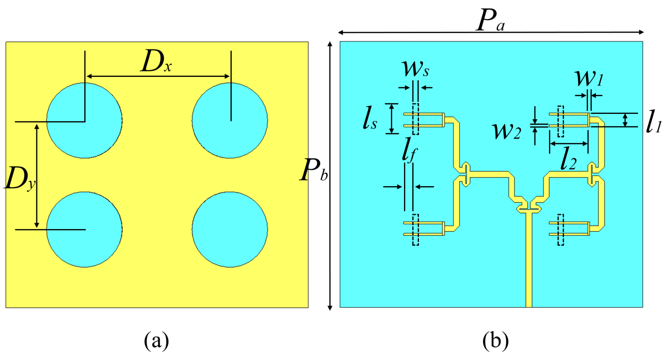

Fig. 7. Geometrical configuration of the DRA array. (a) Top view. (b) Bottom view. Design parameters: P_a = 136.4, P_b = 120.05, D_x = 65.4, D_y = 49.05, w_s = 3.3, l_s = 10, l_f = 5.15, l_1 = 6.2, w_1 = 0.9, l_2 = 17.4, w_2 = 1 (unit: mm).

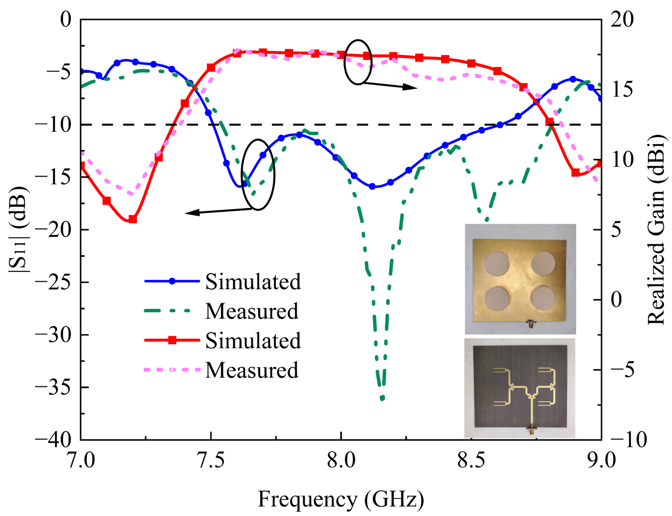

Fig. 8. Simulated and measured $|S_{11}|$ and realized gain.

It is worth noting that due to the design of the feeding network, the distance between the elements in the 2 × 2 array is relatively larger, resulting in a higher sidelobe level in the radiation pattern of the array, but the gain is very competitive. This is an acceptable result obtained by balancing the antenna gain. One may be able to reduce the sidelobe level by properly designing the distance between adjacent antenna elements.

To highlight the contribution of this work, compare the proposed array performance with the DRA array reported in Table II. It can be observed that compared to traditional arrays in [2], [3], [5], and [7], the proposed antenna array exhibits evidently lower design complexity. Moreover, it possesses a wider 3 dB gain bandwidth while achieving higher gain within the same volume. When compared with the designs in [4] and [6] with a larger number of antenna array elements, our proposed array has the advantage of having a relatively smaller overall size and using fewer antenna elements and power dividers to achieve similar antenna gains, thereby reducing energy transmission losses to some extent. As expected, our proposed array also achieves a more significant gain enhancement.

IV. Conclusion

This work has a simple feeding network, while maintaining a compact size and without the need for any additional structure for gain enhancement. The proposed antenna has the advantages of wide bandwidth and stable high gain over 12.4 dBi, substantiating the potential of the high-order mode to enhance antenna gain. Next, a 2 × 2 DRA array is designed, which can demonstrate a more substantial improvement in realized gain of 17.8 dBi with small in-band gain variation. The proposed DRA possesses the benefits of stable high gain, low loss, and simple design, making it a favorable candidate for next-generation wireless communication systems.

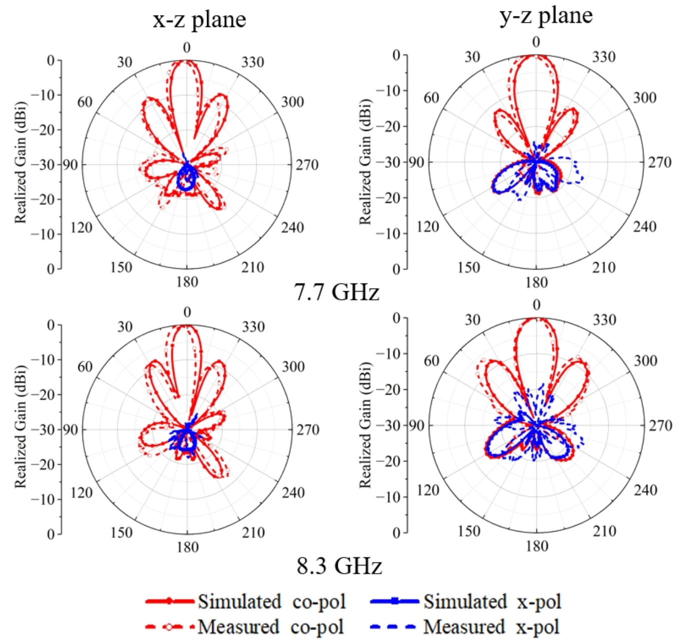

Fig. 9. Simulated and measured radiation patterns at 7.7 and 8.3 GHz.

TABLE II

COMPARISON BETWEEN THE PROPOSED DRA ARRAY AND THE PREVIOUSLY REPORTED DRA ARRAY DESIGNS

Ref	Size/ Volume (λ_0)*	Imp. BW and 3dB Gain BW (%)	No. of Elements/ Dividers	Max. gain (dBi)	Gain per unit volume
[2]	3.8×1.4×0.32/ 1.7	6.98	6/5	9.5	5.59
[3]	N.A.	9.5	8/7	12	N.A.
[4]	2.9×2.9×0.55/ 4.63	16.4	16/7	17.2	3.71
[5]	10.2×4.9×0.2/ 10	10	7/7	7.61	0.76
[6]	N.A.	14	20/10	15.8	N.A.
[7]	8.42×6.35×0.21/ 11.23	4.8	8/8	14	1.25
This work	**3.6×3.2×0.24/ 2.76**	**13.7**	**4/3**	**17.8**	**6.45**

N.A.: Not Available.
*: λ_0 is the free-space wavelength at the center frequency.

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