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A Broadband Differential-Fed Dual-Polarized Hollow Cylindrical Dielectric Resonator Antenna for 5G Communications

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Abstract: A broadband differential-fed dual-polarized hollow cylindrical dielectric resonator antenna (DRA) is proposed in this article. It makes use of the HEM_{111}, HEM_{113}, and HEM_{115} modes of the cylindrical hollow DRA. The proposed DRA is simply fed by two pairs of conducting strips and each pair of strips is provided with the out-of-phase signals. After introducing four disconnected air holes into the DRA, a broadband characteristic is achieved, with little effect on the antenna gain of its higher-order modes. To verify this idea, frosted K9-glass is applied to fabricate the hollow cylindrical DRA. The differential S-parameters, radiation patterns, and antenna gain of the DRA are studied. It is found that the proposed differential-fed dual-polarized DRA is able to provide a broad differential impedance bandwidth of ~68% and a high differential-port isolation better than ~46 dB. Moreover, symmetrical broadside radiation patterns are observed across the whole operating band. The proposed DRA covers the frequency bands including the 5G-n77 (3.4–4.2 GHz), 5G-n79 (4.4–5.0 GHz), WLAN-5.2 GHz (5.15–5.35 GHz), and WLAN-5.8 GHz (5.725–5.825 GHz), which can be used for 5G communications.

Keywords: differential-fed; dual-polarized; hollow cylindrical DRA; broadband

1. Introduction

The dielectric resonator antenna (DRA) [1–3] has been widely investigated in the past three decades. It has lots of attractive characteristics such as light weight, ease of excitation, and being bandwidth-controllable. In recent years, the dual-polarized antenna has received more and more attention. Its main advantage is to save the number of antennas in the base-station system. In addition, it can improve the channel capacity and reduce co-channel interference. As a result, many studies on the dual-polarized DRA have been reported [4–10]. For example, in [4], a dual-polarized DRA fed by a coplanar waveguide is proposed. In this design, even and odd modes of the coplanar waveguide structure are utilized, with a relatively narrow impedance bandwidth of ~7% obtained. The bandwidth of the dual-polarized DRA can be enlarged by using suitable excitation. For instance, in [5], two pairs of balanced probes are used to excite the two orthogonal modes of the HEM_{111} mode of the cylindrical DRA, with an impedance bandwidth of ~20% obtained. In addition, the dual-mode method can be used to widen the bandwidth. For instance, in [6], a dual-polarized cylindrical DRA is designed using its HEM_{111} and HEM_{113} modes, with an impedance bandwidth of ~30% reported. The disadvantage is
that the feeding method of the two ports is not consistent, leading to the different and asymmetric radiation patterns [6].

On the other hand, because of the high-level integration with other solid-state circuits, the on-chip DRA [11–13] can meet the requirements of small size and low cost in high-frequency system. However, for the chip-sets in silicon technology, traditional singly-fed antennas are easily affected by the substrate noise and power supply variations. A differential-fed antenna can avoid this problem because it allows lower offset and higher linearity [14,15]. Hence, differential-fed DRA [16–26] with excellent performance has great potential for high frequency on-chip communication applications. Recently, some efforts have been devoted to the design of the differential dual-polarized DRAs [27–31]. For example, the differential-fed dual-polarized DRAs with dual band performance [27] or filtering characteristic [28] have been reported. The works [27,28] show that using the differential feeding can suppress the unwanted DRA modes. Moreover, it has an important merit that the isolation between the two differential ports is much higher than that of the single-ended version.

The hollow DRAs [32–37] have been extensively studied for the merit of wide impedance bandwidth, but at the cost of high cross-polarization. This can be improved by using the differential-fed method since it can cancel-out the leakage radiation. However, relatively few studies have been done on broadening the differential impedance bandwidth of the DRA (calculated from the mixed-mode S parameters $S_{dd11}$).

In this paper, a broadband differential-fed dual-polarized cylindrical DRA is investigated. With the introduction of four disconnected air holes in the DRA, three designated DRA modes (HEM$_{111}$, HEM$_{113}$, and HEM$_{115}$ modes) merge together and form a broadband dual-polarized DRA. Most importantly, the antenna gain of the higher-order modes is maintained. The results show that the proposed DRA can provide a broad differential impedance bandwidth of ~68% for each differential-port, with a good differential port-isolation higher than ~46 dB achieved.

The rest of this paper will be organized as follows. In Section 2, the theory of the differential-fed dual-polarized antenna is discussed. In Section 3, the configuration of the proposed DRA is given. Additionally, the effect of the air region on the performance of the DRA is studied. In Section 4, the performance of the proposed DRA is shown and assessed. Finally, a conclusion is given in Section 5.

2. Theory

2.1. S Parameters of the Dual-Polarized Antennas Using the Single-Ended and Differential Ports

In designing the dual-polarized antennas, the port matching and port isolation are needed to considered. Table 1 compares the S parameters of the dual-polarized antenna with two single-ended ports and differential ports. When the ports are single-ended, the port matching ($S_{11}$ and $S_{22}$) and port isolation ($S_{12}$ and $S_{21}$) are considered. However, it is different as the ports are differential ones. In this condition, the port matching is defined as $S_{dd11}$ and $S_{dd22}$, while the port isolation is defined as $S_{dd12}$ and $S_{dd21}$. In [38–40], a dual-polarized antenna with two differential-ports is considered as a single-ended four-ports network. Its differential S parameters is given as:

\[
S_{dd11} = \frac{(S_{11} - S_{12} - S_{21} + S_{22})}{2}
\]

\[
S_{dd22} = \frac{(S_{33} - S_{34} - S_{43} + S_{44})}{2}
\]

\[
S_{dd21} = \frac{(S_{31} - S_{41} - S_{32} + S_{42})}{2}
\]

\[
S_{dd12} = \frac{(S_{13} - S_{14} - S_{23} + S_{24})}{2}
\]

where $S_{ij}$ ($i = 1, 2, 3, 4; j = 1, 2, 3, 4$) denotes the single-ended S-parameters. As can be seen from the above formulas, the matching of the differential ports ($S_{dd11}$ and $S_{dd22}$) are related to the matching ($S_{11}$ and $S_{22}$) and isolation ($S_{12}$ and $S_{21}$) of the single-ended ports.
2.2. Strips-Fed Dual-Polarized Cylindrical DRA Using Single-Ended and Differential Ports

In this section, a strips-fed cylindrical DRA is studied to compare the performance of the dual-polarized antennas using the single-ended and differential ports. Figure 1 shows the structure of the DRAs, where Figure 1a uses two single-ended ports and Figure 1b employs two differential ports. The cylindrical DRA ($\varepsilon_r = 6.85$) has a radius of $R = 12$ mm and a height of $H = 10$ mm. For each port, a strip having a width of $W_s = 1$ mm and a length of $L_s = 9$ mm is adhered to the sidewall of the cylindrical DRA, which is used to excite its fundamental HEM$_{111}$ mode. Figure 2 shows the port matching for both cases. Referring to the figure, the 10dB-impedance bandwidth of the single-ended ($|S_{11}| \leq -10$dB) and differential ($|S_{dd11}| \leq -10$dB) versions are obtained as ~16% (3.98–4.65 GHz) and ~17% (3.77–4.49 GHz), respectively. Figure 3 shows the port isolation for both cases. It can be seen from the figure that the single-ended port isolation is only higher than 16 dB (3.98–4.65 GHz), while the port isolation of the differential version is higher than 45 dB (3.77–4.49 GHz). This shows the isolation of the differential version is higher than that of the single-ended. The reason is given here. For the differential version (Figure 1b), ports 3 and 4 are symmetrical about the plane of ports 1 and 2. Under this condition, $S_{13} = S_{14} = S_{23} = S_{24}$ are obtained, resulting in $S_{dd12} = 0$. In other words, the isolation of the differential version is infinite in theory.

<p>| Table 1. Comparison of the Dual-Polarized Antennas with Two Single-ended Ports and Differential Ports. |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|</p>
<table>
<thead>
<tr>
<th>Port Distribution</th>
<th>S Parameter</th>
<th>Diagrammatic Sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two single-ended ports</td>
<td>Port matching: $S_{11}, S_{22}$</td>
<td>Port 1 - Antenna</td>
</tr>
<tr>
<td></td>
<td>Port isolation: $S_{21}, S_{12}$</td>
<td>Port 2</td>
</tr>
<tr>
<td>Two differential ports</td>
<td>Port matching: $S_{dd11} = (S_{11} - S_{12} - S_{21} + S_{22}) / 2$</td>
<td>Port 1 - (Port 1)</td>
</tr>
<tr>
<td></td>
<td>$S_{dd22} = (S_{33} - S_{34} - S_{43} + S_{44}) / 2$</td>
<td>Antenna - Port 1+</td>
</tr>
<tr>
<td></td>
<td>Port isolation: $S_{dd21} = (S_{31} - S_{32} - S_{41} + S_{42}) / 2$</td>
<td>(Port 2)</td>
</tr>
<tr>
<td></td>
<td>$S_{dd12} = (S_{13} - S_{14} - S_{23} + S_{24}) / 2$</td>
<td>(Port 3)</td>
</tr>
<tr>
<td></td>
<td>$S_{21} + S_{12}$</td>
<td>(Port 4)</td>
</tr>
</tbody>
</table>
Four single-ended ports (1, 2, 3, 4), which form two direct rectangular air holes are dug at the bottom of the DRA. Each air hole has a length of \(r = 6.85\) mm and a height of \(H = 25\) mm. These strips are connected with \(W_s = 1\) mm and \(L_s = 9\) mm and \(H = 9\) mm, respectively. The configuration of the strips-fed dual-polarized cylindrical DRAs is shown in Figure 1.

**Figure 1.** Configuration of the strips-fed dual-polarized cylindrical DRAs. (a) Two single-ended ports; (b) Two differential ports.

The \(|S_{11}|\) is for DRA 1 (single-ended port) and \(|S_{dd11}|\) is for DRA 2 (differential port).

**Figure 2.** Reflection coefficient of the strips-fed dual-polarized cylindrical DRAs shown in Figure 1. The \(|S_{11}|\) is for DRA 1 (single-ended port) and \(|S_{dd11}|\) is for DRA 2 (differential port).

The |S11| or |Sdd11| (dB)

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
</tr>
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<tbody>
<tr>
<td>3.0</td>
</tr>
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</table>

大军

**Figure 3.** Port isolation of the strips-fed dual-polarized cylindrical DRAs shown in Figure 1. The \(|S_{12}|\) is for DRA 1 (single-ended port) and \(|S_{dd12}|\) is for DRA 2 (differential port).
3. Antenna Configuration, Air Region Effect and Resonant Modes

3.1. Antenna Configuration

Figure 4 shows the configuration of the proposed broadband differential-fed dual-polarized hollow cylindrical DRA locating on a ground plane of $12 \times 12 \text{ cm}^2$. The hollow cylindrical DRA made of frosted K9 glass ($\varepsilon_r = 6.85$) has a radius of $R = 11 \text{ mm}$ and a height of $H = 25 \text{ mm}$ ($H/R = 2.27$). It should be mentioned that the value of $H/R$ cannot be too small, otherwise the two higher-order modes (HEM$_{113}$ and HEM$_{115}$ modes) would be far away from the fundamental mode (HEM$_{111}$ mode) [41] and they will not be able to merge. In our experience, $H/R$ should be larger than 2. Four approximate rectangular air holes are dug at the bottom of the DRA. Each air hole has a length of $a = 6 \text{ mm}$, a width of $b = 7 \text{ mm}$, and a height of $d = 9 \text{ mm}$. Four metal strips were employed to excite the hollow cylindrical DRA, which has a length of $L_S = 9 \text{ mm}$ and a width of $W_S = 1 \text{ mm}$. These strips are connected with four single-ended ports (1, 2, 3, 4), which form two differential ports (1+, 1−) and (2+, 2−), respectively.

![Figure 4](image_url)

**Figure 4.** The configuration of the proposed broadband differential-fed dual-polarized hollow cylindrical DRA: $a = 6 \text{ mm}$, $b = 7 \text{ mm}$, $d = 9 \text{ mm}$, $R = 11 \text{ mm}$, $H = 25 \text{ mm}$, $L_S = 9 \text{ mm}$, $W_S = 1 \text{ mm}$, and $\varepsilon_r = 6.85$. (a) Perspective view. (b) Top view.

3.2. The Effect of the Air Region

The effect of the air region on the antenna performance is discussed here. Figure 5 shows the solid cylindrical DRA (Figure 5a), as well as three kinds of hollow DRAs (Figure 5b–d) with different air region distributions. The excitation method and ground plane used in Figure 5 is the same as that in Figure 4. For brevity, the ground plane is not shown here. The corresponding simulated $S_{dd11}$ at differential-port 1 is shown in Figure 6. It should be mentioned that the definition of the differential $S$ parameters for a differential-fed dual-polarized antenna has been given in Table 1. With reference to the result of the $S_{dd11}$ for DRA I, the HEM$_{111}$ and HEM$_{113}$ mode of the cylindrical DRA are excited at 3.31 and 4.78 GHz, respectively. However, its matching around 4.0 GHz is not very good, which makes it impossible to achieve a wideband antenna. A similar result of $S_{dd11}$ is observed for DRA II having a rectangular hollow region at its center. To further enhance the bandwidth, DRA III and DRA IV with four approximate rectangular air holes are designed, in which the air holes are connected in DRA III and disconnected in DRA IV. With reference to the results of $S_{dd11}$ for DRA III and DRA IV, the HEM$_{111}$,
HEM_{113} and HEM_{115} modes of the DRA are successfully excited to form a broadband DRA. This is reasonable because the insertion of the air region inside the DRA reduces its effective dielectric constant, and therefore enhances overall bandwidth. Furthermore, as can be seen from Figure 7, the antenna gain of the DRA III ranging from 6.5 to 7.0 GHz has a sharp decline; this is because the hollow region at the center destroys the first standing wave of the HEM_{115} mode more seriously. The above discussion implies that the total volume of the hollow region should be large enough so that the differential impedance bandwidth can be obviously increased. However, the hollow region should be avoided in the middle of the DRA, so as to minimize the influence on the antenna gain of the higher-order HEM_{115} mode. In addition, it should be mentioned that good isolation \(|S_{dd12}|\) between the two differential-ports is obtained for the four cases, with their results shown in Figure 8.

**Figure 5.** Top view of four differential-fed dual-polarized DRAs. (a) Solid cylindrical DRA; (b) Hollow cylindrical DRA with a rectangular air hole \((a = 8 \text{ mm}, b = 8 \text{ mm})\) at its center; (c) Hollow cylindrical DRA with four connected approximate rectangular air holes \((a = 6 \text{ mm}, b = 8 \text{ mm})\); (d) Hollow cylindrical DRA with four disconnected approximate rectangular air holes \((a = 6 \text{ mm}, b = 7 \text{ mm})\). All the air holes are at the bottom and have the same height \(d = 9 \text{ mm}\).

**Figure 6.** Comparison of the simulated \(|S_{dd11}|\) of four DRAs shown in Figure 5.
Figure 7. Comparison of the simulated antenna gain at differential-port 1 of four DRAs shown in Figure 5.

Figure 8. Comparison of the simulated $|S_{dd12}|$ of four DRAs shown in Figure 5.

3.3. Resonant Modes

The resonant modes of the proposed hollow cylindrical DRA (DRA IV) are verified by the corresponding near field in this section. The H-fields (x–z plane) of the proposed DRA at the resonance frequencies are given in Figure 9. The analysis is similar with that in [42]. With reference to Figure 9a, the typical H-field of the HEM$_{111}^y$ mode was found at 3.56 GHz, which has one energy concentration zone inside the DRA. Referring to Figure 9b,c, two and three energy concentration zones along z-direction were observed, respectively. This denotes the resonant modes at 4.88 GHz and 6.08 GHz are caused by the HEM$_{113}^y$ and HEM$_{115}^y$ modes, respectively.
3.3. Resonant Modes

The resonant modes of the proposed hollow cylindrical DRA (DRA IV) are verified by the simulation. Figure 9 shows the simulated H-fields (x-z plane) inside the proposed differential-fed dual-polarized DRA. (a) HEM$_{111}^y$ mode at 3.56 GHz. (b) HEM$_{113}^y$ mode at 4.88 GHz. (c) HEM$_{115}^y$ mode at 6.08 GHz.

3.4. Parametric Study

In this part, parametric study is carried out to characterize the proposed DRA. Figure 10 shows the simulated $|S_{dd11}|$ versus frequency with the length of the strips $L_s = 7$, 8, and 9 mm. Referring to the figure, increasing $L_s$ would improve the matching of the DRA, and a good result is obtained as $L_s = 9$ mm. Its inset gives the simulated $|S_{dd11}|$ versus frequency with the width of the strips $W_s = 0.5$, 1, and 1.5 mm. As can be seen from the figure, altering $W_s$ has little effect on the matching of the DRA. Next, the sizes of the hollow region on the effect of the DRA performance is investigated. Figure 11 shows the simulated $|S_{dd11}|$ versus frequency with the length of the hollow region $a = 4$, 5, and 6 mm. Its inset shows the simulated $|S_{dd11}|$ versus frequency with the width of the hollow region $b = 5$, 6, and 7 mm. With reference to the figure, increasing $a$ and $b$ would shift the third resonance modes obviously upward, and thus enhance the differential impedance bandwidth of the DRA. Figure 12 presents the simulated $|S_{dd11}|$ of the proposed DRA versus frequency for different $d = 8$, 9, and 10 mm. Referring to the figure, changing $d$ has a small effect on the differential impedance bandwidth of the DRA. However, a larger $d$ would have a negative effect on the antenna gain around 6.5 GHz. Based on the above analysis, a design guideline is also concluded as follows:

1. Determining the dimension of the cylindrical DRA: $R \sim 0.47 \lambda_d$ and $H \sim 1.07 \lambda_d$, in which $\lambda_d$ is the wavelength in the dielectric corresponding to the center frequency;
2. Introducing four rectangular hollow regions ($a \sim 0.26 \lambda_d$, $b \sim 0.3 \lambda_d$ and $d \sim 0.39 \lambda_d$) into the DRA, and then adjusting $L_s$ to obtain a good matching;
3. Slightly adjusting $a$ and $b$ to obtain an optimal differential impedance bandwidth of the DRA;
4. Slightly adjusting $d$ to optimize the antenna gain of the high frequency band.
Sensors 2020, 20, x 9 of 17

(1) Determining the dimension of the cylindrical DRA: \( R \approx 0.47 \lambda_d \) and \( H \approx 1.07 \lambda_d \), in which \( \lambda_d \) is the wavelength in the dielectric corresponding to the center frequency; \( \lambda_d \) was 0.26 m for 3.56 GHz, 0.34 m for 4.88 GHz, and 0.47 m for 6.26 GHz. Adjusting \( R \) and \( H \) to optimize the antenna gain of the high frequency band.

(2) Determining the dimension of the rectangular hollow cylindrical DRA: \( W_s = 0.5 \text{mm} \) and \( L_s = 7 \text{mm} \) to obtain a good matching; \( W_s = 1.0 \text{mm} \) and \( L_s = 8 \text{mm} \) to obtain an optimal differential impedance bandwidth of the DRA; \( W_s = 1.5 \text{mm} \) and \( L_s = 9 \text{mm} \) to obtain a good matching.

In this part, the measured results of the proposed broadband differential-fed dual-polarized hollow cylindrical DRA are reported. The DRA was fabricated using frosted K9 glass, with its hollow cylindrical DRA shown in Figure 13. Figure 14 shows the measured and simulated differential S-parameters of the proposed DRA versus frequency for different \( a \) and \( b \). The inset shows the simulated \( |S_{dd11}| \) of the proposed DRA versus frequency for different \( d \).

Figure 10. Simulated \( |S_{dd11}| \) of the proposed DRA versus frequency for different \( L_s \). The inset shows the simulated \( |S_{dd11}| \) of the proposed DRA versus frequency for different \( W_s \).

Figure 11. Simulated \( |S_{dd11}| \) of the proposed DRA versus frequency for different \( a \). The inset shows the simulated \( |S_{dd11}| \) of the proposed DRA versus frequency for different \( b \).

Figure 12. Simulated \( |S_{dd11}| \) of the proposed DRA versus frequency for different \( d \). The inset shows the simulated antenna gain of the proposed DRA at the differential-port 1 versus frequency for different \( d \).
4. Results

In this part, the measured results of the proposed broadband differential-fed dual-polarized hollow cylindrical DRA are reported. The DRA was fabricated using frosted K9 glass, with its prototype shown in Figure 13. Figure 14 shows the measured and simulated differential S-parameters of the proposed DRA at two differential-ports. With reference to the figure, the three resonance frequencies for the differential-port 1 are measured as 3.58 GHz, 4.88 GHz and 6.26 GHz, respectively. This agrees with the simulated resonance frequencies of 3.56 GHz (0.55% error), 4.88 GHz (0.00% error), and 6.08 GHz (2.87% error). A similar result was obtained for the differential-port 2. The measured differential impedance bandwidth ($|S_{dd11}|&|S_{dd22}| ≤ -10$ dB) at the differential-port 1 and 2 are obtained as 68.4% (3.23–6.59 GHz) and 69.4% (3.22–6.64 GHz), respectively. The above results are summarized in Table 2 for the ease of reference. Figure 15 shows the measured and simulated isolation between two differential-ports. As can be seen from the figure, the isolation between differential-port 1 and 2 ($|S_{dd12}|$) is less than 46 dB across the whole operating band.

![Prototype of the proposed broadband differential-fed dual-polarized hollow cylindrical DRA.](image1)

**Figure 13.** Prototype of the proposed broadband differential-fed dual-polarized hollow cylindrical DRA. (a) Overview of the antenna. (b) The hollow cylindrical DRA fabricated using frosted K9 glass.

![Simulated and measured $|S_{dd11}|$ and $|S_{dd22}|$ of the proposed DRA versus frequency.](image2)

**Figure 14.** Simulated and measured $|S_{dd11}|$ and $|S_{dd22}|$ of the proposed DRA versus frequency.
Table 2. Summary of the resonance frequency and impedance bandwidth of the proposed differential-fed dual-polarized DRA.

<table>
<thead>
<tr>
<th>Diff. Port (i)</th>
<th>Resonant Modes</th>
<th>Resonance Frequency (GHz)</th>
<th>Mea. Diff. Impedance Bandwidth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sim.</td>
<td>Mea.</td>
<td>Error (%)</td>
</tr>
<tr>
<td>1</td>
<td>HEM_{111}^{y}</td>
<td>3.56</td>
<td>3.58</td>
</tr>
<tr>
<td></td>
<td>HEM_{113}^{y}</td>
<td>4.88</td>
<td>4.88</td>
</tr>
<tr>
<td></td>
<td>HEM_{115}^{y}</td>
<td>6.08</td>
<td>6.26</td>
</tr>
<tr>
<td>2</td>
<td>HEM_{111}^{x}</td>
<td>3.56</td>
<td>3.56</td>
</tr>
<tr>
<td></td>
<td>HEM_{113}^{x}</td>
<td>4.88</td>
<td>4.84</td>
</tr>
<tr>
<td></td>
<td>HEM_{115}^{x}</td>
<td>6.08</td>
<td>6.26</td>
</tr>
</tbody>
</table>

Figure 14. Simulated and measured $|S_{dd11}|$ and $|S_{dd22}|$ of the proposed DRA versus frequency.

Figure 15. Simulated and measured $|S_{dd12}|$ of the proposed DRA versus frequency.

The simulated and measured radiation patterns of the proposed DRA at differential-port 1 for the three DRA modes are shown in Figure 16. In the measurement, a broadband external 180° hybrid coupler (2–18 GHz) was applied to provide the differential signals. Referring to the figure, symmetrical broadside radiation patterns were presented for the three resonant modes. In the boresight direction, the co-polarized field is stronger than its cross-polarized counterpart by more than 20 dB for the E- and H-planes. It is also observed that the level of the cross-polarization field of all angles is smaller than −20 dB, which is due to the use of differential feeding.

Figure 17 presents the simulated and measured antenna gains at the differential-port 1. Referring to the figure, the three measured peak gains are obtained as 3.54 dBi (@3.1 GHz), 6.06 dBi (@5.0 GHz) and 9.67 dBi (@6.8 GHz), which are due to the HEM_{111}, HEM_{113}, and HEM_{115} modes, respectively. It is found that the peak gain of the three DRA modes increase in turn, showing that the air holes have a relatively small effect on the antenna gain of the higher-order modes. The measured antenna efficiency of the proposed DRA at the differential-port 1 is also given in Figure 18. With reference to the figure, its range is from 0.74 to 0.95 in the usable frequency band (3.23–6.59 GHz). The radiation patterns, antenna gain and efficiency at the differential-port 2 are very similar with that of the differential-port 1. For brevity, the results are not given here. Figure 19 shows the simulated and measured envelope correlations (ECs) of the proposed DRA. The formula provided in [43] is used to calculate this parameter. With reference to the figure, both the simulated and measured ECs are smaller than 0.005 across the whole frequency band, satisfying the requirement of the MIMO system (EC ≤ 0.5).
to the figure, the three measured peak gains are obtained as 3.54 dBi (@3.1 GHz), 6.06 dBi (@5.0 GHz) and 9.67 dBi (@6.8 GHz), which are due to the HEM111, HEM113, and HEM115 modes, respectively. It is found that the peak gain of the three DRA modes increase in turn, showing that the air holes have a relatively small effect on the antenna gain of the higher-order modes.

The measured envelope correlations (ECs) of the proposed DRA. The formula provided in [43] is used to calculate this parameter. With reference to the figure, both the simulated and measured ECs are smaller than 0.005 across the whole frequency band, satisfying the requirement of the MIMO system.

Figure 16. Simulated and measured radiation patterns of the proposed DRA at differential-port 1. Referring to the figure, the range is from 0.74 to 0.95 in the usable frequency band (3.23–6.59 GHz). The radiation efficiency of the proposed DRA at the differential-port 1 is also given in Figure 18. With reference to the figure, its range is from 0.74 to 0.95 in the usable frequency band (3.23–6.59 GHz). The radiation efficiency of the proposed DRA at the differential-port 1 is also given in Figure 18.

(a) 3.56 GHz. (b) 4.88 GHz. (c) 6.08 GHz.
Figure 17. Simulated and measured antenna gain of the proposed DRA at differential-port 1 versus frequency.

Figure 18. Measured antenna efficiency of the proposed DRA at differential-port 1 versus frequency.

Figure 19. Simulated and measured envelope correlations of the proposed DRA.
Finally, the performance of the proposed differential-fed dual-polarized DRA is assessed. Table 3 summarizes the different dual-polarized DRAs. As can be seen from the table, using the differential feeding ([27] and proposed) can obtain a better isolation than the single-ended feeding. In addition, compared with other works [4–8,27], our DRA has a broader impedance bandwidth and higher antenna peak gain, with an excellent isolation and medium cross-polarization level obtained. Additionally, its consistence of the radiation patterns observed at two ports is good. However, the cost is that a DRA of a relatively large size is required.

Table 3. Comparison of the Different Dual-Polarized DRAs.

<table>
<thead>
<tr>
<th></th>
<th>Size ($\lambda_d$)</th>
<th>Impedance Bandwidth (%)</th>
<th>Isolation (dB)</th>
<th>X-Pol Level (dB)</th>
<th>Peak Gain (dBi)</th>
<th>Feeding Type</th>
<th>Consistence of the Radiation Patterns at Two Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. [4]</td>
<td>0.219</td>
<td>7</td>
<td>25</td>
<td>-20</td>
<td>6.45</td>
<td>single-ended</td>
<td>Medium</td>
</tr>
<tr>
<td>Ref. [5]</td>
<td>0.472</td>
<td>20</td>
<td>25</td>
<td>-30</td>
<td>NA</td>
<td>single-ended</td>
<td>Good</td>
</tr>
<tr>
<td>Ref. [6]</td>
<td>0.826</td>
<td>31.7</td>
<td>37</td>
<td>-20</td>
<td>9.42</td>
<td>single-ended</td>
<td>Medium</td>
</tr>
<tr>
<td>Ref. [7]</td>
<td>0.294</td>
<td>7.9</td>
<td>36</td>
<td>-34</td>
<td>6.8</td>
<td>single-ended</td>
<td>Medium</td>
</tr>
<tr>
<td>Ref. [8]</td>
<td>0.25</td>
<td>25</td>
<td>29</td>
<td>-15</td>
<td>7.4</td>
<td>single-ended</td>
<td>Good</td>
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<tr>
<td>Ref. [27]</td>
<td>0.580</td>
<td>4.3</td>
<td>47</td>
<td>-33</td>
<td>6.94</td>
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<tr>
<td>Proposed</td>
<td>0.747</td>
<td>68</td>
<td>46</td>
<td>-22</td>
<td>9.67</td>
<td>Differential</td>
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</table>

5. Conclusions

A broadband differential-fed dual-polarized hollow cylindrical DRA has been investigated. The HEM$_{111}$, HEM$_{113}$, and HEM$_{115}$ modes of the hollow cylindrical DRA have been used for the design. The effect of the air region distribution on the performance of the hollow DRA has been investigated. It has been found that the hollow DRA with four disconnected air holes can have a broad differential impedance bandwidth and good antenna gain. It shows that the proposed DRA has a measured differential impedance bandwidth of ~68% for each differential-port. Furthermore, a good differential-port isolation higher than ~46 dB has been obtained. The proposed DRA covers the frequency bands including the 5G-n77, 5G-n79, WLAN-5.2 GHz, and WLAN-5.8 GHz. Additionally, the proposed design concept is potentially suitable for designing the on-chip DRA at high frequency.

Author Contributions: Conceptualization, X.F. and Y.S.; Supervision, X.F.; software, K.S.; writing—original draft preparation, X.F.; writing—review and editing, X.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

References


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