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4×4 RHCP Array Antenna Base on LTCC and Quartz Interposer

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ABSTRACT: This paper designs, simulates, fabricates, and measures a right hand circular polarization (RHCP) array antenna, which is based on a low temperature co-fired ceramic (LTCC) and quartz interposer. The proposed array antenna consists of 4×4 antenna cells, and axis ratio of the antenna element in array antenna can be optimized after array expansion. This RHCP antenna's wide frequency band and good axial ratio band are obtained by the stacked patches. The thickness of the proposed antenna without fixed structure is about 1.7 mm, and it is realized by a LTCC substrate with 14 layers and a quartz interposer with the thickness of 0.254 mm. The measured results demonstrate that for the operated frequency band of 17.5 GHz $\sim$ 21.5 GHz, the VSWR of the proposed antenna is better than 1.7, the RHCP gain more than 15.5 dB, the axial ratio less than 3 dB, and the size of the proposed antenna without connectors is 29.6 mm $\times$ 29.6 mm $\times$ 1.7 mm.

1. INTRODUCTION

Recently, phased array antenna that exhibits low profile and widely frequency band is a research hotspot [1, 2]. Especially for wideband satellite communication system, K-band satellite communication band as 17.7 GHz $\sim$ 21.2 GHz for the earth receiving band has been allocated by the International Telecommunication Union (ITU), Federal Communications Commission (FCC), and European Telecommunication Standard Institute (ETSI) [3–5]. Meanwhile, the polarization mode of the antenna is right hand circular polarization [6].

Compared with traditional microstrip patch antenna, the antenna using stacked patches has an advantage, which exhibits wide frequency band [7]. Usually, stacked patches are printed on a multilayer printed circuit board (PCB) [8], whose loss has a direct influence on the gain of the antenna. Therefore, the multilayer PCB with a low loss tangent angle, typically, such as Panasonic Megtron 6 [9, 10] and Rogers RT 6002 substrates [11], is as the antenna substrate.

In order to enhance the frequency band while reducing the thickness of the antenna, Cheng et al. [12] and Sayeed Sajal and Latif [13] have both proposed stacked patches with a foam as the middle layer. However, there are some existing problems with the antenna. For example, the antenna is affected by vibration and other severe environments. Hossain et al. [20] provided a solution of a stacked antenna with air gap and fixed with bolt. However, the antenna pattern is easily affected by bolts. Ref. [22] has proposed a circularly polarized antenna with stacked patches, which are fixed together with plastic screws. However, there is also a problem of low reliability.

To solve the above problems, Li et al. [14] designed a compact stacked patch antenna in LTCC multilayer packaging modules. Compared with multilayer PCB, LTCC is becoming more and more popular for high frequency antenna, because it has some advantages of the processing technology, such as multilayer substrate with buried/blind via and blind cavity. Alsuwayyeh et al. [15] designed a Ka-band aperture-coupled microstrip patch antenna based on LTCC technology, and the antenna provided an impedance bandwidth of 4.2% with an axial ratio better than 3 dB. Li et al. [16] presented a bandwidth-enhanced antenna using an inkjet-printed multilayer microstrip fractal patch, and SU-8 dielectric is utilized to fabricate the spacer to decrease the antenna's feed loss.

In this paper, a novel stacked patch antenna is proposed. In this antenna, a quartz interposer with a relatively lower loss is as the top patch's substrate, and the LTCC with a cavity and some blind vias is as the bottom patch's substrate. The air gap between the top patch and bottom patch does not affect the antenna's gain. The proposed antenna has been simulated, analyzed, fabricated, and measured. The measurement results demonstrate that, from 17.5 GHz $\sim$ 21.5 GHz, the antenna has excellent performance.

This proposed antenna can meet the needs of the high frequency array antenna with broadband, circular polarization, and lower profile, and can also be as a packaging substrate for dies.

2. DESIGN OF THE PROPOSED RHCP STACKED ARRAY ANTENNA

2.1. Structure of Single Stacked Antenna Element

The proposed stacked antenna element structure is as illustrate in Fig. 1. The antenna is designed by Ferro-A6 LTCC (the dielectric permittivity ε_r of a substrate is 5.9) with 14 layers and quartz with a thickness of 0.254 mm (the dielectric permittivity ε_r of a substrate is 3.78).

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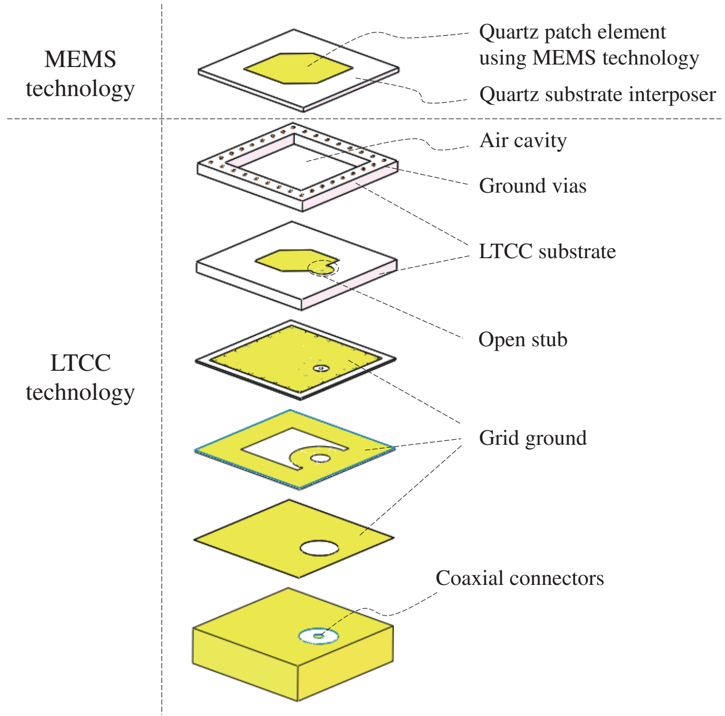

FIGURE 1. Structure of the proposed RHCP antenna element.

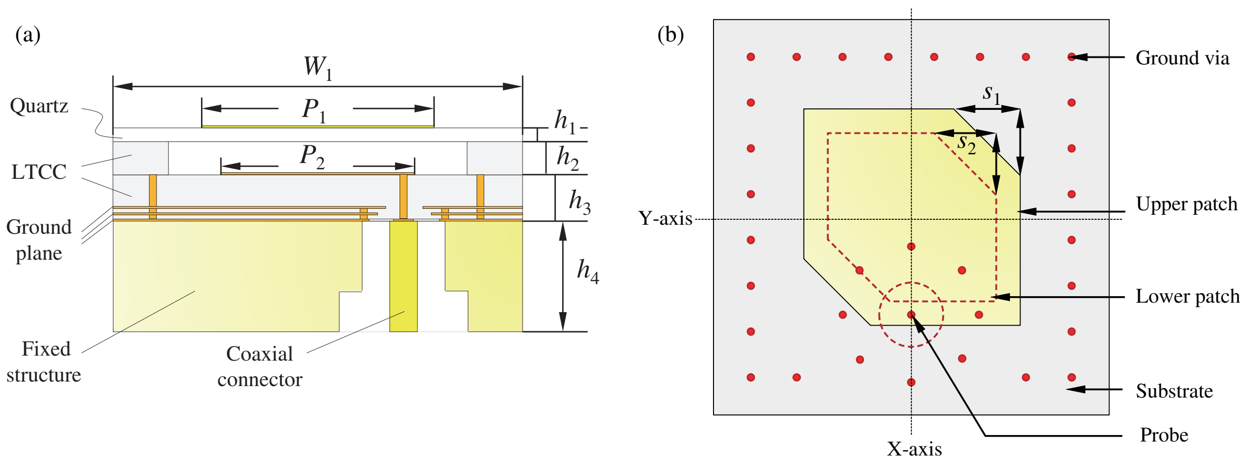

FIGURE 2. Geometry of the proposed stacked-patch, wideband, circularly polarized antenna element.

The proposed antenna uses stacked patches with a rectangular chamfered structure, whose lower patch is fed by a coaxial cable vertically. The upper patch is fed by electromagnetic coupling from the bottom patch.

The upper patch element is located at the quartz substrate with loss tangent and is fabricated by Micro-Electro-Mechanical System (MEMS) surface micro-processing technology. The lower patch element is formed by LTCC technology. The lower patch is loaded with an open stub to tune the VSWR of the antenna. An air cavity is between the quartz substrate and the lower patch, to decrease the lower patch's radiation loss. Three layers of different grid grounds are as the antenna's ground plane, used to prevent the leak of the patches' electromagnetic power. The antenna feeding is realized by a coaxial transmission line.

As illustrate in Fig. 2, the structures of the upper patch and lower patch are both using corner cut rectangular blank, to form circular polarization. The parameters of P_1, P_2, s_1, and s_2 represent the sizes of the upper patch and lower patch, and the parameters of h_1, h_2, h_3, and h_4 represent the thicknesses of the quartz substrate, air cavity, LTCC substrate, and the fixed structure. The parameter of W represents the distance between adjacent antenna elements. The values of above parameters are as shown in Table 1.

Using electromagnetic (EM) software, the simulated EM performances include voltage standing wave ratio (VSWR), axial ratio, and gain of the proposed single antenna, as shown

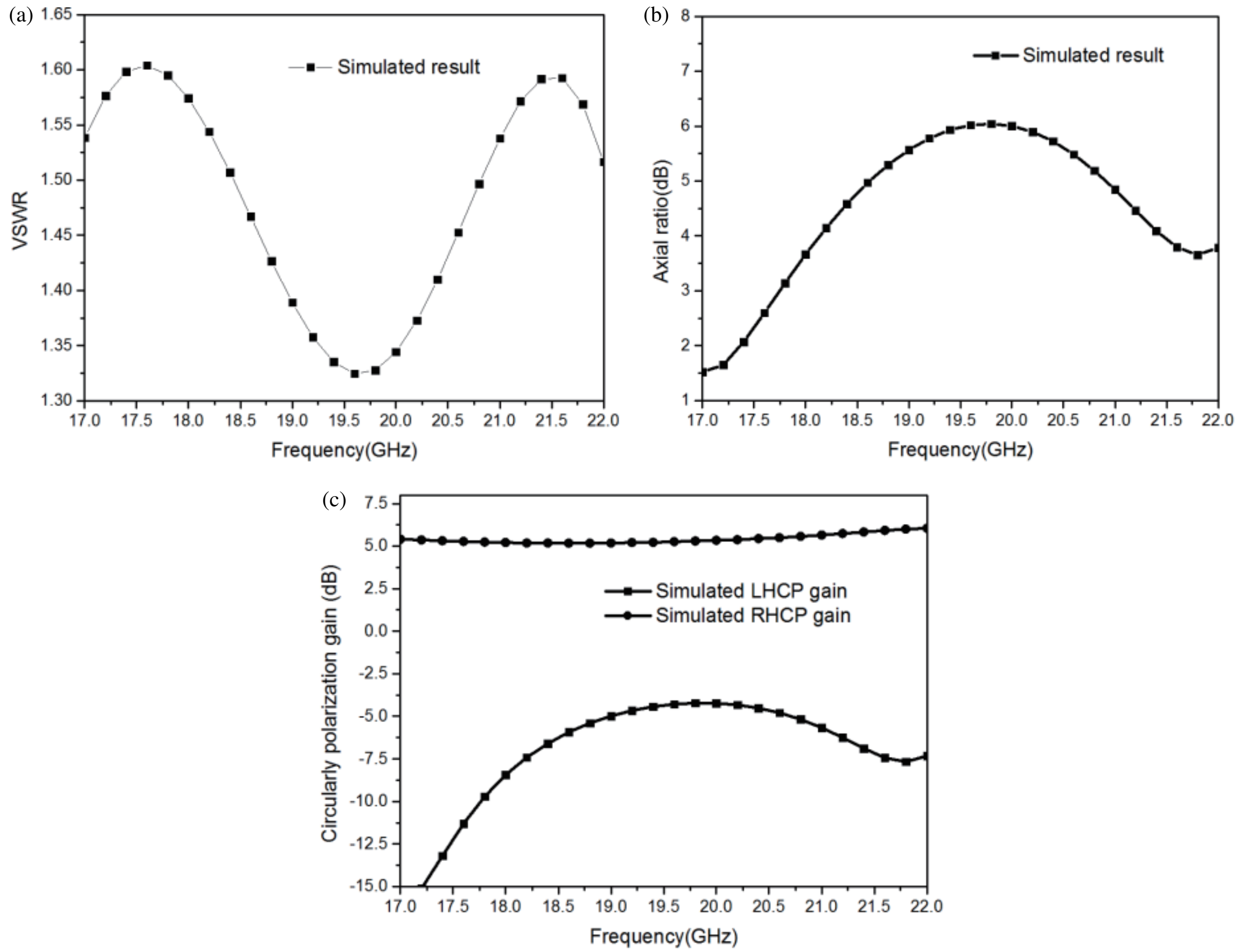

FIGURE 3. Simulated EM results of the proposed antenna element.

TABLE 1. The values of the antenna's parameters.

Parameter	value	Parameter	value
P_1	3.95 mm	h_1	0.254 mm
P_2	3 mm	h_2	0.4 mm
s_1	1.375 mm	h_3	1.4 mm
s_2	1.3 mm	h_4	2 mm

Figs. 3(a), (b), and (c). The simulated results of the proposed antenna show that, from 17 GHz to 22 GHz, the VSWR is better than 1.6, axial ratio better than 6 dB, and RHCP gain better than 5 dB.

Using EM software, the 2×2 units antenna model is established as illustrate in Fig. 4. The distance between the antenna units is approximately half of a wavelength λ. Simulated EM performances include VSWR, axial ratio, and gain of the proposed single antenna, as shown Figs. 5(a), (b), and (c). The simulated results of the proposed antenna show that, from 17 GHz to 22 GHz, the VSWR is better than 1.75, and the axial ratio is better than 4 dB. The RHCP gain is better than 9 dB. Comparing Fig. 3 and Fig. 5, it can be seen that, due to electromagnetic coupling of antenna units, the VSWR is deteriorated, but the axial ratio is improved.

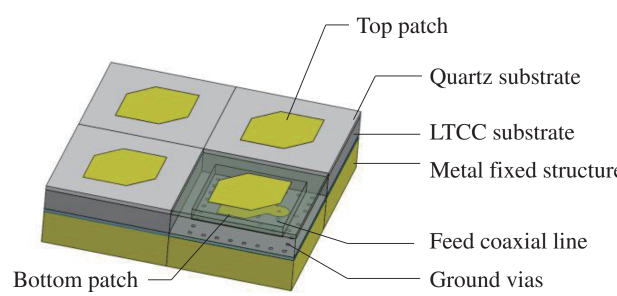

FIGURE 4. The simulated model of the proposed antenna with 2×2 elements.

2.2. Design of RHCP Array Antenna

The structure of the proposed array antenna is as illustrate in Fig. 6 and Fig. 7. The proposed RHCP stacked array antenna consists of a layer of quartz patch, layer of cavity of LTCC, layer of LTCC patch, layer of 1st grid ground, layer of 2nd grid ground, layer of 3rd grid ground array, and layer of connectors. The total LTCC layer of this proposed array antenna is 14. The thickness of the quartz is 0.254 mm, and the form of radio frequency (RF) connectors is SubMiniature version P (SMP) connector.

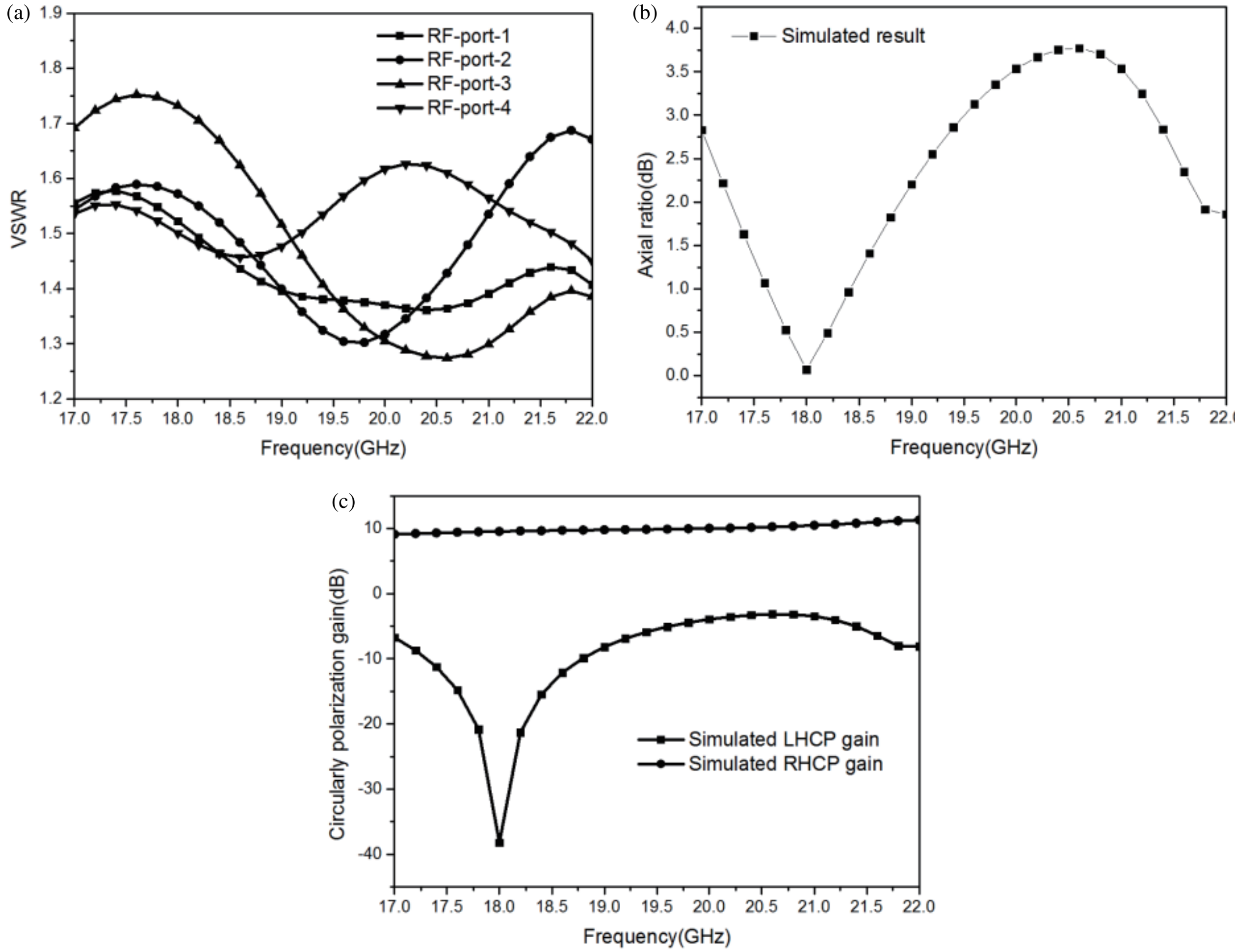

FIGURE 5. Simulated EM results of the proposed antenna 2 by 2 element.

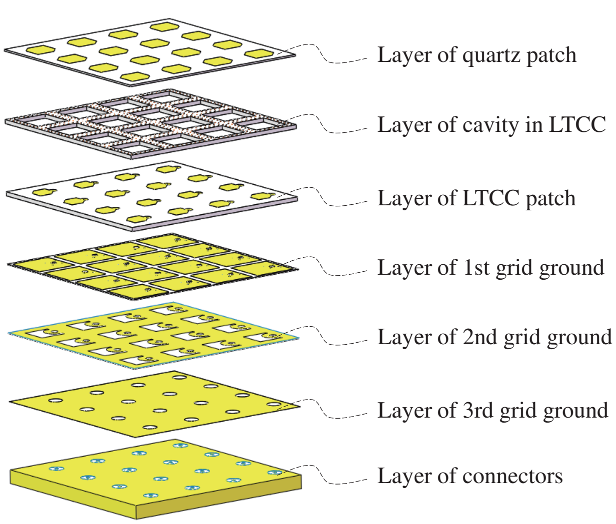

FIGURE 6. Each functional layer of the proposed array antenna.

The beamwidth θ_{BW} is given by formula (1)

$$\theta_{BW} = \frac{k\lambda}{Md\cos\theta_0} \times \frac{360}{2\pi} = \frac{k\lambda}{L\cos\theta_0} \times \frac{360}{2\pi} \qquad (1)$$

where $L = Md$ and is the length of the antenna. Equation (1) is valid for $\theta_0 = 0$ which is the typical equation used to estimate antenna's beamwidth. In Equation (1), the parameter of k is the beamwidth factor and varies depending on the aperture distribution, and $k = 0.886$ for the 3 dB beamwidth of a uniformly illuminated array antenna. Theoretically, according to formula (1), the 3 dB beamwidth of this antenna is 29.40°, 26.38°, and 23.93° at 17.5 GHz, 19.5 GHz, and 21.5 GHz, respectively, and the simulated result is 29.48°, 26.36°, and 23.67° , respectively.

The 4×4 stacked array antenna is modeled and simulated by simulation software. The simulation results of gain, axial ratio, and VSWR are as illustrate in Fig. 8. For the frequency of 17.5 to 21.5 GHz, the gain of the proposed antenna is more than 15.4 dB, the axial ratio better than 3 dB, and the VSWR better than 1.9 dB.

3. FABRICATION

The fabricated RHCP array antenna is as shown in Fig. 9. The stacked array antenna is fabricated by a quartz interposer and Ferro A6, and the quartz interposer is bonded with the LTCC by an insulating adhesive. Fig. 7(a) shows a photo of the fabricated antenna.

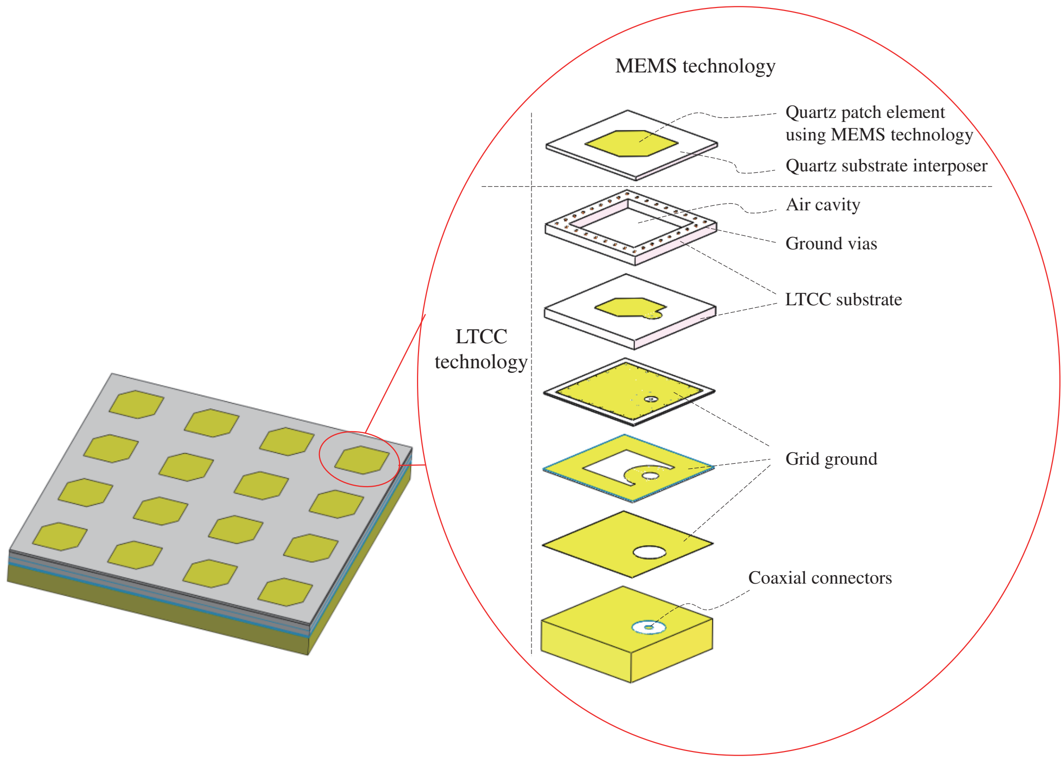

FIGURE 7. Structure of the proposed 4×4 array antenna.

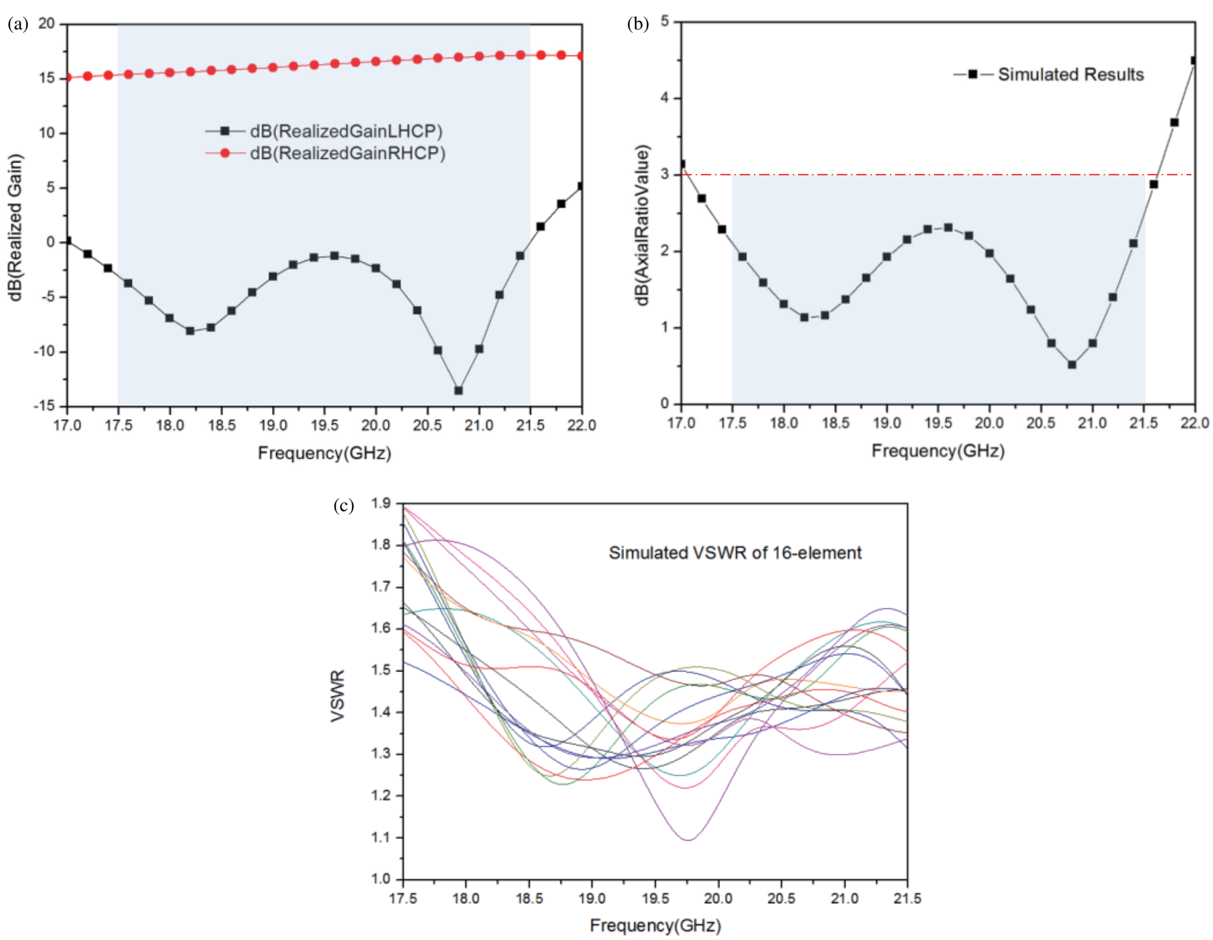

FIGURE 8. Simulated results of the proposed array antenna.

TABLE 2. Comparison of this work with other circularly polarized antennas.

Type	Frequency (GHz)	3 dB-AR & 10-dB bandwidth	Gain (dB)	VSWR	Size (mm^3) ($\lambda_0 \times \lambda_0 \times \lambda_0$ @ antenna array element
LTCC, 2×2 [10]	31–39	26%	> 9	< 1.5	$15.3 \times 28.3 \times 1.3$ ($1.78 \times 3.3 \times 0.15$)
LTCC, 4×4 [11]	$60.2 \sim 67$	2.67%	> 11	< 4	$15.4 \times 15.4 \times 2.02$ ($3.28 \times 3.28 \times 0.04$)
LTCC, 4×4 [9]	$52.5 \sim 65.5$	5.5%	> 11	< 2	$12 \times 10 \times 2$ ($2.36 \times 1.96 \times 0.39$)
RO3003, 4×4 [17]	$22 \sim 27.5$	22.2%	> 11	< 2	$> 24 \times 24 \times 1.143$ ($2 \times 2 \times 0.09$)
FR-4 , single element [12]	1.87–2.03	8.2%	7	> 7	$> 80 \times 80 \times 10$ ($0.52 \times 0.52 \times 0.07$)
Rogers RT/duroid 6002, 4×4 [19]	$23.22 \sim 24.37$	4.8% (sim)	17.19@max (sim)	< 1.5 (sim)	$> 24 \times 24 \times 1.52$ ($1.9 \times 1.9 \times 0.12$)
Rogers RT/duroid 6010, single element [20]	7.02–8.18	15.3% (sim)	7.9 (sim)	< 2 (sim)	$17 \times 17 \times 6.6$ ($0.43 \times 0.43 \times 0.17$)
FR4, single element [21]	1.259–1.276	1.6%	2.15	< 1.7	$> 80 \times 80 \times 4$ ($0.338 \times 0.338 \times 0.016$)
FR4 single element [22]	2.4–2.485	7% (sim)	7 (sim)	< 2 (sim)	$96 \times 96 \times 39$ ($0.78 \times 0.78 \times 0.128$)
FR4, single element [23]	5.49–6.73	20.7%	> 7.9	< 1.4	$40 \times 40 \times 4.5$ ($0.8 \times 0.8 \times 0.09$)
This work, 4×4	$17.5 \sim 21.5$	< 3 (20.5%)	> 15.2	< 1.86	$29.6 \times 29.6 \times 1.7$ ($1.9 \times 1.9 \times 0.11$)

*AR = Axial Ratio, NA = Not Available

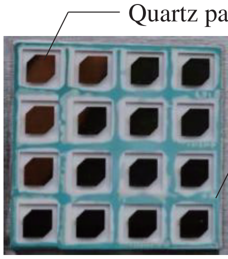

FIGURE 9. The fabricated stacked array antenna.

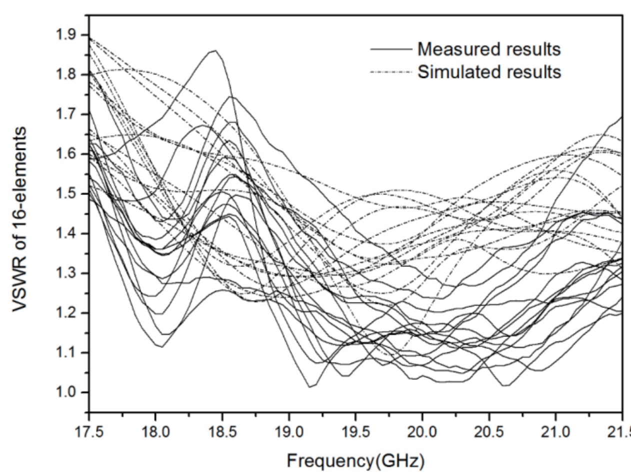

FIGURE 10. Simulated and measured results of VSWR of the proposed antenna.

4. MEASUREMENT AND ANALYSIS

Figure 10 demonstrates the comparison of the measured and simulated VSWR results of the proposed array antenna. Fig. 10 shows that, from 17.5 GHz to 21.5 GHz, the measured VSWR result is better than 1.86 and the simulated one better than 1.9. The difference between of the measured and simulated results is caused by the assembly errors of the SMP connector.

The pattern results of xoz-plane of this antenna are measured at 17.5 GHz, 19.5 GHz, and 21.5 GHz, respectively. The power combining of the array antenna with 16 RF ports is realized by 16 : 1 combiner. The comparison of the measured and simulation results is demonstrated in Fig. 11. For the frequency of 17.5 GHz, the measured gain of the antenna is about 15.8 dBi at theta 0°. For the frequency of 19.5 GHz and 21.5 GHz at theta 0°, the measured gain is about 16.6 dBi and 16.0 dBi, respectively. Correspondingly, the simulated results of these three frequencies are 15.4 dBi, 16.3 dBi, and 17.1 dBi, respectively. At 21.5 GHz of the proposed antenna, the difference between simulation and measurement is mainly caused by the test combiner with phase imbalance. At 17.5 GHz and 19.5 GHz, the

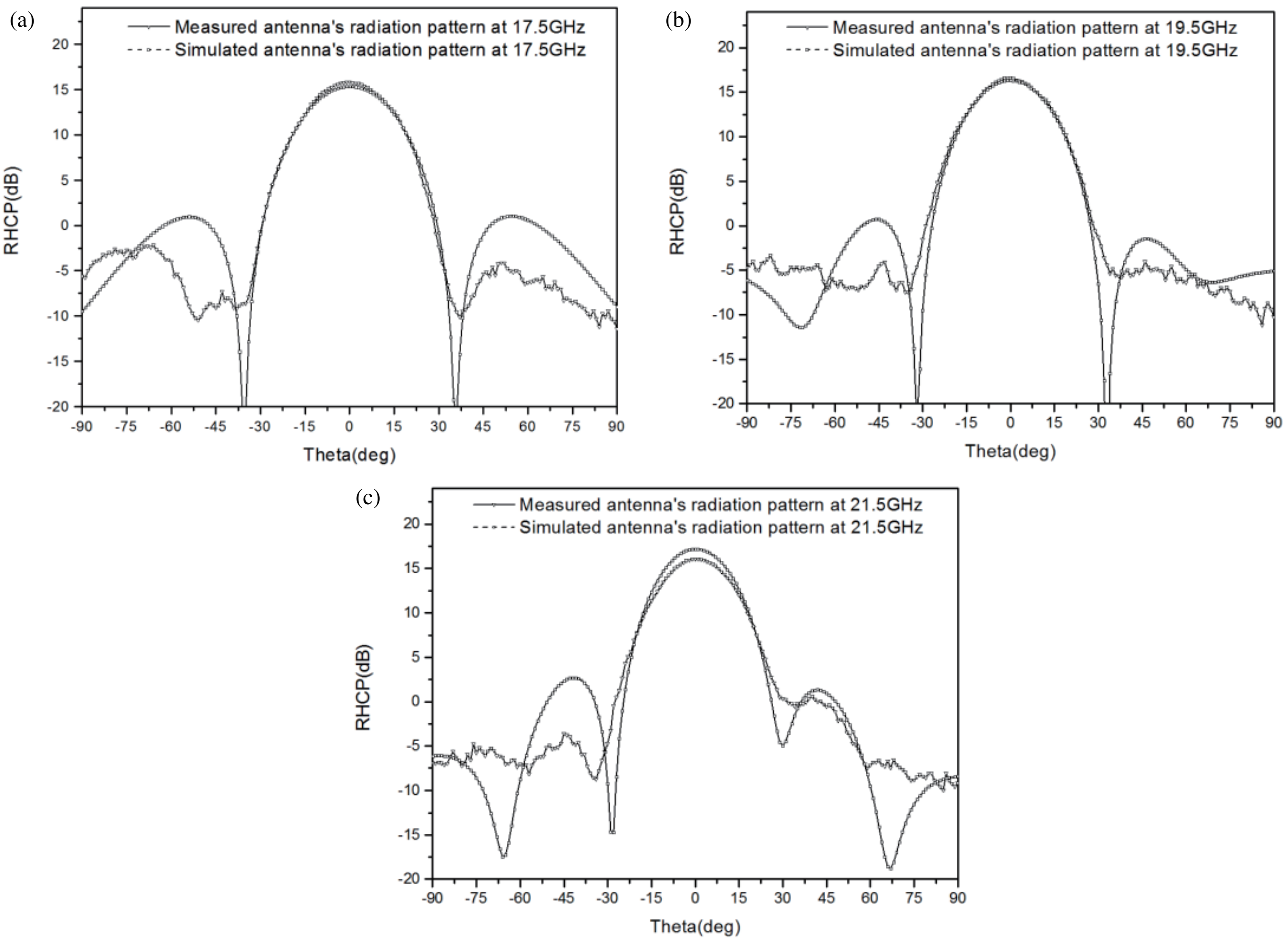

FIGURE 11. Radiation pattern of *xoz*plane of the proposed antenna (a) at 17.5 GHz (b) at 19.5 GHz (c) at 21.5 GHz.

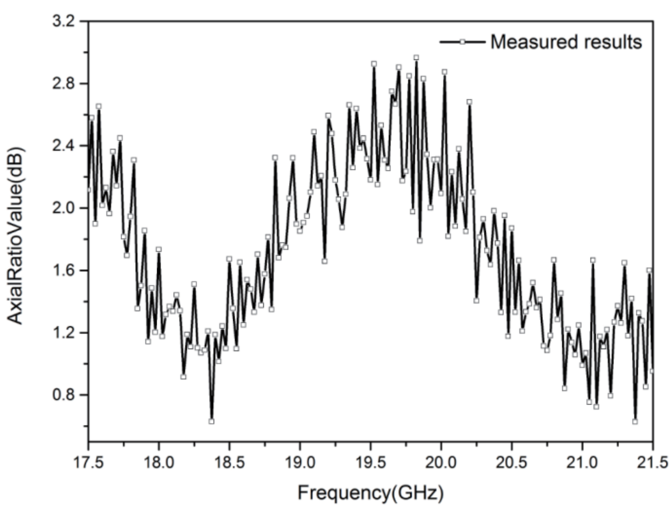

FIGURE 12. Measured axial ratio results of the proposed array antenna.

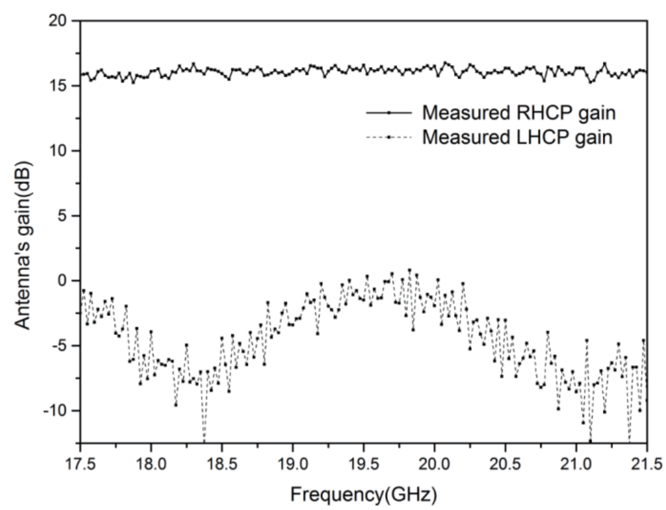

FIGURE 13. Measured gain of the proposed array antenna.

measured results of the antenna match well with the simulated ones.

As illustrated in Fig. 12, the measured axial ratio of this proposed array antenna from 17.5 GHz to 21.5 GHz is demonstrated, and the measured results are better than 3 dB. The measured RHCP and LHCP gains of the proposed array antenna are as shown in Fig. 13.

Compared with other circularly polarized antenna in Table 2, this proposed antenna with the size of the same electrical length has a higher gain and better axial ratio bandwidth.

5. CONCLUSION

Recently, low-profile antenna is a research highlight. For wide angle scan array antenna, the distance between the antenna elements is half of a wavelength of the operated frequency, and the degradation of the circularly polarization purity is caused by the mutual coupling effect in the array antenna. To enhance the circular polarization purity, the circular polarization (CP) antenna pattern is obtained by the antenna elements with a unit cell of every four elements, sequentially counterclockwise by 90 deg. The antenna is verified by actual measurement, and good agreement is achieved between the simulation and measurement. This design of an RHCP array antenna gives a solution for the electrical scan antenna used for satellite communication.

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