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A Stacked Patch Antenna With Broadband Circular Polarization and Flat Gains

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ABSTRACT In this paper, a stacked circular polarization (CP) patch antenna with broad impedance bandwidth, axial-ratio (AR) bandwidth, and flat gains is investigated. The antenna is composed of a square ring, double layers' stacked patches, and four vertical patches. The corner truncated loop served as a sequential phase feeding structure for four driven patches. To improve the impedance matching, four square patches are stacked on the bottom layer. Furthermore, four vertical patches are introduced on the ground plane to broaden the AR bandwidth. Simulated and measured studies are conducted on an antenna prototype to validate the proposed design. The proposed design shows that the measured impedance bandwidth is 4.65–7.21 GHz (43.2%), measured 3-dB AR bandwidth at broadside is 4.9–6.4 GHz (26.5%) and the 1-dB gain bandwidth is 4.75–6.6 GHz (32.6%). Compared with other similar CP stacked patch antennas, the antenna owns advantages of wide bandwidth, compact size, and flat gain.

INDEX TERMS Broadband antenna, circular polarization, stacked antenna, patch antenna.

I. INTRODUCTION

Due to the advantages of suppressing multipath interferences and reducing polarization mismatch, some wireless communication systems require the antenna to have wideband and CP characteristics [1], [2]. Besides, CP antennas with wide bandwidth, compact size, and flat gain are necessary to meet the demand for high data rate transmission and processing [3]–[6].

To achieve the broadband operation, many antennas have been proposed accordingly, such as dipole antennas [7]–[9], dielectric resonator antennas [10], and microstrip patch antennas. Crossed dipoles [11], [12] or cross-bowtie antenna [13] are commonly used structures for achieving wideband CP operation due to their orthogonal feed method. In [11], parasitic loops were introduced to a printed crossed dipole to generate one extra CP mode. Moreover, the CP bandwidth can be enhanced to 106.1% by using metallic plates [12]. However, metallic reflectors [11], [12] or artificial magnetic conductor (AMC) reflector [13] are usually required in the design, and therefore, cavity-backed ground planes with a high profile and complex structure are needed. Among the CP antenna designs, single-fed patch antennas are much preferred owing to their compact structure. However, single-fed microstrip patch antennas always have narrow AR bandwidth [14]. Consequently, many investigations have been conducted to enhance their AR bandwidth [15]–[17]. A widely used method for achieving broadband CP operation is to use stacked patches [18]–[20]. Rotated stacked rectangular patches were presented in [21] to achieve a 3-dB AR bandwidth of 33.6%. However, the wide AR bandwidths were obtained at the expense of large size and high profile. In [22], a perturbed ring resonator with a pin-loaded structure was proposed to realize a wider AR bandwidth as well as high gain. However, the narrow AR bandwidth (6%) is not enough for wideband systems. In addition, the sequential phase feed technique was developed in [23] to increase the AR bandwidth with a stacked structure. An E-shaped patch was also employed in [24] and near-field resonant parasitic (NFRP) patch was used to further improve the bandwidth. Besides, parasitic elements were also employed to increase bandwidth in [25]. A substrate integrated suspended line antenna was

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proposed in [26] to achieve broadband impedance matching and wideband CP characteristics. Another kind of stacked antenna with wideband CP operation is metasurface-based stacked antenna [27]–[30]. Although excellent performance is obtained, periodic cells are usually needed leading to an increase of the design complexity.

To obtain wide 3-dB AR bandwidth and flat gain, a stacked patch antenna with coupled vertical patches is developed in this paper. The square loop is initially proposed to obtain the original CP mode, then the double layers' stacked structure is employed not only to improve the impedance matching but also to generate extra CP mode. Moreover, four vertical walls are embedded on the ground plane to enhance CP performance. A fabricated antenna model is used to verify the simulation results.

II. ANTENNA DESIGN

A. ANTENNA CONFIGURATION

The geometry of the proposed broadband CP stacked antenna is shown in Fig. 1. The proposed structure is composed of a coaxial-fed square loop, double layers' stacked patches, and vertical patches embedded on the ground plane. The square ring fabricated on the bottom substrate ($\varepsilon_r = 2.2$, $\tan\delta = 0.001$) works as a feeding network, so a minimum AR point can be obtained by exciting the fundamental one-wavelength mode of the loop [4]. On the basis of the origin loop, a double layers' stacked structure is introduced. The stacked patches are printed on the top layer of substrate ($\varepsilon_r = 2.2, \tan\delta = 0.001$), and the gap between the top and bottom layer is h_3. The impedance matching is improved by introducing the double layers' stacked structure, and extra CP mode is also generated at the upper band. Meanwhile, the gain at the upper band is also improved, and therefore wide gain bandwidth is also enhanced by the stacked patches. In order to improve CP performance, four vertical patches are sequentially placed on the ground plane. The designed structure is simulated by ANSYS HFSS to obtain both wide impedance bandwidth and CP bandwidth. The optimized parameters of the design are shown in Table 1.

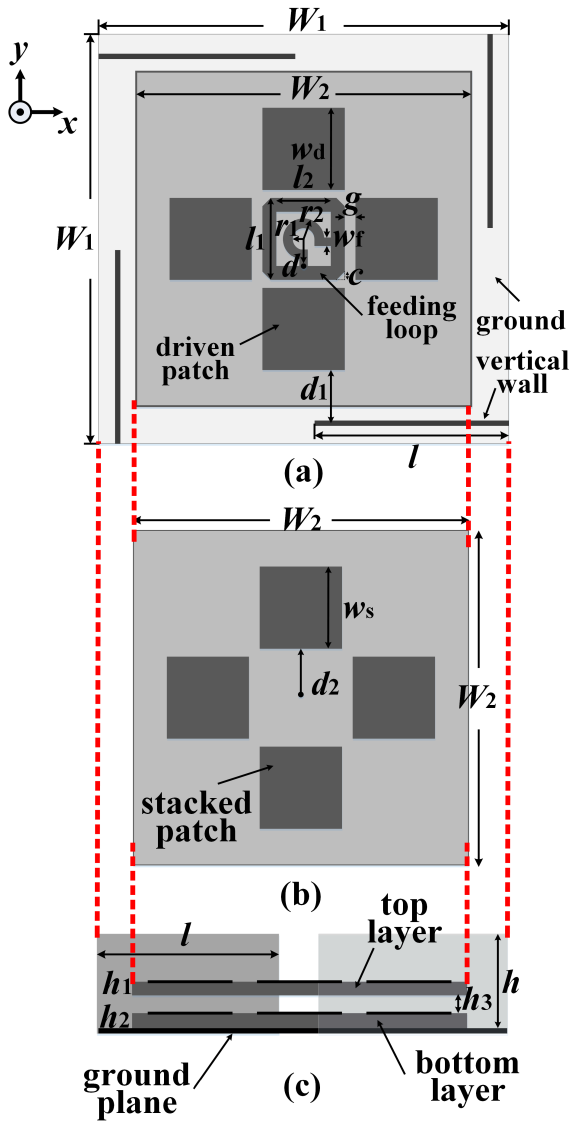

FIGURE 1. Configurations of the proposed antenna. (a) bottom layer. (b) top layer. (c) side view.

TABLE 1. Parameter of the stacked antenna (unit: mm).

symbol	value	symbol	value
l_1	12.9	l_2	9
r_1	1	r_2	3
d	4.5	d_1	0.65
d_2	6.5	g	0.4
c	1.5	w_d	12
w_s	12	l	18
h	6	h_1	1
h_2	2	h_3	2
W_1	44	W_2	38

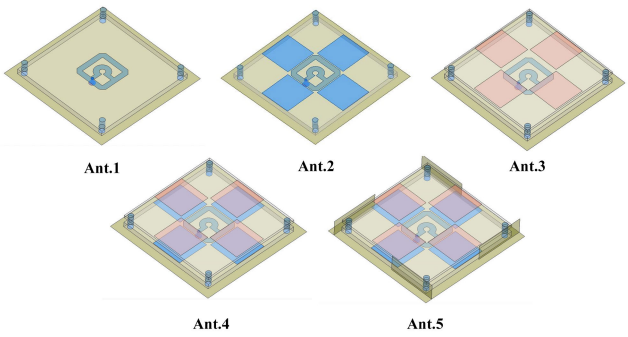

FIGURE 2. Various stages of evolution of the designed antenna.

B. EVOLUTION PROCESSES

To clarify the design procedure, five different prototypes in Fig. 2 are studied. Ant.1 is a traditional microstrip square ring antenna with arc-shaped delay line. The arc-shaped delay line inside of the square-ring radiator has a length of $\lambda_g/4$, so 90° phase difference for CP operation is achieved. Ant.2 is

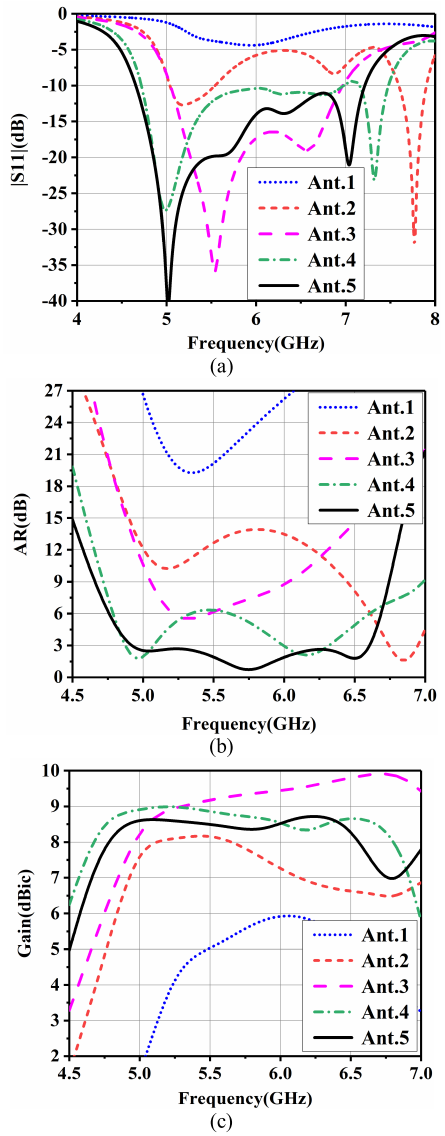

FIGURE 3. Simulated results of the designed antenna at different stages: (a) S-parameter, (b) AR, (c) Gain.

a loop antenna with surrounding driven patches. In Ant.3, four stacked patches are introduced to Ant.1. Ant.4 combined the surrounding driven patches and stacked patches together. Four vertical patches are applied in Ant.4 to form Ant.5. In order to provide a comprehensive comparison, simulated results of An.1 to Ant.5 are shown in Fig. 3. In general, the square ring antenna possesses a narrow impedance bandwidth due to the large input impedance. Hence, Ant. 1 owns only one resonance at 6.0 GHz and the impedance matching is poor, as shown in Fig. 3(a). To increase the impedance bandwidth, Ant.2 is loaded with four driven patches which are placed around the loop antenna. By the capacitive coupling between the loop and the driven patches, another two resonances and a new AR minimum point at 6.7 GHz are yielded due to the sequential phase provided by the loop antenna. However, the resonances are far from each other, and cannot be combined together to obtain wide bandwidth. Besides, the gains at the upper band decrease dramatically, and thus the 3-dB gain bandwidth is also narrow. In order to improve the antenna performance, only four stacked patches are introduced to Ant.1. For Ant.3, both the impedance matching and gain bandwidth are enhanced. The improved impedance bandwidth is due to the coupling between the stacked patch layer and driven patch layer. Besides, the stacked patch are arranged in a loop way to obtain loose coupling. And the two resonant frequencies at 5.5 and 6.6 GHz of Ant.3 is attributed to the driven patch and stacked patch respectively. Meanwhile, the AR value of Ant. 3 is also reduced when it is compared with Ant.1. However, it can be seen from the curve that Ant.3 cannot obtain wide CP bandwidth since it has only one minimum AR point. By combining the surrounding patches and stacked patches simultaneously, wide 10-dB impedance bandwidth from 4.75 GHz to 7.5 GHz is obtained for Ant.4.

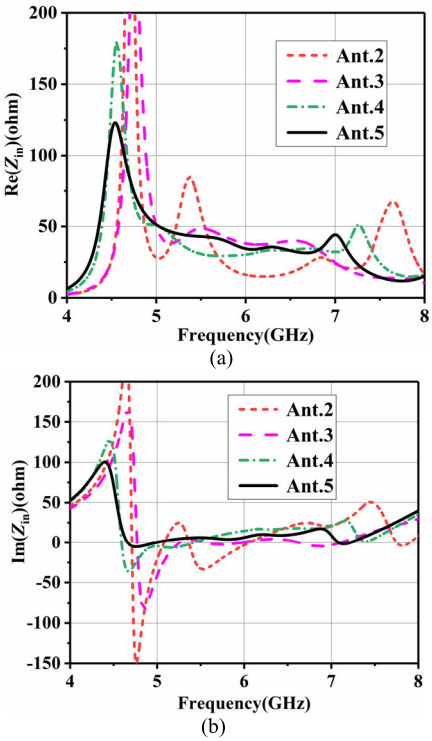

FIGURE 4. Input impedance of different antennas: (a) real part, (b) imaginary part.

Fig. 4 shows the simulated input impedance of different antennas. With the help of stacked patches, the real part of input impedance is closer to 50 Ω and the imaginary part also fluctuates around 0 Ω. The results shows the impedance matching is greatly improved. Furthermore, the gains at the upper band also increase and flat gain in the whole band is realized by introducing the stacked patches. However, the ARs are still high than 3 dB from 5.2 to 6.0 GHz which is because the two AR minimum are far away. To extend the CP bandwidth, four vertical patches are embedded on the

four corners of the ground plane. Finally, Ant.4 is evaluated into Ant.5. Actually, the vertical patches could be regarded as modified conducting walls which have proven to be a good way to increase bandwidth in [8] and [31]. The studied results in [8], [31] indicated that the radiation of cavity-based antenna consists of two parts, including original radiation and surrounding walls. When the primary radiator is excited, the walls are energized by the radiation coupling, and then the radiation aperture formed by the walls act as additional radiator. It has been pointed out in [8] and [31] that the additional radiator can improve the antenna's performances, which produce wider impedance and AR bandwidth when compared with those traditional reflector without vertical walls. In this design, the modified walls are introduced to generate a new AR minimum point at 5.75 GHz is introduced, leading to an extended CP bandwidth of 29.9% (4.90–6.62 GHz). It is worth mentioning that the AR bandwidth of Ant.4 is not the optimal result since the dimensions are directly copied from the optimized wideband design that has vertical patches. Furthermore, the impedance matching is also improved by the vertical patches.

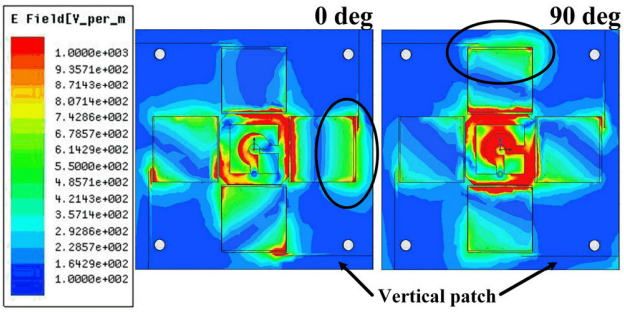

FIGURE 5. Simulated E-field distribution of the proposed antenna at 5.75 GHz.

The electric field distribution at 5.75 GHz is investigated in Fig. 5, and different distributions of E-field with different phases are observed. Furthermore, it can be seen that the currents concentrate on the feeding loop and surrounding coupled patches. At 0° phase, the maximum E-field focuses on the right part and strong field distribution is observed between the stacked patches and vertical patches. When it comes to the 90° phase, a strong E-field occurs at the top part. Comparing with the field distribution results, it can be deduced that vertical patches contribute to the generation of CP mode. To explain the working principle of this CP antenna, vector current distributions on the upper layer and lower layer were investigated. They are illustrated in Fig. 6 over a period corresponding to the frequency of 5.75 GHz. At the phase of 0°, the dominant current flows in the vertical direction, whereas at the phase of 90° the dominant currents flow in the horizontal direction. Besides, it is clear that a right-hand CP (RHCP) wave toward the $+z$-direction is generated.

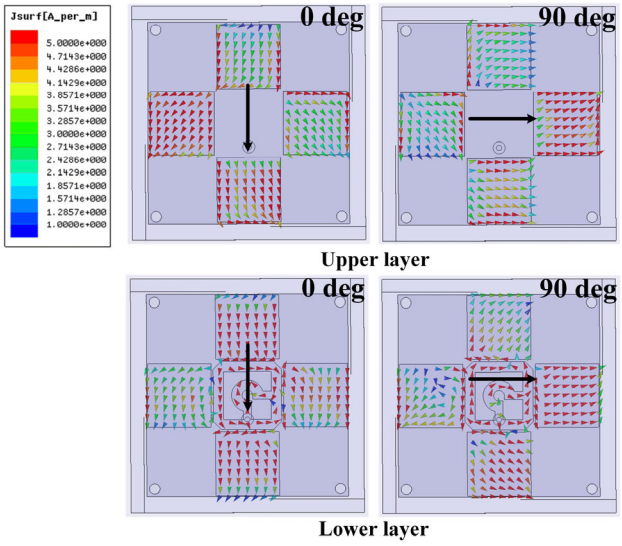

FIGURE 6. Vector current distributions of the stacked CP antenna at 5.75 GHz.

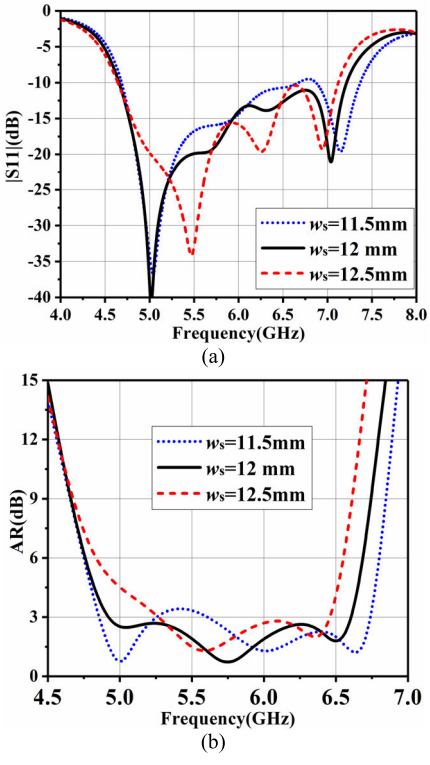

FIGURE 7. Effect of w_s on the performance of the proposed antenna: (a) S-parameter, (b) AR.

C. PARAMETRIC STUDIES

To verify the operating mechanism of the proposed stacked wideband CP patch antenna, a parametric analysis is discussed in this section. Fig. 7 shows the simulated $|S_{11}|$ and ARs with different w_s which is defined as the length of the stacked patch. From the figure, it could be observed

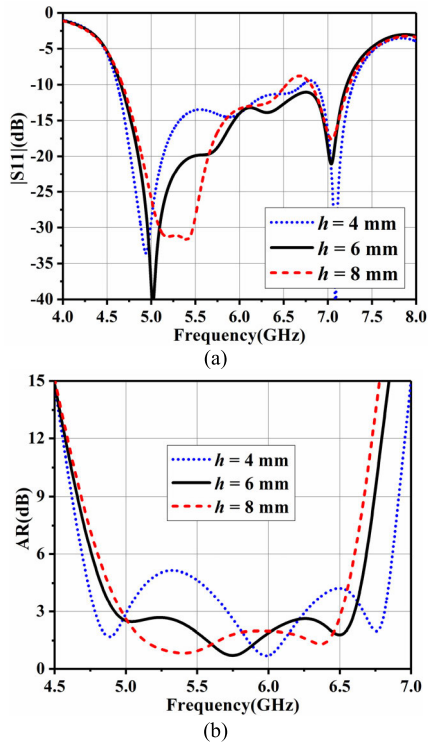

FIGURE 8. Effect of h on the performance of the proposed antenna: (a) S-parameter, (b) AR.

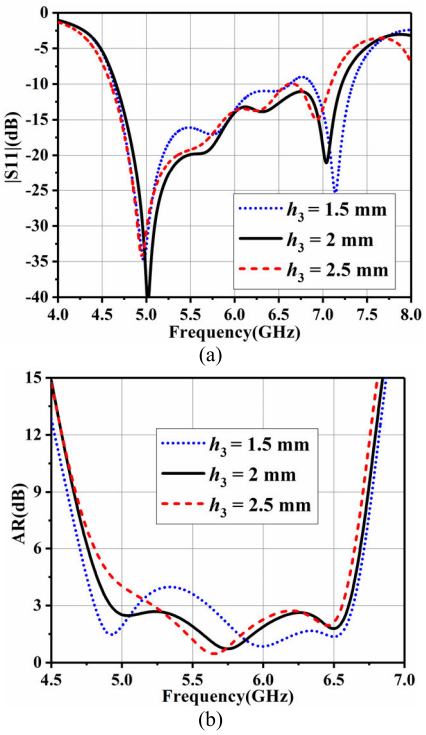

FIGURE 9. Effect of h_3 on the performance of the proposed antenna: (a) S-parameter, (b) AR.

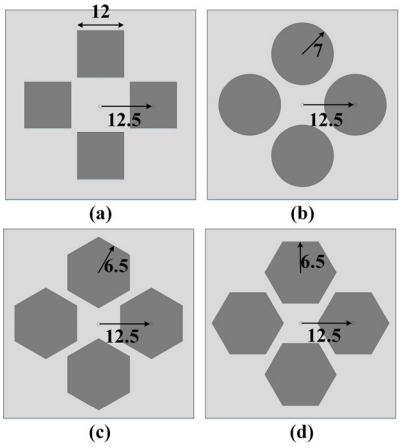

FIGURE 10. Stacked antennas with different shapes: (a) Square, (b) Circle, (c) Hexagon-1, (d) Hexagon-2.

that the $|S_{11}|$ has slight shifts at the upper band while it is greatly affected at the lower band with different w_s. A wide impedance bandwidth is achieved when w_s is selected as 12 mm. As w_s increases from 11.5 to 12.5 mm by a step size of 0.5 mm, the CP mode at the upper band shifts downward and the ARs at 5.0 GHz get worse. The results indicate that the CP performance at the higher band is affected by the stacked patches and w_s could be used as an important parameter to tune the value of AR at the lower band.

Fig. 8 depicts the simulated results under the different height of the vertical patch. As for $|S_{11}|$, obvious effect is seen at the lower band. With the decreases of h, the impedance matching at 5.5 GHz gets worse. In Fig. 8(b), the resonant frequency at the upper band shifts upward as h decrease from 8 to 4 mm. Meanwhile, the variation of h has a notable impact on the lower band ARs, which indicates the vertical patches contribute to the CP performance in the whole band. The influences of h_3 are also studied in Fig. 9. The results indicate that the $|S_{11}|$ is not sensitive to the variation of h_3. Moreover, the gap between the two substrates only affects the CP property at the lower band. The h_3 is changed from 1.5 to 2.5 mm, leading to great change at the lower frequency but little change at the upper frequency. Therefore, we could utilize the appropriate gap to optimize the ARs at the lower band.

Based on the parameter analysis, a design principle is summarized as follows:

1) First, design a loop antenna with four surrounding patches to cover the lower and upper band, respectively.

2) Second, place four stacked patches above the bottom layer to improve the impedance matching.

3) Third, add four vertical patches around the antenna to improve the CP performance at upper band.

4) Lastly, tune each parameter to optimize the design for optimal bandwidth.

D. COMPARISON OF DIFFERENT STACKED PATCHES

Four different stacked patches are studied for comparison. The stacked patch examples are shown in Fig. 10, where all the dimensions are in millimeter. The distance between the patch element and the center of the substrate slab is

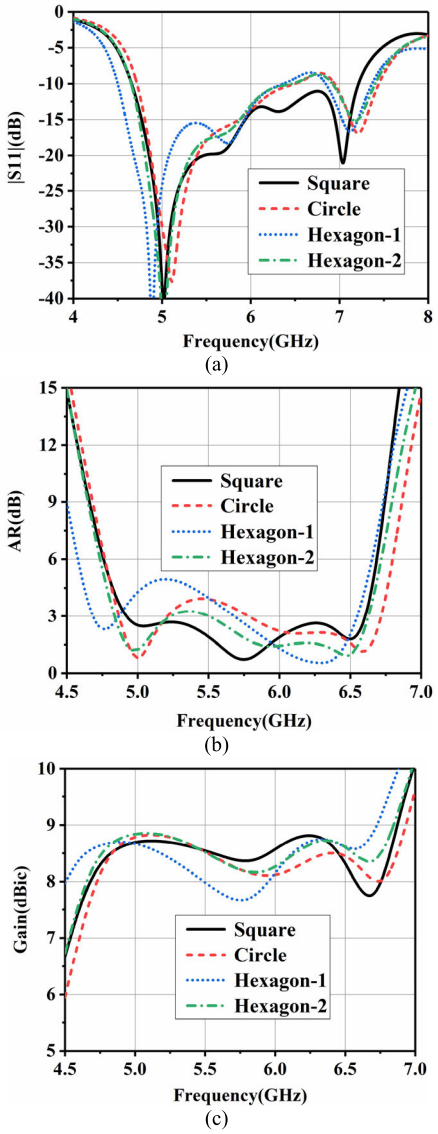

FIGURE 11. Simulated results of the designed antenna with different stacked patches: (a) S-parameter, (b) AR, (c) Gain.

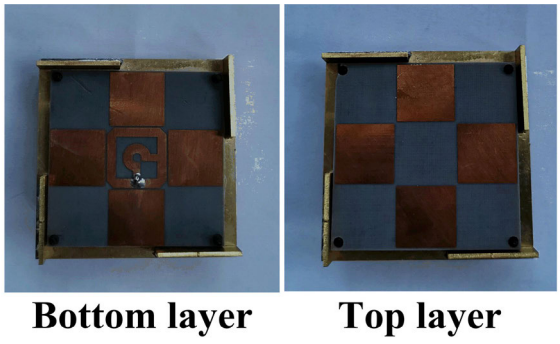

FIGURE 12. Photograph of the fabricated prototype.

fixed (12.5 mm) for all examples. The square-, circular, and two hexagonal stacked patches performances are compared in Fig. 11. The resonant frequency at upper band has small

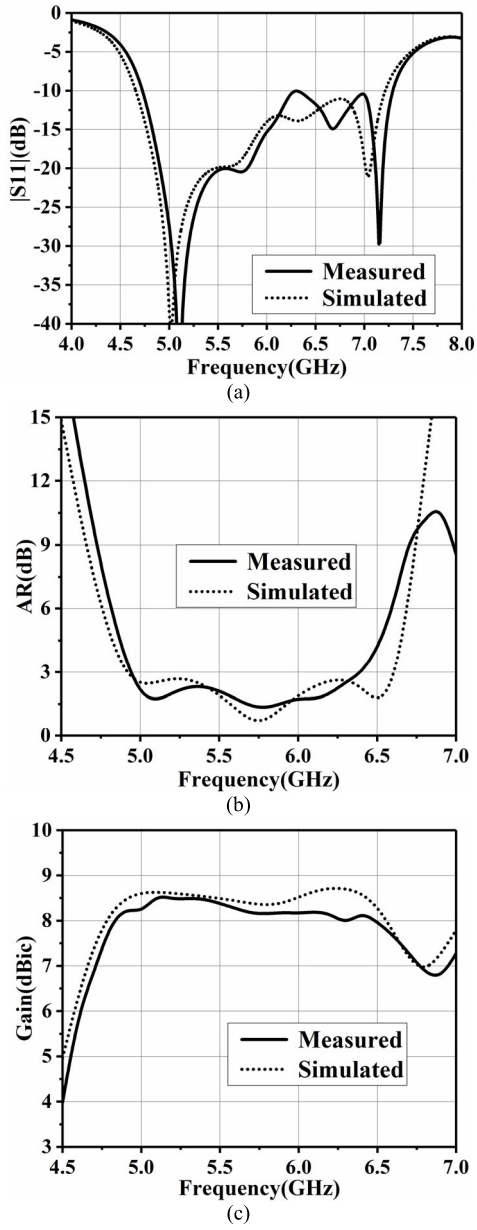

FIGURE 13. Simulated and measured results of the stacked antenna. (a) $|S_{11}|$. (b) AR. (c) Gain.

shifts with different shapes of stacked patches. The square patch shows the lowest resonant frequency at upper band. It is noted that the impedance match at high frequencies is poor for circular and hexagonal patches as the resonant frequencies are far apart from the other resonance points. The same phenomenon also occurs for AR and gain curves. The ARs in middle band are affected due to the shifting of minimum AR points. In addition, greater influences for hexagon-1 patches is observed because the hexagon-1 shaped patches with sharp corners lead to the coupled surface current with vertical patches flowing in a unsmooth path. In this paper, the square patches are chosen as stacked patches to obtain a wider bandwidth. The reason that the square patches are selected is mainly because straight edges could bring about

TABLE 2. Comparison of different cp stacked patch antennas.

Ref	Volume (λ_0^3)	Impedance bandwidth	AR bandwidth	1-dB gain bandwidth	Peak gain(dBic)
[20]	0.8 ×0.8 ×0.09	31.5%	20.7%	16.7%	8.6
[23]	1.5 ×1.5 ×0.058	20.8 %	17.6%	9.7%	11.5
[26]	2.4 ×2.4 ×0.102	20.2 %	18.9%	10.8%	13.8
[28]	1.0 ×1.0 ×0.068	25.7%	8%	8.3%	8.0
Our work	**0.88 ×0.88 ×0.12**	**43.2%**	**26.5%**	**32.6%**	**8.5**

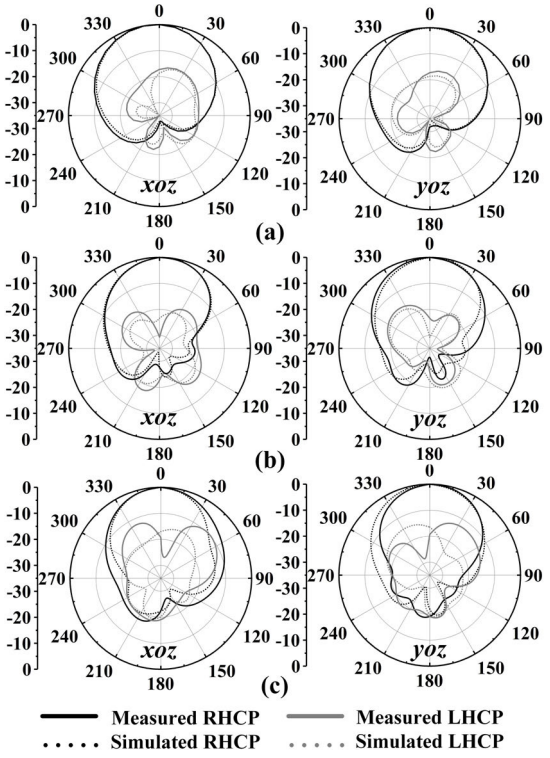

FIGURE 14. Measured and simulated radiation patterns in *xoz* and *yoz* planes at: (a) 5.0 GHz, (b) 5.75 GHz, (c) 6.2 GHz.

surface current flowing through smooth paths when they are coupled with the nearby vertical walls.

III. EXPERIMENTAL VERIFICATION

To verify the performance of our stacked antenna, the designed antenna is fabricated and measured. The antenna prototype is shown in Fig. 12, which is composed of two substrates. The comparison of simulated and measured results is illustrated in Fig. 13. It can be seen that the designed antenna is able to obtain a good impedance matching from 4.65 to 7.21 GHz (43.2%), which is in good agreement with the simulated results. The measured AR results are also compared with simulated results in Fig. 13(b). The 3-dB AR bandwidth is from 4.9 to 6.4 GHz, or a fractional bandwidth of 26.5%. Fig. 13(c) illustrates the measured gain at the broadside direction and its CP gain of 8.5 dBic is obtained at 5.2 GHz. Besides, the measured 1-dB gain bandwidth is around 32.6% (4.75-6.6 GHz). Flat gain with a variation of less than 1 dB is realized within the operating frequency. Fig. 14 shows the normalized radiation pattern in the *xoz* and *yoz*-planes at different frequencies. It is observed that the RHCP level is 18 dB stronger than the LHCP components at the broadside direction, which indicates a good RHCP antenna. Table 2 summarized the performances of our designed stacked CP antenna, where λ_0 is the wavelength at the center frequency of passband. The compared results with other similar stacked antennas in the literature is listed. It indicates that the designed stacked CP antenna has wider bandwidth including impedance, AR, and 1-dB gain bandwidth among the reported designs.

IV. CONCLUSION

In this paper, a stacked patch antenna with wide bandwidth and flat gains has been proposed. Moreover, four vertical patches are embedded on the ground plane to broaden the CP bandwidth. An antenna prototype is fabricated and measured. The measurement results indicate that the designed antenna can exhibit an impedance bandwidth of 43.2%, and a CP bandwidth of 26.5%. Besides, a flat gain is also obtained within the operating frequency.

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