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K-Band 4 × 4 RHCP Helical Antenna Array Using LTCC Technology

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Abstract—In this paper, a K-band right hand circularly polarized (RHCP) antenna array with 4×4 elements is designed, fabricated, measured, and analyzed. The RHCP pattern is obtained from the helical antenna elements, with a unit cell of every four elements, sequentially counterclockwise by 90 deg. To decrease the profile of the vertical interconnection between the helical antenna and its feeding network, the integration of this RHCP antenna and its feeding network is realized by low temperature co-fired ceramic (LTCC) technology. The antenna's feeding network consists of eight directional couplers, four circulators, and one power divider. In the feeding network, different RF channels' isolations are improved by the shield structures which are realized by metal filled via holes. For the operating frequency, the measured axial ratio (AR) is better than 1.25 dB. The proposed antenna is small in size, and it is a very good candidate for mobile satellite communications.

1. INTRODUCTION

Recently, low profile circularly polarized (CP) antenna is a research hotspot [1–3]. LTCC has some advantages of multilayer printing and blind holes, to be used in packaging form for the compact integration of high frequency with a small size package [4]. Antenna in package (AIP) based on LTCC technology has been studied by many researchers [4–6].

Many CP antennas based on LTCC technology have been reported. Qian and Tang [7] have designed a compact LTCC CP antenna using stacked-patch configuration, and the 3 dB AR bandwidth is 1.1%. Lai et al. [8] have designed a CP dielectric resonator antenna with 3 dB AR bandwidth of 4%. In order to enhance the AR bandwidth, Huang [9] has proposed a technique using sequential rotation method for an antenna array to generate circular polarization. Chen et al. [10] have proposed a four-element circularly polarized microstrip antenna array using sequentially rotated series-parallel stub technique, resulting in a good AR of polarization, and the AR bandwidth is more than 5.3%. Huang and Wu [11] have designed a 4×4 Ka-band LTCC CP microstrip antenna array with a laminated waveguide feeding network, and the sequential rotation of array elements is used for increasing the AR bandwidth. Bisharat et al. [12] have proposed a CP 4×4 antenna array based on LTCC, and a sequential rotation feeding scheme is used to enhance the AR bandwidth. Sun et al. [13] have reported an LTCC CP which employs a strip line sequential rotation feeding scheme to improve the AR property. However, when the feeding network works at a relatively wide range of frequencies in [10–13], the phase dispersion is serious, and the feeding power's compatibility of different antenna elements is bad.

For mobile satellite communication system in China, K-band ($19.6 \sim 21.2$ GHz) RHCP is as the receive antenna [14–16]. Helical antenna has been widely applied in satellite communication, because of its good CP property [17]. Traditional helical antenna usually employs conductor with a bending structure [18]. This design form has some disadvantages, such as difficult fabrication for high frequency (such as K band) application.

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This paper designs a 4×4 LTCC RHCP helical antenna with a measured 1.5 dB-AR bandwidth of more than 7.8%, which uses sequential rotation method to enhance AR bandwidth. To obtain a good performance of feeding phases and feeding powers, the feeding network is composed of a directional coupler, a circulator, and a power divider. The feeding network and external test equipment are interconnected by an SSMP connector. This designed antenna is fabricated, measured, and analyzed. The measured results indicate that the frequency response of the proposed antenna in operated frequency is good.

2. DESIGN OF THE PROPOSED RHCP HELICAL ANTENNA ARRAY

2.1. Structure of the Helical Antenna Array

The antenna is designed by Ferro A6 LTCC (the dielectric permittivity ε_r of a substrate is 5.9) with 11 layers, whose structure is as illustrate in Fig. 1. The geometrical configuration of this proposed helix

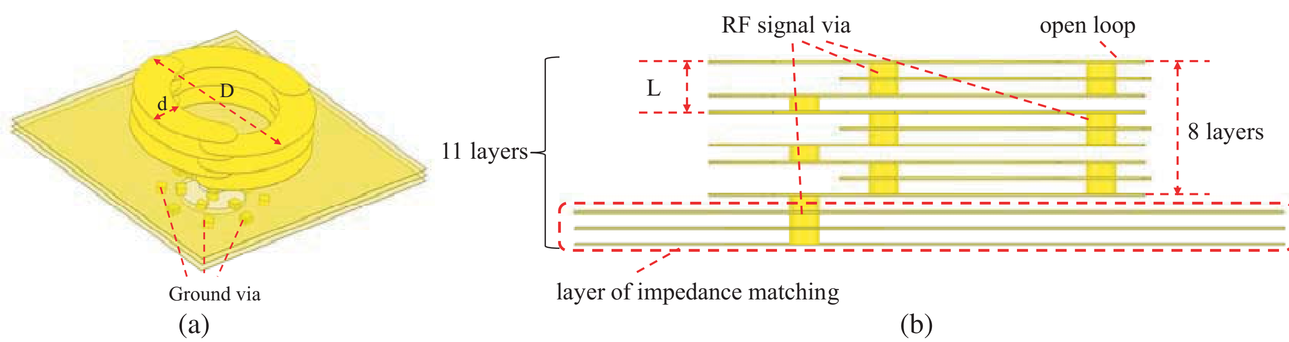


Figure 1. Structure of the proposed antenna element.

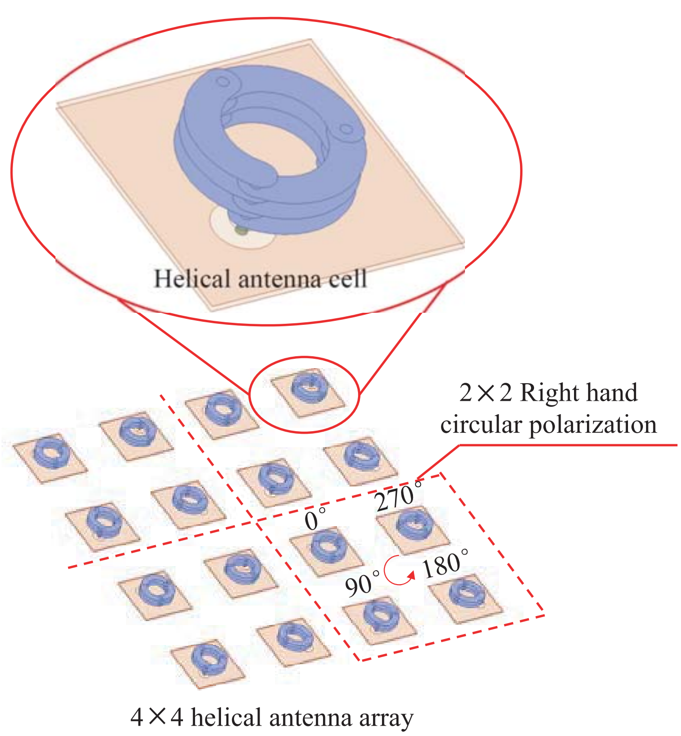


Figure 2. Structure of the proposed 4×4 antenna array.

consists of 3 turns, with diameter D and spacing L between neighboring turns. 1/3 helix is placed in the same layer. Parameters D and L represent the diameter of the helix and the spacing between neighboring turns, and their values are 2.5 mm and 0.3 mm, respectively. The circumference of the helix is about a wavelength of the center frequency. A helical line's width is 0.5 mm, and the diameter of a hole is 0.17 mm. The VSWR performance of this helical antenna is improved by the layer of impedance matching.

As illustrated in Fig. 2, the RHCP helical antenna array is obtained by helical antenna elements, with a unit cell of every four elements, sequentially counterclockwise by 90 deg. The distance between neighboring antenna units is approximately half of a wavelength λ. The beamwidth θ_{BW} is given by Equation (1)

$$\theta_{BW} = \frac{\lambda}{Md\cos\theta_0} = \frac{\lambda}{L\cos\theta_0} \tag{1}$$

where parameters M, d, and θ_0 are the number of linear array elements, the distance between adjacent antenna elements, and the beam direction angle, respectively. From Equation (1), the calculated values of 3 dB beamwidth are 26.3°, 25.2°, and 24.3° at 19.6, 20.4, and 21.2 GHz, respectively. The simulated results using FEM software are 26.08°, 24.72°, and 24.46°, respectively.

The 4×4 helical antenna is modeled and simulated by HFSS. The simulation results of gain, AR, and VSWR are illustrate in Figs. 3(a)–(c). For 19.6 $\sim$ 21.2 GHz, the gain of the proposed antenna is

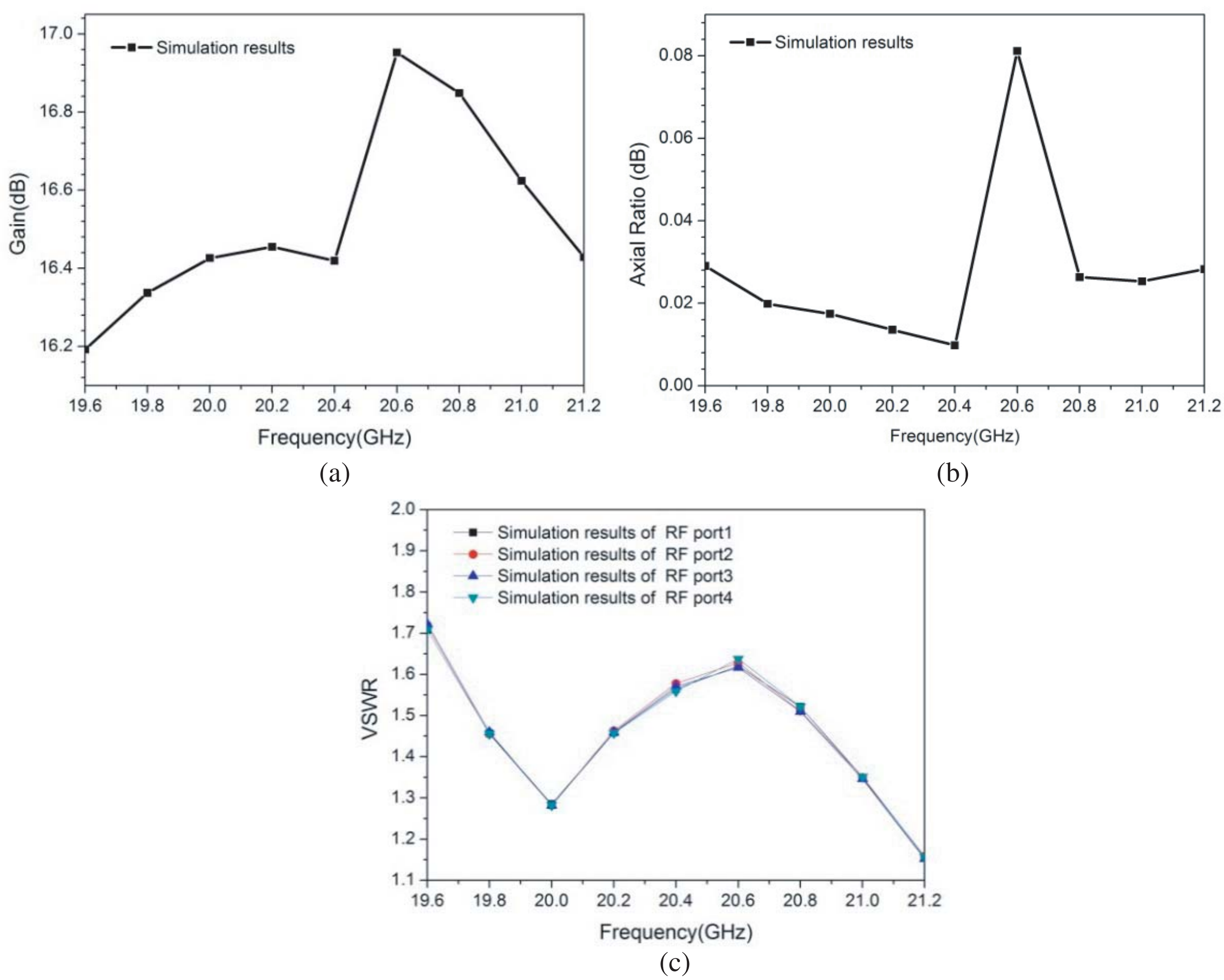


Figure 3. Simulation results of the proposed antenna array.

more than 16.2 dB, and the simulated gain of an active antenna cell is more than 4.2 dB. The AR's result is less than 0.1 dB, and the VSWR is better than 1.75 dB.

2.2. Design of the Proposed Antenna's Feeding Network

This section describes the structure of the antenna's feeding network. As shown in Fig. 4, a feeding network cell of RHCP helical antenna array consists of a circulator, directional couplers, and shield via holes. The feeding network unit is obtained by LTCC with 6 layers. The feeding network element includes five RF ports and three 50 Ω-loads. The feeding network consists of four feeding network elements, which are interconnected by a Wilkinson power divider. The circumference of the circulator is two thirds of a wavelength of the center frequency. The feeding network is optimized to achieve a good return loss.

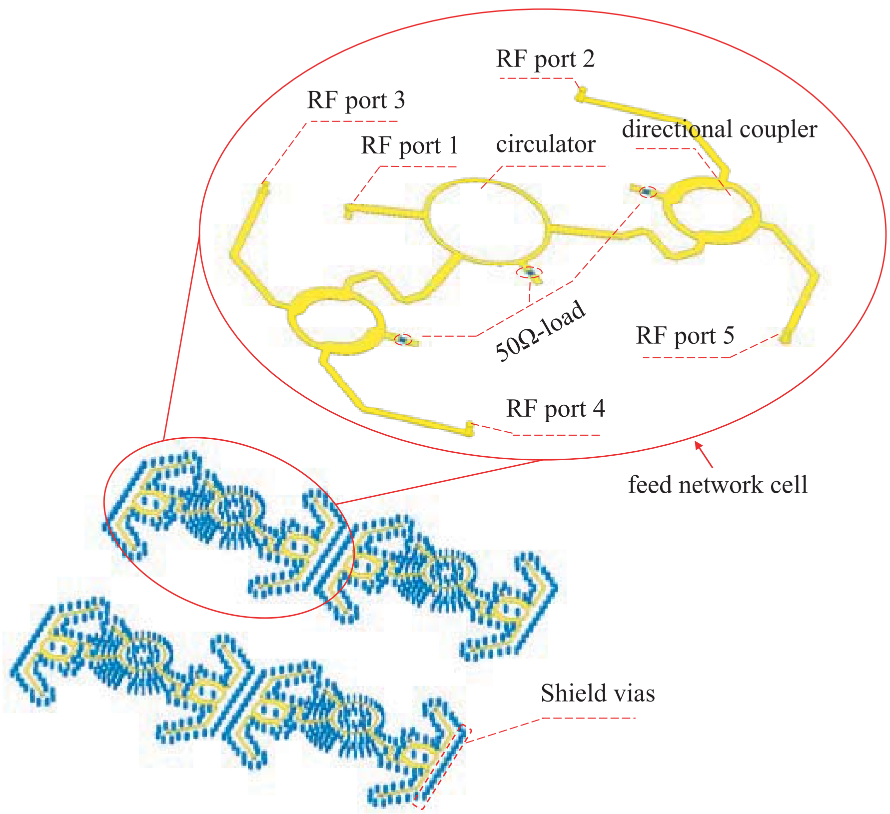


Figure 4. Structure of the proposed feeding network.

The simulated S parameter of a feeding network unit is as shown in Fig. 5, for the operating frequency of 19.6 $\sim$ 21.2 GHz, and $|S_{25}|$ and $|S_{34}|$ are both more than 15.8 dB. $|S_{23}|$, $|S_{24}|$, $|S_{35}|$, and $|S_{45}|$ are all more than 24.8 dB. The simulated VSWRs of RF port 1 $\sim$ 5 are all better than 1.3. The power loss of a feeding network unit is about 6.5 dB, and the difference among $|S_{21}|$, $|S_{31}|$, $|S_{41}|$, and $|S_{51}|$ is about 0.3 dB. As shown in Table 1, in 19.6 $\sim$ 21.2 GHz, the max numerical value of the phase error is 3°.

2.3. Design of 16-Element RHCP Helical Antenna Array

The structure of the proposed antenna array is illustrated in Fig. 6. The proposed RHCP helical antenna array consists of layer of the antenna array, layer of the feeding network, and layer of the combiner. The total number of layers of this RHCP antenna array is 25, and the RF connector is SSMP.

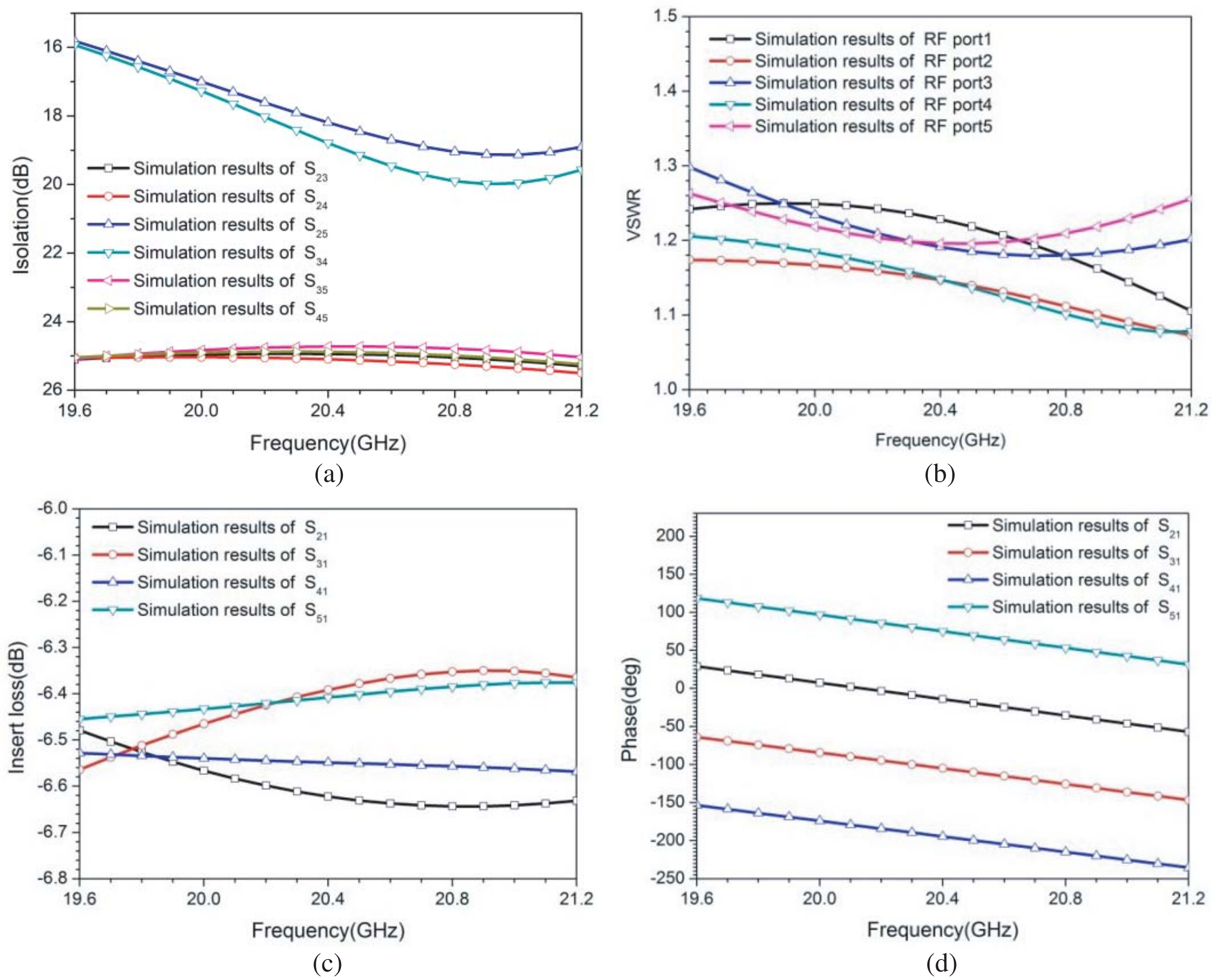


Figure 5. Simulated S parameter of the proposed feeding network unit.

Table 1. The numerical value of a feeding network unit's phases.

	S_{21}	S_{31}	S_{41}	S_{51}
19.6 GHz	29.09°	−63.92°	−153.53°	118.47°
20.4 GHz	−14.01°	−104.94°	−194.44°	75.17°
21.2 GHz	−56.98°	−146.68°	−235.39°	31.35°

3. FABRICATION

The RHCP antenna array is fabricated by LTCC process, which is as shown in Fig. 7. Fig. 7(a) shows the comparison of the proposed antenna and a coin. A measured structure of this antenna and the proposed antenna array are bonded together by conducting resin. Fig. 7(b) shows the size of this antenna and the geometry of a helical antenna cell.

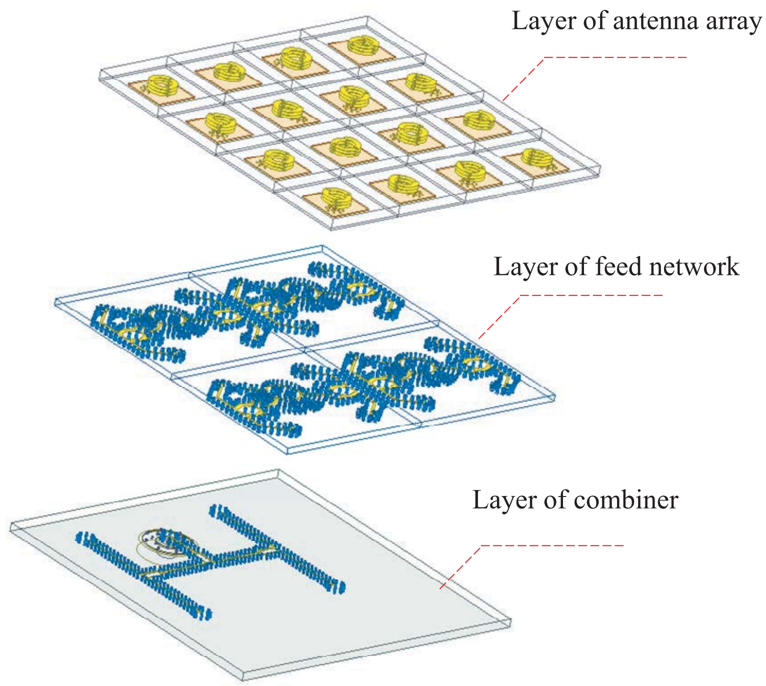


Figure 6. Structure of the proposed RHCP antenna array integrated with the feeding network.

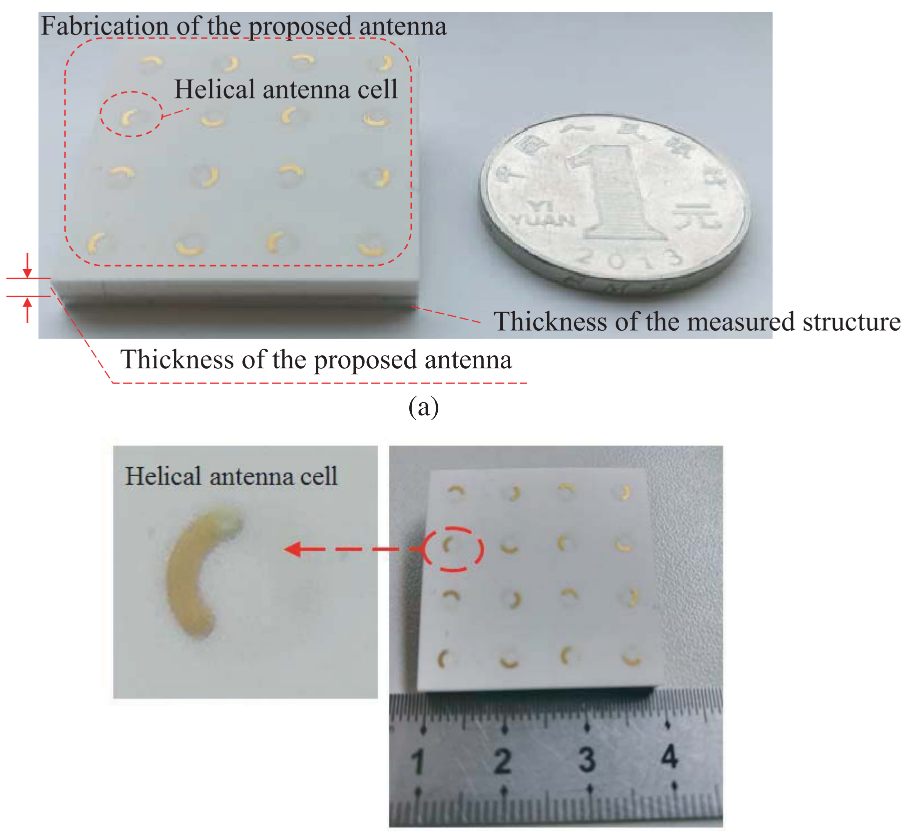


Figure 7. The fabricated RHCP antenna array.

4. MEASUREMENT AND ANALYSIS

The antenna is measured in a microwave darkroom (Fig. 8). Two circularly polarized horn antennas operated from 19 to 22 GHz are as the standard antennas. One antenna is RHCP, and the other is LHCP. They are used to measure the proposed antenna's radiation pattern. The VSWR of the antenna is measured by a vector network analyzer, and the antenna is fixed on a rotating platform.

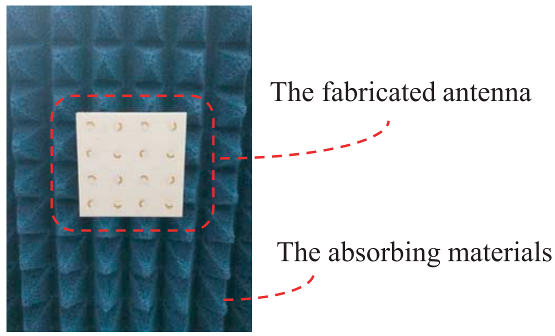


Figure 8. The fabricated antenna was measured in microwave darkroom.

Figure 9 shows the comparison of the measured and simulated VSWR results of the proposed antenna array, and it shows that the measured VSWR result is less 1.7 and the simulated one less 1.35. The difference between of the measured and simulated results is caused by the assembly errors of the SSMP connector.

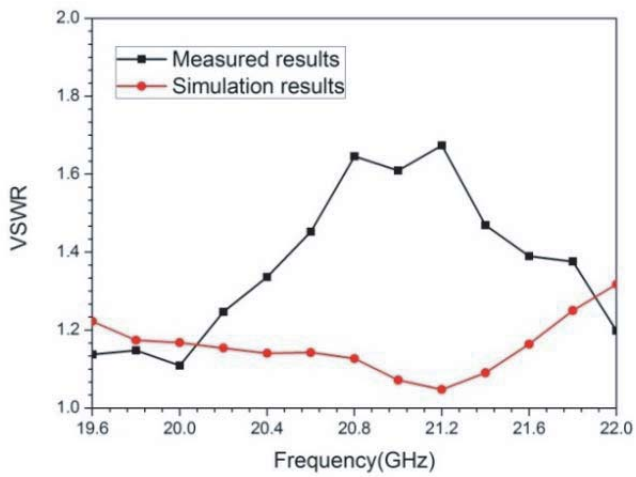


Figure 9. Simulated VSWR results and measured VSWR results of the proposed antenna.

The radiation pattern results include RHCP and LHCP (cross polarization) of xy-plane of this antenna which are measured at 19.6, 20.4, and 21.2 GHz, respectively, and the comparison of the measured and simulated results is demonstrated in Fig. 10. For 19.6, 20.4, and 21.2 GHz, the maximum values of RHCP gains are achieved when theta is 0°, and they are 13.3, 13.8, and 14.5 dBi, respectively. For theta is 0°, the antenna's LHCP gains are −9.6, −10.3, and −9.5 dB, respectively. The maximum values of the polarization isolations are 22.9, 24.1, and 24 dB, respectively.

As illustrated in Fig. 11, the AR properties of this proposed antenna array at 19.6, 20.4, and 21.2 GHz are measured, and the comparison of the measured and simulated results is given. From the AR's results, the measured results match the simulated ones well within the proposed antenna's HPBW (half power beamwidth). The AR properties for these three frequencies are all better than 1.25 dB when theta is 0°.

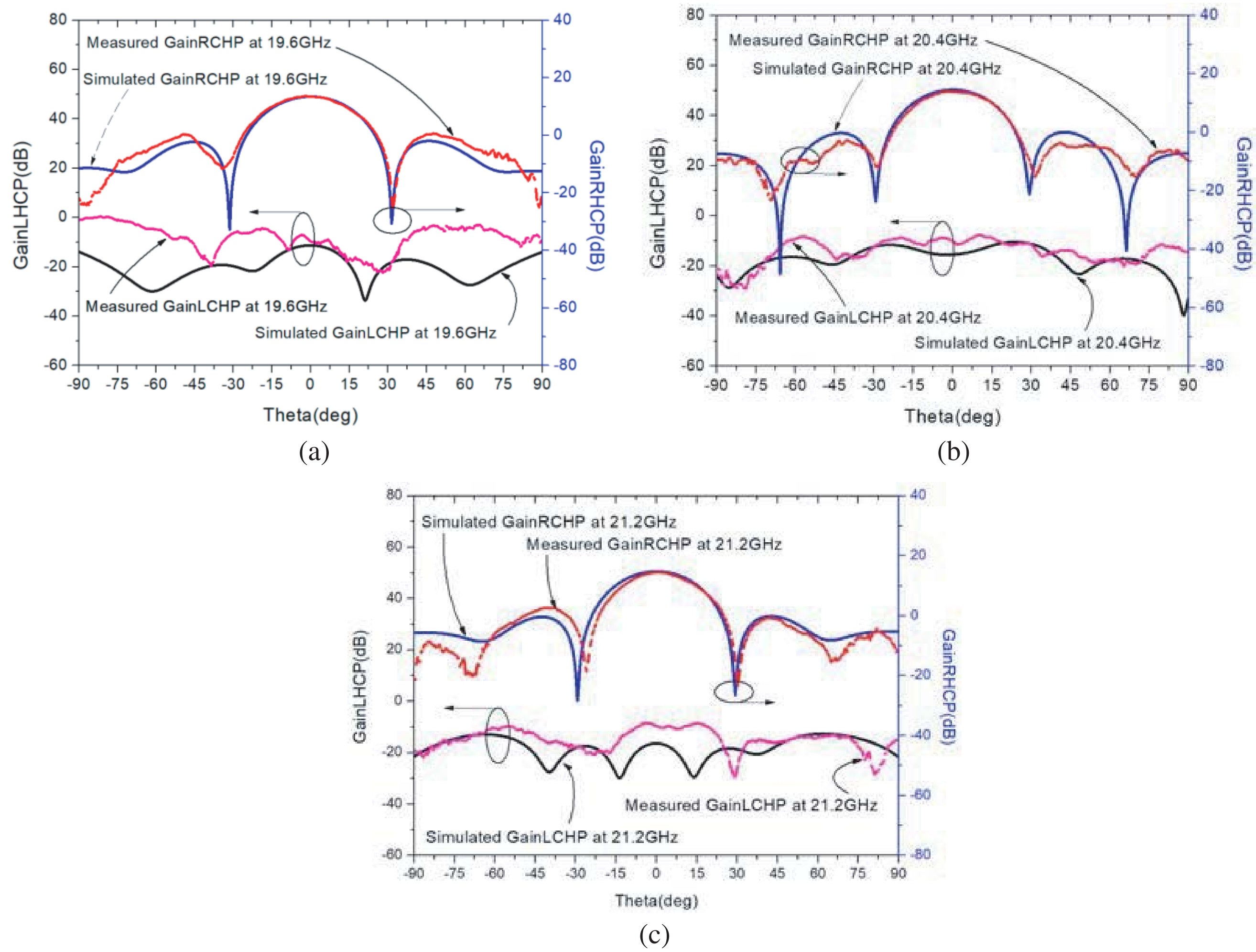
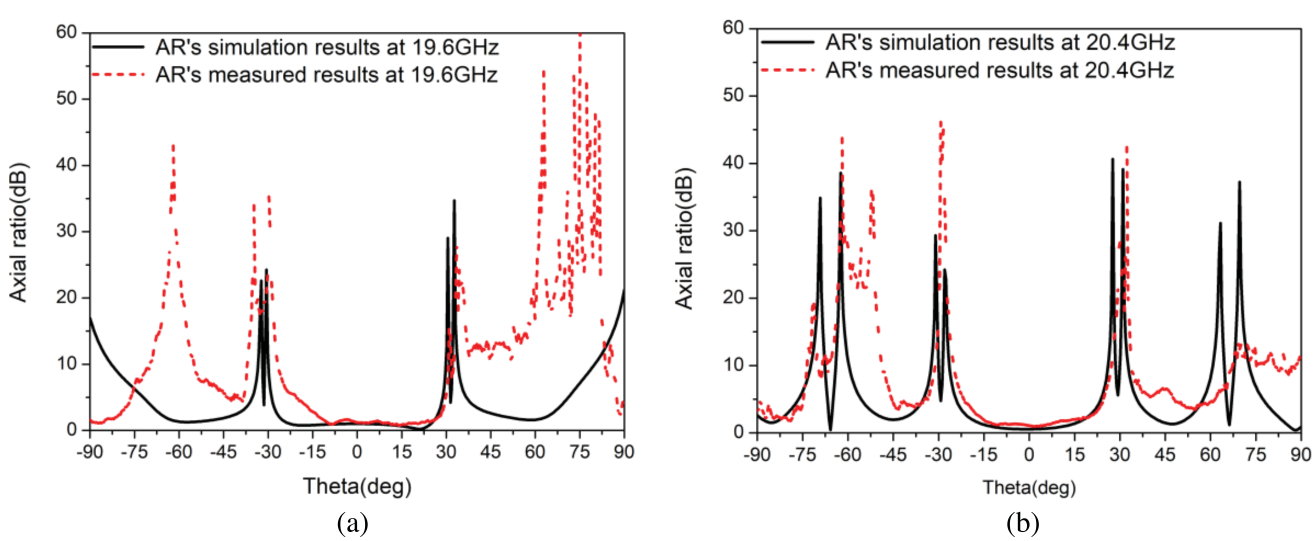
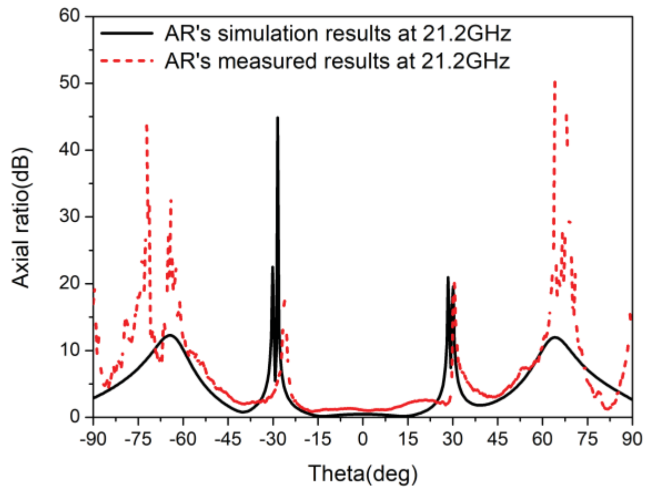


Figure 10. Radiation pattern of the proposed antenna (a) at 19.6 GHz, (b) at 20.4 GHz, (c) at 21.2 GHz.





(c)

Figure 11. AR properties of the proposed antenna array.

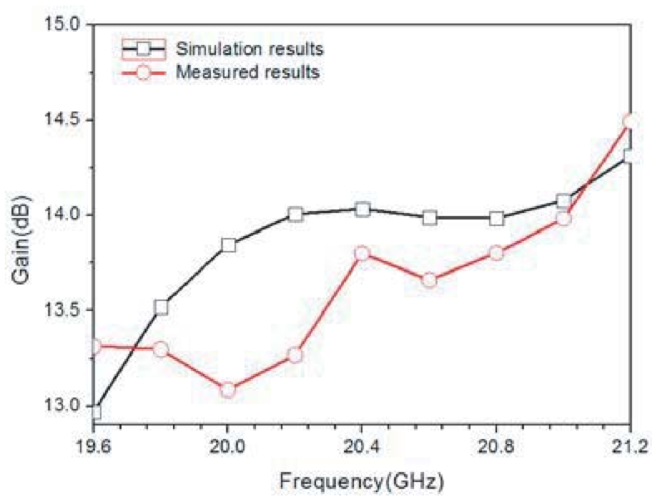


Figure 12. Gain performance of the proposed antenna array.

Table 2. Compared with existing work on circularly polarized antenna.

Reference	[20]	[19]	[21]	[13]	This work
substrate	LTCC	LTCC	LTCC	LTCC	LTCC
Scale	2×2	4×4	4×4	4×4	4×4
Polarization	CP	CP	CP	CP	CP
Frequency (GHz)	$31 \sim 39$	$60.2 \sim 67$	$52.5 \sim 65.5$	$54 \sim 62$	$19.6 \sim 21.2$
AR (dB) & bandwidth	< 3 (26%)	< 3 (2.67%)	< 3 (5.5%)	< 3 (13.4%) Only simulated	< 1.25 ($> 7.8\%$)
Gain (dB)	> 9	> 11	> 11	NA	> 13
VSWR	< 1.5	< 4	< 2	< 2	< 1.7
Size (mm^3)	$15.3 \times 28.3 \times 1.3$	$15.4 \times 15.4 \times 2.02$	$12 \times 10 \times 2$	$13 \times 18.7 \times 1.4$	$29.6 \times 29.6 \times 2.5$

*AR = Axial Ratio, NA = Not Available

The measured maximum gain results of the proposed antenna array from $19.6 \sim 21.2$ GHz are shown in Fig. 12. Compared with simulated results, the measured gain is 0.8 dB less at same frequencies. This difference is caused by conduct loss of the connector, feeding network, and radiation structure.

Compared with other circularly polarized antennas based on LTCC technology in Table 2, the proposed antenna in this paper exhibits a higher gain and better AR bandwidth.

5. CONCLUSION

A 4×4 LTCC RHCP antenna array is proposed in this paper. To achieve a good CP performance, the CP antenna pattern is obtained by the antenna elements with a unit cell of every four elements, sequentially counterclockwise by 90 deg. Meanwhile, the antenna's feeding network unit is obtained by the directed coupler, the circulator. The antenna is verified by actual measurement. Measured results show that the VSWR of the antenna array is better than 1.7, the gain more than 13.5 dB, the AR less than 1.25 dB, and the size of the proposed antenna is only $29.6 \times 29.6 \times 2.5\,\text{mm}^3$. Good agreement is achieved between the simulation and measurement. This design of RHCP antenna array can be applied to mobile satellite communication system.

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