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Twelve-Element MIMO Wideband Antenna Array Operating at 3.3 GHz for 5G Smartphone Applications

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Abstract: This work presents a 12-element multiple-input-multiple-output (MIMO) wideband antenna array for mobile smartphones. The antenna element is mainly composed of two parts, greatly improving the antenna array bandwidth: one is a meandering, looped radiating element and the other is a U-shaped slot. For the antenna element design, the meandering, looped radiating element measures $12.95 \times 6 \text{ mm}^2$, while the U-shaped slot has a size of $15 \times 3 \text{ mm}^2$. Meanwhile, the reflection coefficient indicates that the designed antenna array operates at 3.3 GHz with a bandwidth of 500 MHz; the transmission coefficient shows that the isolation between the antenna elements is better than 12 dB. In addition, more antenna array performances are presented, including nearly omnidirectional radiation characteristics, antenna efficiency ranging from approximately 17 to 60%, envelope correlation coefficients (ECCs) below 0.065, and diversity gain (DG) values of the MIMO antenna system close to 10 dB. The measurement results are highly consistent with the simulation results of the designed wideband antenna array, indicating its great potential for future practical engineering applications.

Keywords: MIMO antenna; 5G; smartphone applications; wideband



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1. Introduction

With the development of modern wireless communications, the field of mobile communications has now begun the process of industrializing 5G systems. As a multi-functional, multi-level, and technology-converged system, the 5G communication system is accelerating the deep integration of new infrastructures such as the Internet of Things, Artificial Intelligence, and Industrial Internet with the real economy [1,2]. As is well known, widebandwidth and MIMO technology can utilize multipath characteristics to improve channel capacity and spectrum efficiency without increasing input power, thereby improving the high throughput of wireless systems [3–5].

Currently, although 2×2 [6,7] and 4×4 MIMO [8–10] antenna systems have been implemented in mobile devices, which are significantly below the 10 Gbps peak data rate, they remain inadequate for meeting 5G communication requirements. Therefore, integrating more antennas within smartphones has become an inevitable trend. Designing high-performance and cost-effective antenna arrays has increasingly attracted attention from scholars. In previous work, eight-, ten-, twelve, and sixteen-antenna-array MIMO systems were designed for smartphones in LTE bands [11–18]. A design of a simple antenna array structure only includes an inverted U-shaped radiating element and vertical stubs printed on the bilateral substrates without introducing any decoupling structure, which would achieve higher isolation [15]. Ref. [17] proposed a compact building block including two asymmetric mirror loop antennas that has a -6 dB bandwidth of about 300 MHz and

an ECC below 0.1. Furthermore, an eight-antenna MIMO array consisting of an antenna element that generates a balanced slot pattern is proposed [18].

However, as the number of antenna elements within a smartphone system increases, the isolation between antenna elements decreases significantly. To address this problem, antenna miniaturization and decoupling techniques should be the key technologies considered in future antenna designs. In most antenna design works, scholars adopted additional decoupling techniques or specific antenna structures and layouts to improve isolation and reduce ECC values. Among them, the decoupling techniques mainly include a defected ground structure [19,20], an orthogonal mode method [16,21], and a decoupling network [22]. For example, in [19], by introducing a $30 \times 2 \text{ mm}^2$ T-shaped slot on the ground plane between two symmetrical inverted F antenna elements, the researchers achieved an excellent isolation degree of -15 dB . Meanwhile, under the influence of multi-mode orthogonal technology, an antenna element composed of a bent monopole and an edge-fed dipole, measuring a size of $7 \times 12 \text{ mm}^2$, achieved an isolation degree better than 17 dB and ECC values below 0.07. This method effectively addresses the mutual coupling issues caused by closely spaced antennas. Furthermore, researchers of another study [22] designed a dual-frequency coupled resonator decoupling network, which was used in a planar antenna and adjusted the coupling coefficient between the two coupled resonator pairs. The experimental results show that the antenna system achieves both high isolation and good radiation performance. However, designing a mobile phone antenna with high isolation remains challenging.

On the other hand, increasing the operating -6 dB bandwidth of mobile phone antennas and improving spectral efficiency can also enhance the data transmission rate in 5G communications. A -6 dB bandwidth means that 75% of the electromagnetic energy can be guaranteed to enter the antenna within the working frequency band, which is the working bandwidth of mobile phone antennas. Although some high-isolation 5G mobile terminal antennas have been designed in previous studies, there are relatively few dual-band wideband MIMO antenna designs that can be applied in smartphone systems. For example, [23] discusses an eight-antenna array designed using slot technology for metal-frame smartphones. Although it shows good isolation, it only covers a single LTE 42 band, and its operating bandwidth does not meet the requirements for 5G communications. Furthermore, in a recent work [24], dual-band performance was achieved by etching an “L” slot on a planar antenna. However, its operating bandwidth was only about 50 MHz, and a larger value is needed for 5G communications.

To address those problems, a wideband (500 MHz) 12-element MIMO antenna array with an isolation degree better than 12 dB is designed in this work. A 12×12 MIMO antenna array with better bandwidth performance formed using a meandering, looped radiating element and a U-shaped slot is applied for 5G smartphones. First, the designed wideband antenna array structure is simulated and experimentally tested in detail, and its simulation and computational measurement results are discussed. Then, the simulated radiation performances are compared and analyzed, the results presenting that the antenna has an isolation degree better than 12 dB , an ECC below 0.065 and an antenna efficiency of around 15–60%. The innovation of this work lies in its further modification of the structure of the meandering, looped radiating elements based on the literature [25], and the introduction of U-shaped slots on the ground plane, which increases the operating bandwidth by 300 MHz and further reduces the ECC values. These results indicate that the designed antenna array exhibits excellent MIMO performance, demonstrating great potential for future 5G communications and significant engineering implications.

The rest of this work is organized as follows. Section 2 presents the structure design of the antenna element and the antenna array. Section 3 shows the simulation and measurement results of the designed MIMO array system. Finally, Section 4 concludes this work.

2. Twelve-Element MIMO Wideband Antenna System Design

2.1. Antenna Element Design and Analysis

To sufficiently analyze the design process of the designed antenna element, Figure 1 presents three different design cases of the antenna element, all of which use a T-shaped 50-ohm microstrip line for feeding. In Case 1, the vertical side of the substrate is a C-shaped radiating element. The S-parameter results obtained through CST simulation, as shown in Figure 2, indicate that the resonance frequency of this antenna element is 3.6 GHz, but the reflection coefficient is high and the impedance matching is poor, leading to current being concentrated on the T-shaped feed line, while the current on the C-shaped radiating element is almost zero, as shown in Figure 3a. However, Case 2 is derived from Case 1 by introducing a U-shaped slot on the ground plane of the main substrate and adding a rectangular radiating element on the left side of the T-shaped microstrip line. Compared with the S_{11} parameter in Case 1, the antenna element in Case 2 shows improved impedance matching, with a resonance frequency of 3.4 GHz and a bandwidth of 300 MHz. As shown in Figure 3b, in Case 2, there is current present on the outer sides of the U-shaped slot and the left rectangular radiating element, and the T-shaped feed line radiates electromagnetic energy toward the C-shaped radiating element. As a result, the current on the C-shaped radiating element is no longer zero, but the current on its two side arms remains low. To address these problems, the C-shaped radiating element was modified into a meandering looped radiating element using bending techniques based on Case 2. By analyzing the S-parameters in Figure 2, it can be concluded that the resonance frequency shifts to the left, generating a second resonance point, which increases the operating bandwidth to 400 MHz, achieving wideband performance and better impedance matching. Figure 3c shows that the current is mainly distributed along the sides of the meandering, looped radiating element and the U-shaped slot, significantly increasing the effectiveness of the radiating elements compared to those in Case 2.

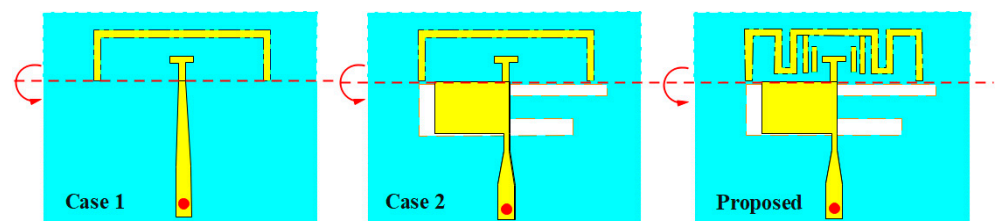


Figure 1. Three design cases.

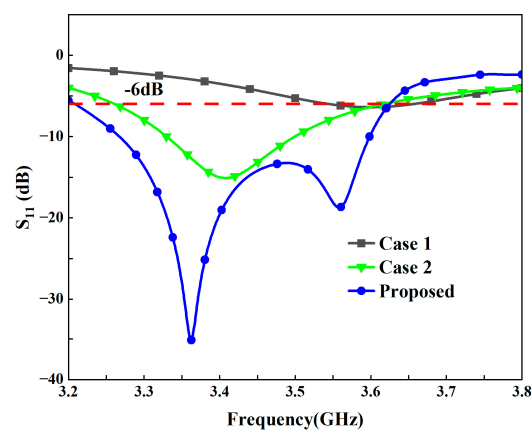


Figure 2. S_{11} coefficient simulation results for the three design cases.

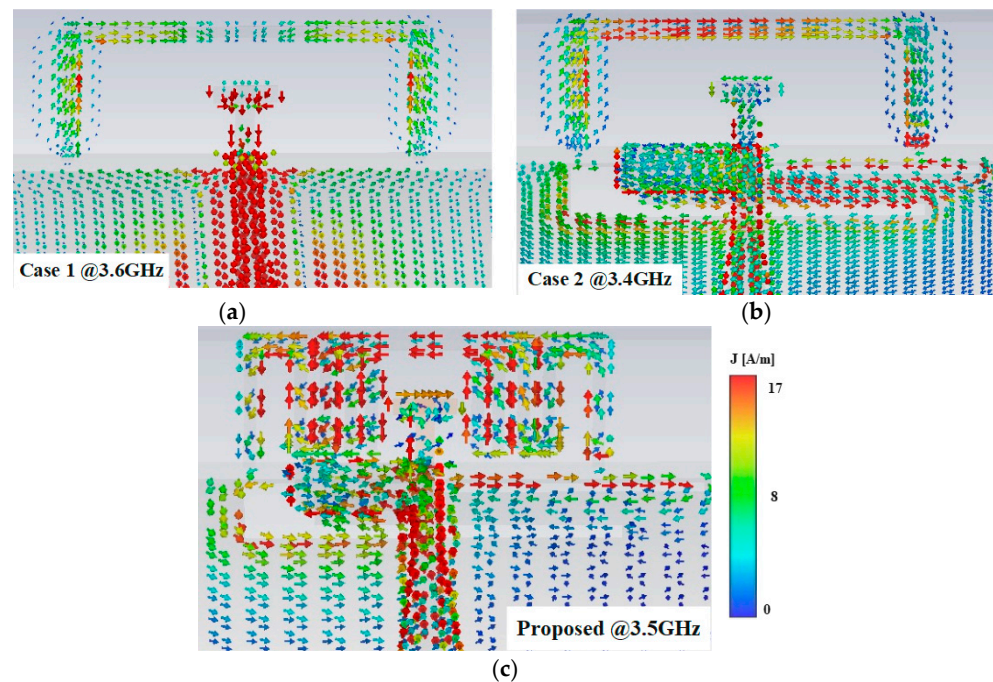


Figure 3. Current distributions for the three design cases: (a) Case 1. (b) Case 2. (c) Proposed case.

2.2. Wideband Antenna Array Design and Analysis

As shown in Figure 4, the layout and specific dimensional details of the designed 12-element antenna array are presented. In addition, the antenna element mainly consists of two parts: a meandering, looped structure and a U-shaped slot. Figure 5 depicts the fabricated photographs of the designed antenna array. For the intelligent communication terminals presently concerned, it can be applied on a $150 \times 75 \times 0.8 \text{ mm}^3$ system-grounded substrate. As shown in Figure 4a, two of the same 6-antenna arrays are, printed on the bilateral-system-grounded substrate, thus forming a 12-element antenna array. Certainly, all substrate models in the designed smartphone antenna array system are FR-4 ($\epsilon_r = 4.4$, $\tan \delta = 0.02$), and their thickness is 0.8 mm. Due to the confined space within a smartphone, clearance areas on the system-grounded substrate are necessary to accommodate the presence of two antennas in order to support 2G/3G/4G communications. For example, a dual-wideband loop antenna is proposed for the LTE frequency band and can be used in reserved clearance regions [26]. However, in this work, the impact of the two antennas arranged in the two clearance regions on the designed antenna system is not considered.

Firstly, Figure 4b shows the detailed antenna element structure, which contains a meandering, looped structure and a U-shaped slot on the grounded plane. Secondly, the structure of the meandering, looped structure is depicted in Figure 4c, and a higher-resonant-frequency point (3.6 GHz) of the antenna element can be introduced. Similarly, the U-shaped slot is shown in Figure 4d; the use of this slot results in the generation of a lower-resonant-frequency point (3.35 GHz). Finally, Figure 4b also shows that the T-shaped microstrip line is equipped with stubs to feed the antenna element, which generates a wider bandwidth. After calculation and optimization, the size of this short section is $5 \times 3 \text{ mm}^2$.

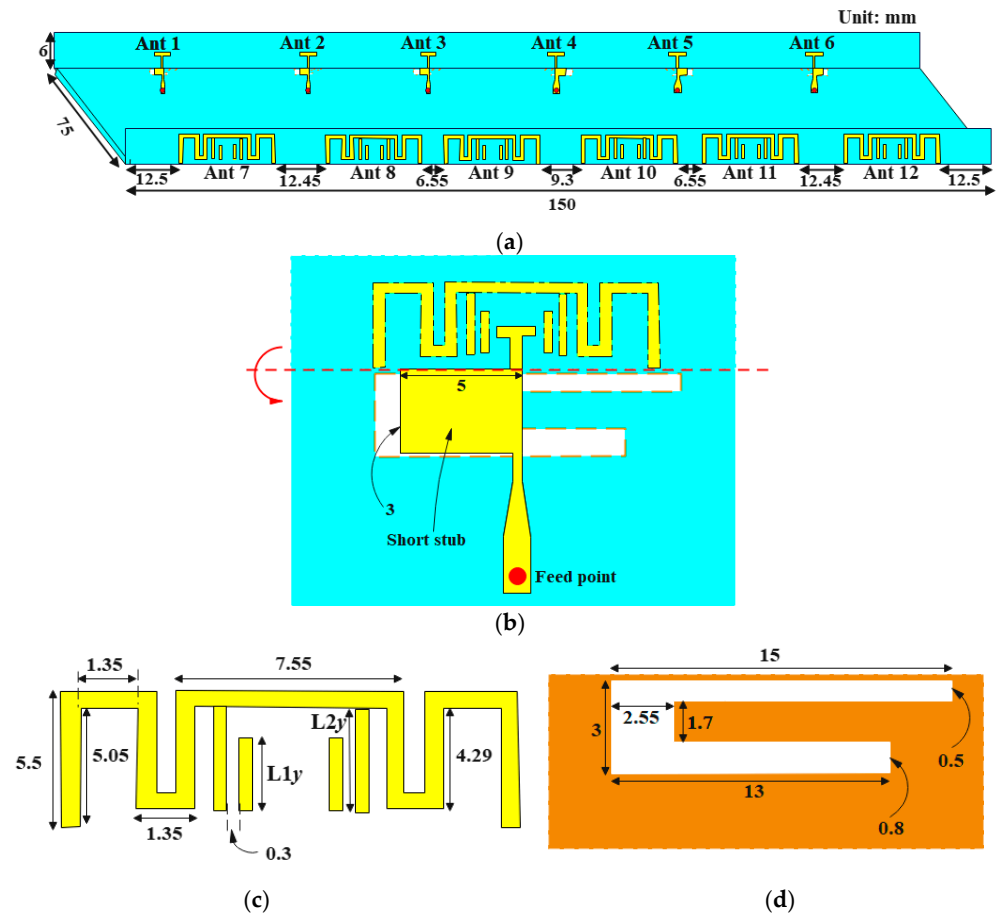


Figure 4. Configuration of (a) the designed wideband antenna array. (b) Overall view of the antenna element, describing its structural composition. (c) Front view of single element on the vertical substrate. (d) Detailed structure of the U-shaped slot on the grounded plane.

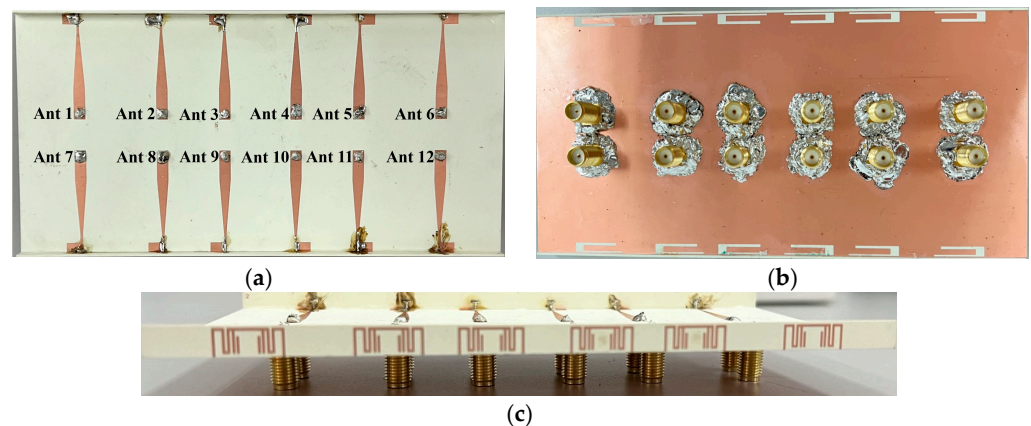


Figure 5. Photos of the fabricated 12-element antenna array: (a) Top view. (b) Back view. (c) Side view.

Scanning and analyzing some of the parameters of the meandering, looped radiating element and U-shaped slot helped us to better study the working mechanism of the designed antenna. According to Figure 6a, the generation of the 3.35 GHz resonance point for this antenna element is not only related to the U-shaped slot but also to the rectangular radiating element with a length of $L1y$ on the vertical substrate. As shown in Figure 7a, when the antenna element operates at 3.35 GHz, the surface current is primarily distributed around the U-shaped slot and the rectangular radiating element, thereby verifying the aforementioned point. As $L1y$ continues to increase, the S_{11} value at 3.35 GHz continues to

increase, which also means that the impedance matching of the antenna element near this frequency point becomes worse, so the final analysis shows that the value of $L1y$ is 3.25 mm. Similarly, the analysis of Figure 6b indicates that the $L2y$ height of the meandering, looped radiating element also affects the higher resonance point (3.6 GHz). When the value of $L2y$ changes from 2 mm to 4.3 mm, the S_{11} value near 3.6 GHz continuously decreases. To verify this point, Figure 7b also shows that the current distribution of the antenna element at 3.6 GHz is mainly concentrated around the meandering, looped radiating element. In addition, Figure 6c shows that as the length of one end of the U-shaped slot ($U1y$) increases, the entire operating frequency band moves to the left, in which the lower resonance frequency undergoes larger shifts. The length variation of the other end of the U-shaped slot ($U2y$) primarily affects the impedance matching characteristics of the antenna element. As shown in Figure 6d, when $U2y$ changes from 13 mm to 13.5 mm, the higher-frequency resonance point does not shift, while the lower-frequency resonance point shifts to the left.

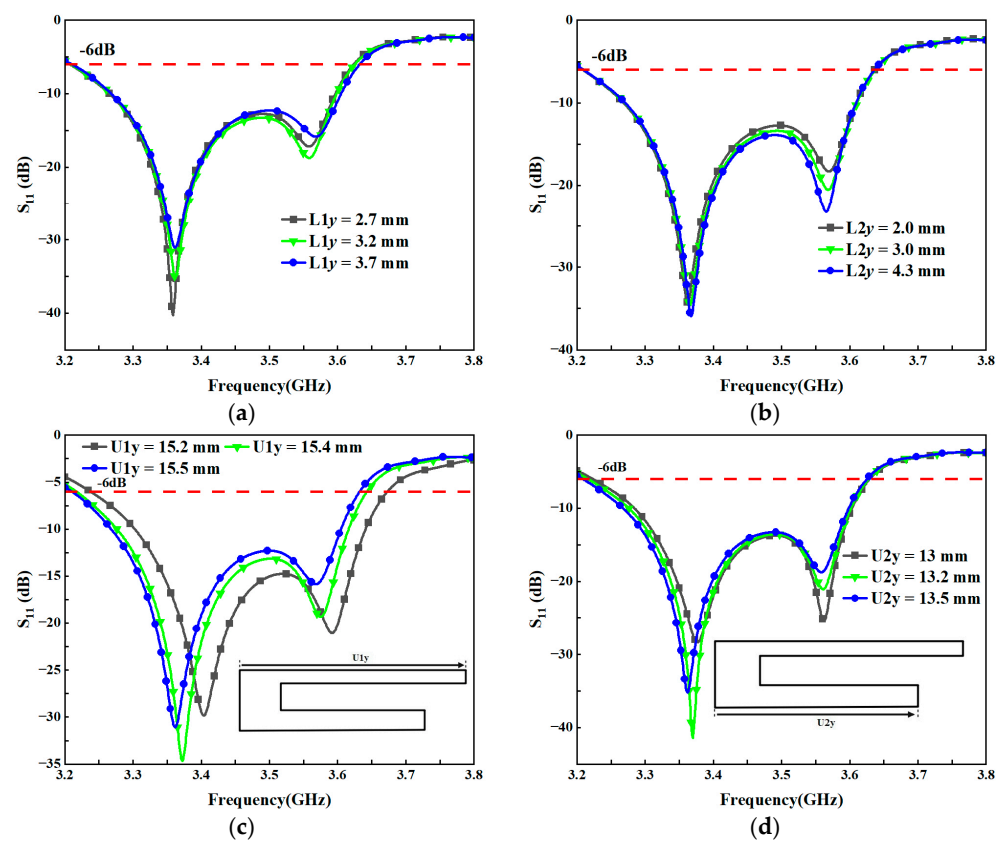


Figure 6. Parameter analysis of the resonant frequency point of the antenna element with different values: (a) $L1y$, (b) $L2y$, (c) $U1y$, and (d) $U2y$.

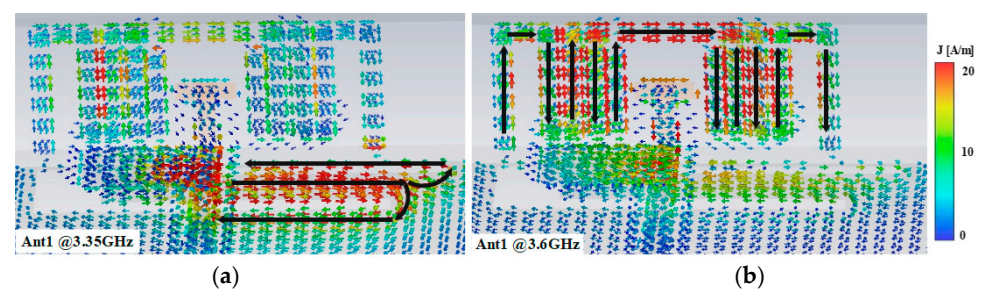


Figure 7. Current distribution of the antenna element (a) at 3.35 GHz and (b) at 3.6 GHz.

3. Results and Discuss

In this section, the simulation and measurement results of the designed wideband antenna array will be discussed and analyzed

3.1. S-Parameters Analysis

The performances of the designed 12-element MIMO wideband antenna array are determined by using CST Microwave Studio 2021. Figure 8 illustrates the simulation and measurement of S-parameters of the designed 12-element wideband antenna system. As shown in Figure 8a, for the reflection coefficients, the antenna array has a wider -6 dB bandwidth (3.2–3.7 GHz) and good impedance matching within the required frequency band (because the antenna array has a symmetrical structure: $S_{11} = S_{66}$, $S_{22} = S_{55}$, and $S_{33} = S_{44}$); for the transmission coefficients, the isolation between any two antennas from Ant1 to Ant12 is maintained above 12 dB (only the S_{21} , S_{31} , S_{32} , S_{43} , S_{71} , S_{81} , and S_{91} s curves are shown due to the symmetrical structure). Furthermore, according to Figure 9a, when Ant1 is excited, the current is mainly concentrated on the meandering, looped radiating element of Ant1, while the current transmitted to Ant2 is minimal. This indicates that the electromagnetic energy of Ant1 has small coupling effects on Ant2, demonstrating good isolation between Ant1 and Ant2. Similarly, when Ant2 and Ant3 are excited, their current distributions are as shown in Figures 9b and 9c, respectively. The current in the adjacent antenna elements is minimal, further confirming the excellent isolation between the antenna elements. This excellent isolation is attributed to the layout technique of the antenna array, where the distance between antenna elements is carefully adjusted to reduce the metallic coupling effect.

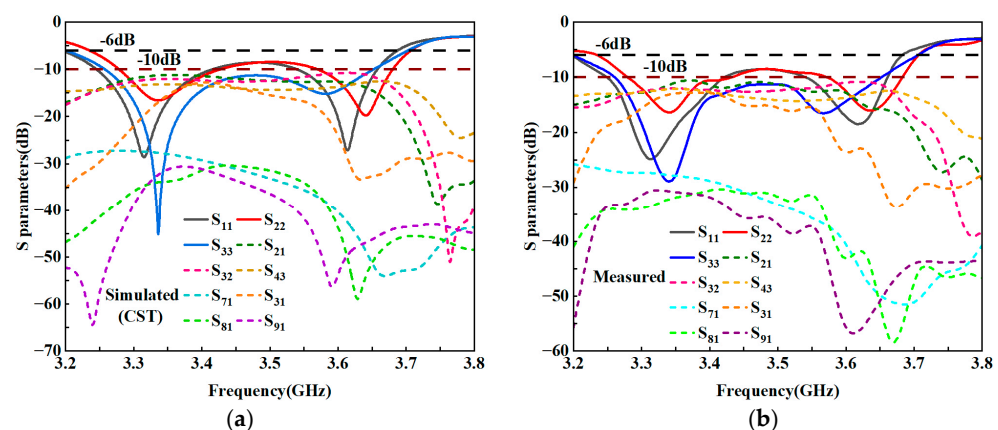


Figure 8. Simulation: (a) S-parameters and measurement and (b) S-parameter measurement for Ant1 to Ant7.

It is worth noting that, by comparing Figures 2 and 8a, it can be seen that the low-resonance point, 3.35 GHz, shifted to the left by about 50 MHz, while the high-resonance point 3.6 GHz has shifted to the right by about 10 MHz, and the operating bandwidth has been increased from the original 400 MHz to 500 MHz. This is thanks to the layout technology of the antenna array, which causes a slight shift in the two resonance points of the designed antenna, and increases the operating bandwidth by 100 MHz. However, due to the influence of uncertain factors such as fabrication errors and the experimental environment, there is a certain error between the S-parameter simulation results and the measurement results of the antenna. In other words, the experimental S-parameters in Figure 8b are essentially consistent with the simulated S-parameters in Figure 8a.

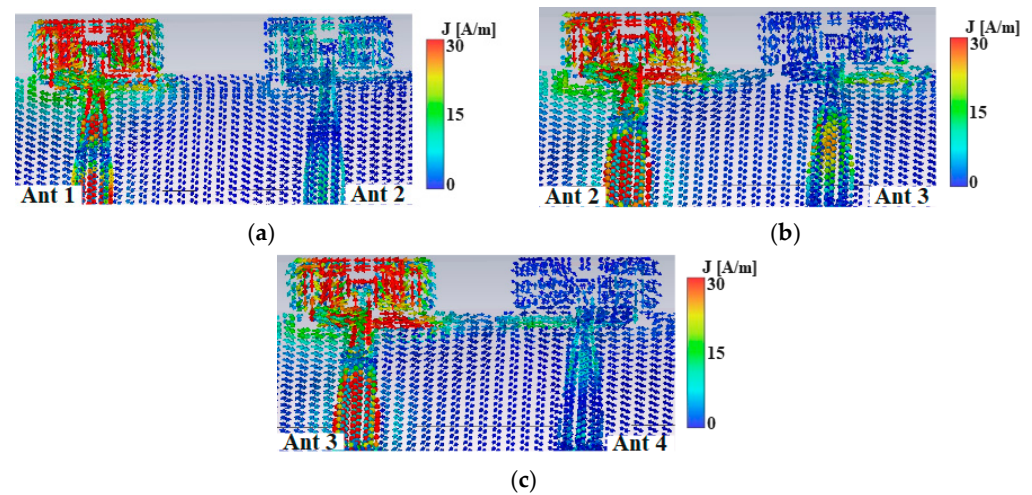


Figure 9. Current distribution. (a) Ant1 is excited. (b) Ant2 is excited. (c) Ant3 is excited.

3.2. Radiation Performance of Antenna Array

To thoroughly analyze the radiation characteristics of the designed wideband antenna array, we conducted rigorous and comprehensive tests in a microwave anechoic chamber to ensure its accuracy and reliability, as shown in Figure 10. During the experimental measurements and simulations, each port was individually fed, while other ports were matched to $50\ \Omega$. As illustrated in Figure 11, the 2D far-field radiation patterns of Ant1 to Ant6 in the E-plane ($\phi = 0$) and H-plane ($\phi = 90$) at 3.36 GHz and 3.63 GHz frequencies demonstrate that the antenna exhibits nearly omnidirectional radiation characteristics in the XOZ plane at both frequencies, with exhibiting slightly stronger radiation in the Z direction. In contrast, the YOZ plane reveals the unique characteristics of the antenna, with slightly stronger radiation in the +Y direction. In addition, to further intuitively analyze the radiation performance of the designed antenna, Figure 12 provides a 3D far-field radiation pattern that offers a better explanation of Figure 11. From Figures 11 and 12, it can be observed that the far-field radiation patterns of Ant1 to Ant3 and Ant4 to Ant6 are mirror-symmetrical in the XOZ plane, which is consistent with the structure of the antenna array. Due to the symmetric design of the designed MIMO antenna system, the far-field radiation patterns of the remaining antenna elements are omitted here for brevity. Overall, these results indicate that the wideband antenna array possesses omnidirectional radiation and good gain characteristics within its operating frequency range, meeting the radiation performance standards for smartphone antennas.

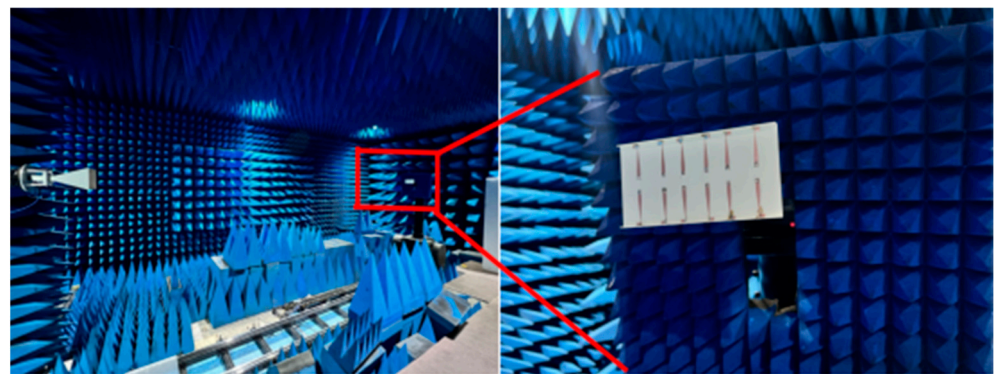


Figure 10. Experimental equipment for testing the far-field pattern of the designed antenna array in the microwave anechoic chamber.

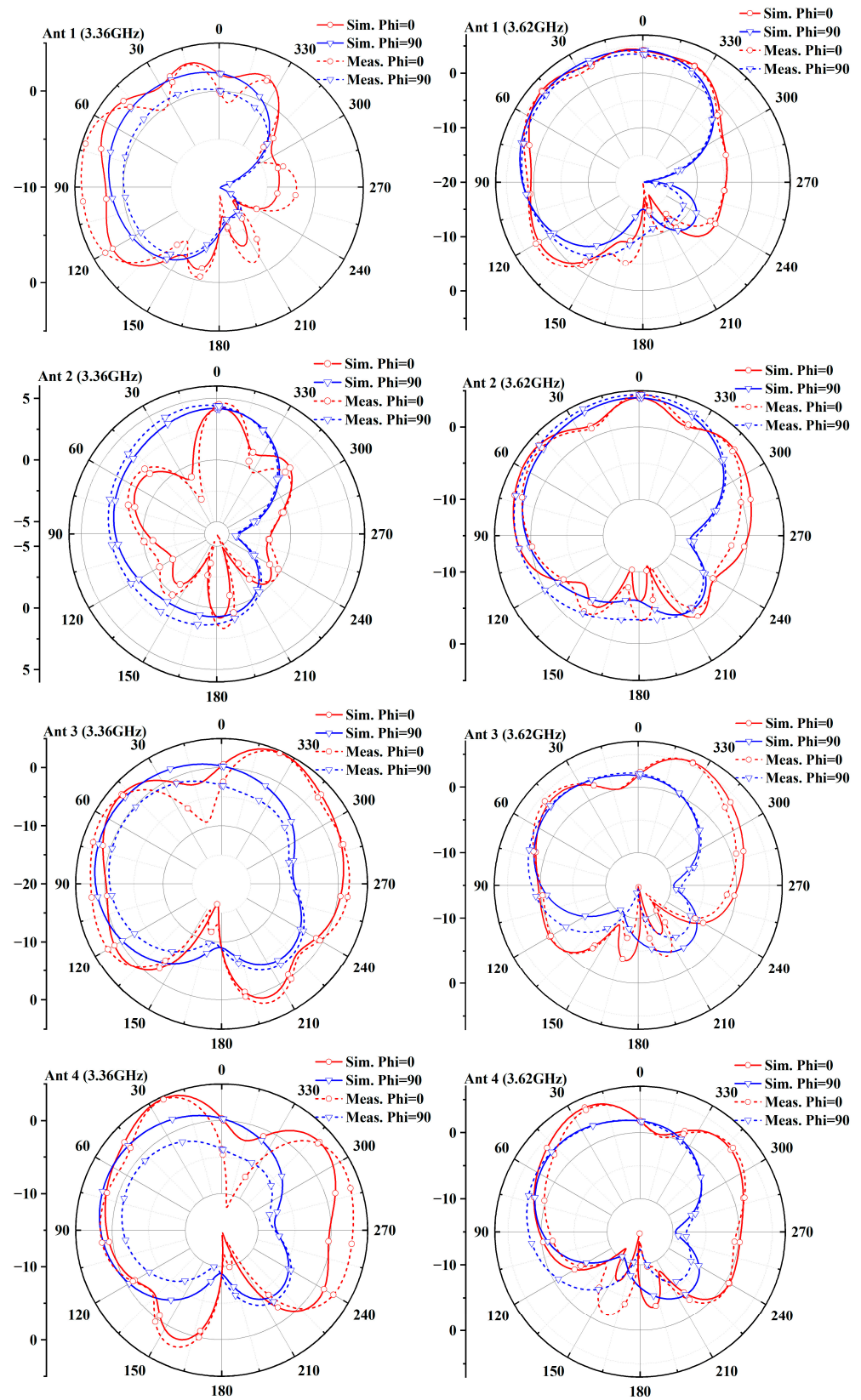


Figure 11. Cont.

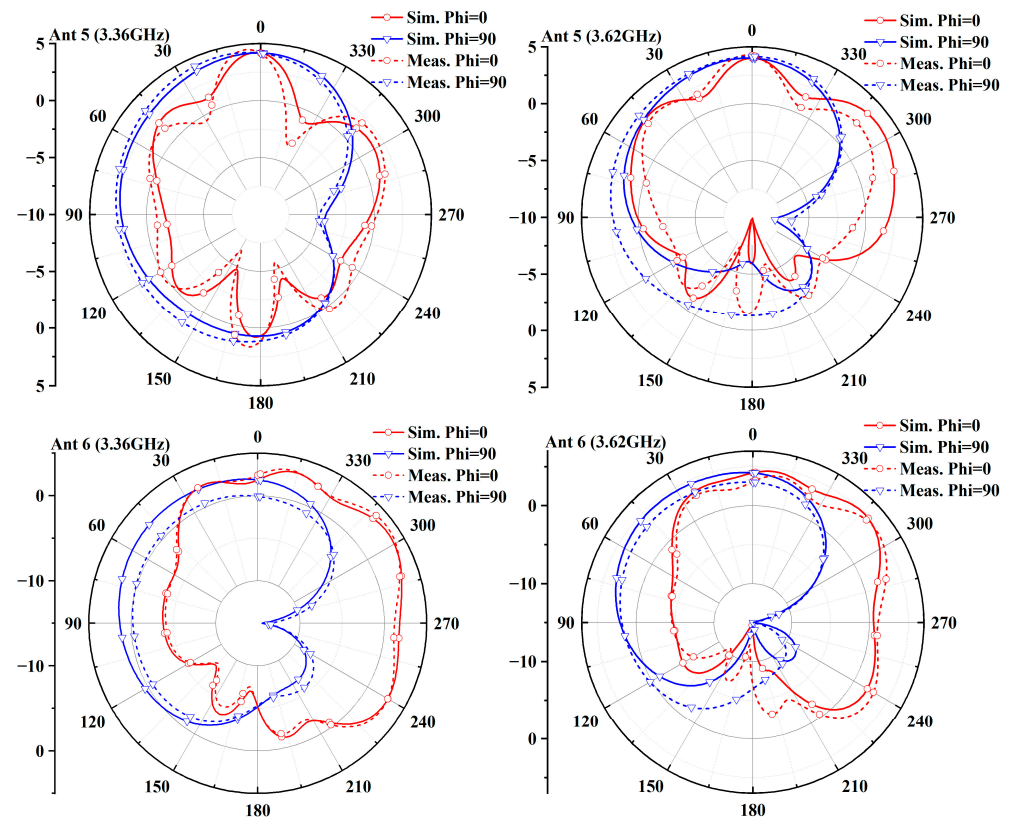


Figure 11. Simulated and measured 2D far-field patterns of the designed antenna array.

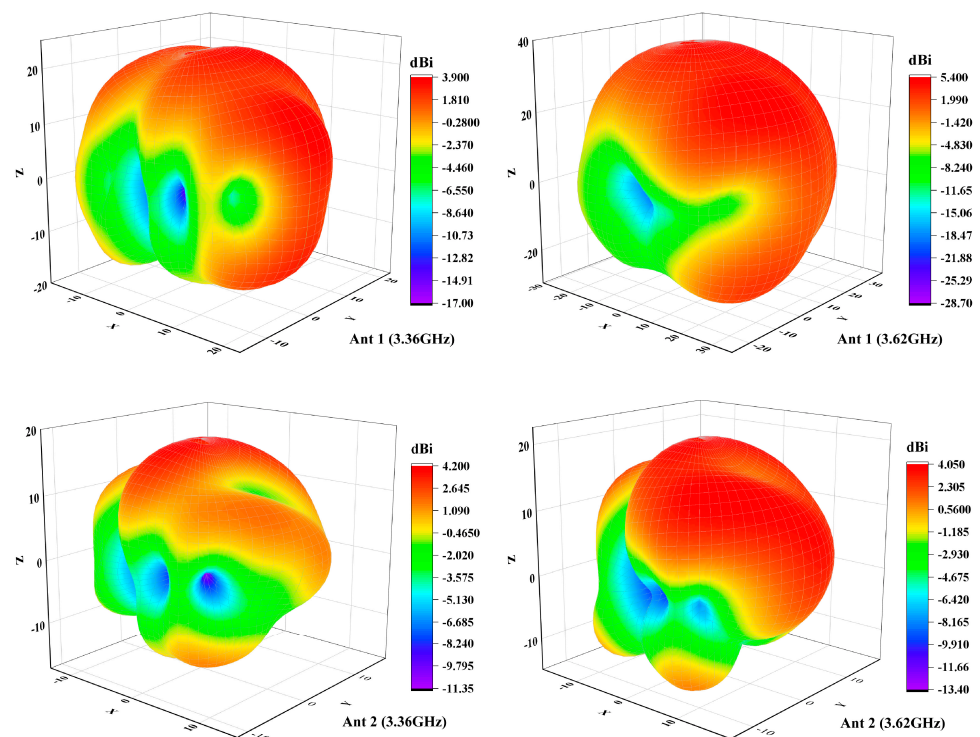


Figure 12. Cont.

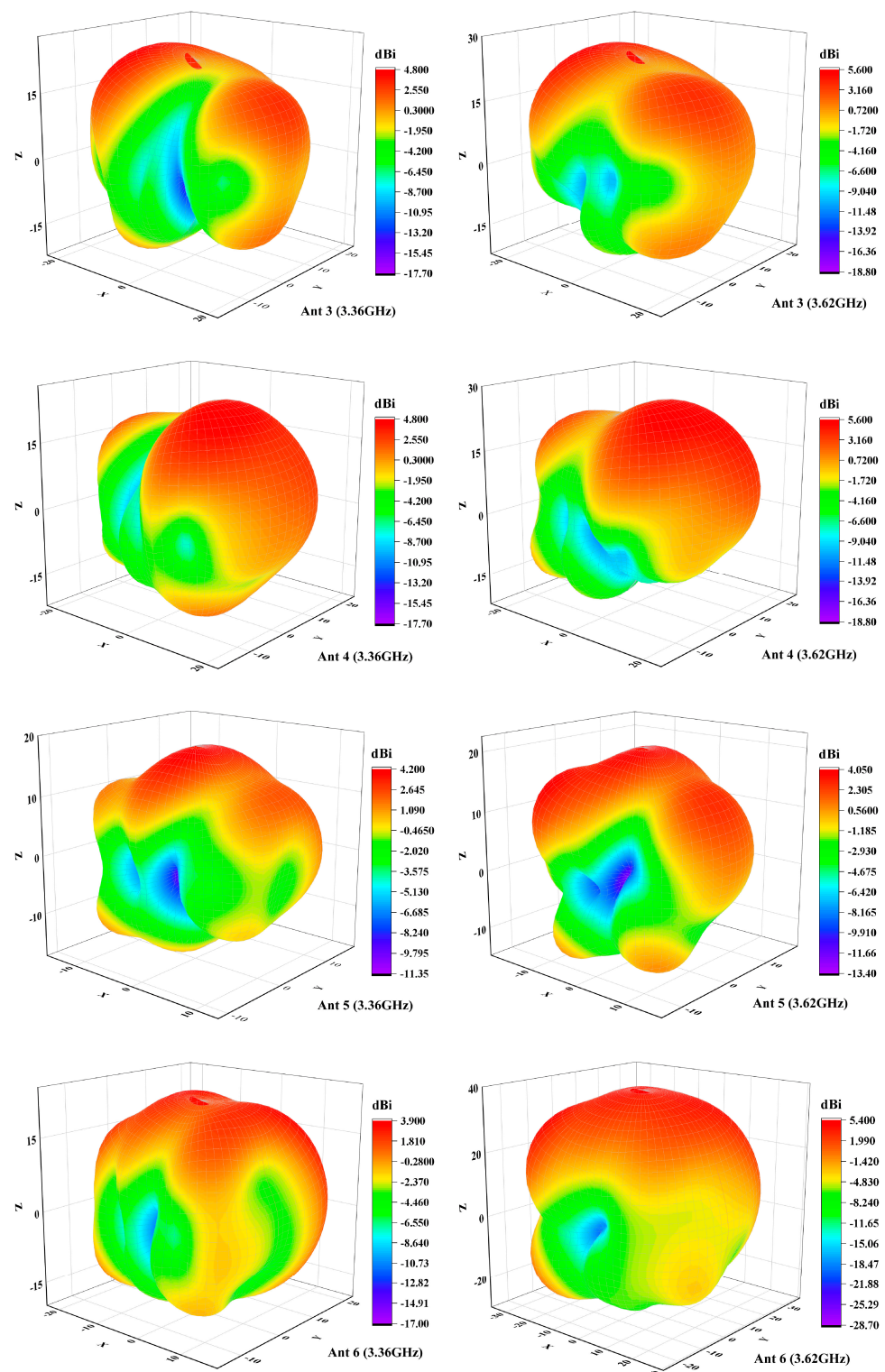


Figure 12. The 3D far-field radiation patterns of the designed antenna array.

3.3. Efficiency of the Designed Antenna Array

Antenna efficiency is a key parameter used to evaluate the ability to convert input power into radiated power, typically expressed in terms of $G(\theta, \phi)$ as follows:

$$\eta = \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi [G_\theta(\theta, \phi) + G_\phi(\theta, \phi)] \sin \theta d\theta d\phi \quad (1)$$

For Ant1 to Ant3, Figure 13 clearly presents the simulation and measurement results of the total efficiency, where Figure 13a states that within the required operating bandwidth, the simulated antenna efficiency of Ant1 is about 2% to 10% higher than that of Ant2 and Ant3. This is because Ant1, arranged on the outside of the antenna array, has lower coupling loss and better antenna efficiency. In contrast, the antennas of Ant2 and Ant3 are slightly less efficient because of higher coupling losses from the adjacent antennas on either side of them. As depicted in Figure 13b, the antenna experimental efficiencies are approximately 16–62%, aligning well with the simulation results.

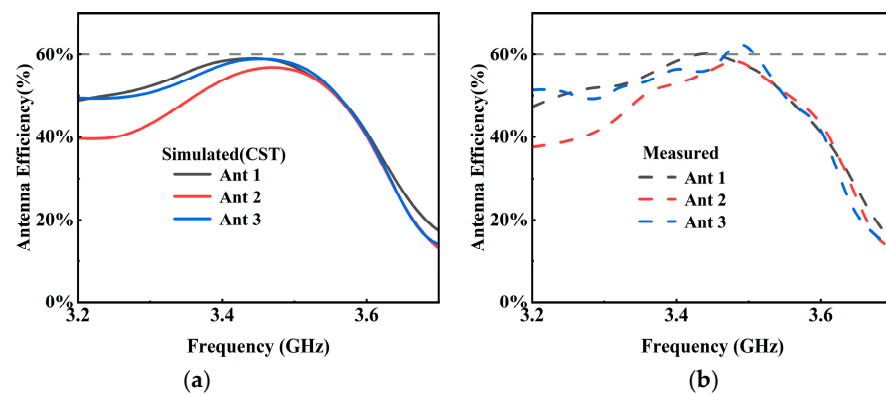


Figure 13. Simulated (a) antenna efficiency and measured (b) antenna efficiency for Ant1 to Ant3.

3.4. Analysis of ECC and DG Parameters

To further analyze the MIMO performances of the designed 12-element antenna array, the ECC needs to be considered another important parameter. The ECC is not only an important parameter for evaluating the correlation of radiation patterns between any two antennas in antenna array [27], but also a key parameter with which to evaluate diversity gain in MIMO antenna systems. The ECC can be determined through the computation of experimentally experimental complex electric field patterns, and its value should be less than 0.5 in engineering applications [28]. Figure 14 illustrates the simulated and measured ECC values for any adjacent antennas within the designed wideband antenna array. As shown in Figure 14a, at 3.2–3.6 GHz, all ECC values are less than 0.05; however, at 3.6–3.7 GHz, except for the ECC values between Ant3 and Ant4, the other ECC values are all less than 0.03. In conclusion, the designed wideband antenna array exhibits excellent performance, with ECC values lower than 0.065 among the antenna elements, which means that there is a low correlation between the individual antenna elements and that the measurement and simulation results show excellent agreement, as demonstrated in Figure 14b.

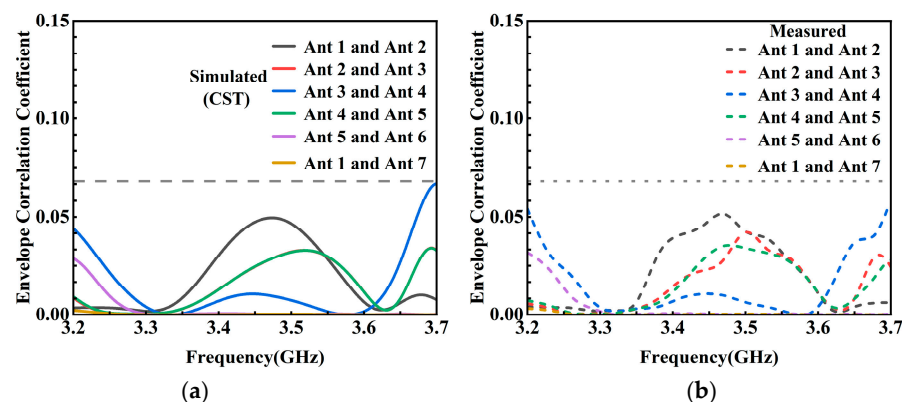


Figure 14. ECC values between adjacent antenna elements. (a) Simulation and (b) measurement results.

Figure 15 depicts the simulated diversity gain (DG) values of the designed antenna, which can be calculated using the Envelope Correlation Coefficient (ECC) [29]. It clearly illustrates that the DG of the antenna array exceeds 9.8 dB within the operating bandwidth, except for the minimum DG value of 9.6 dB between Ant1 and Ant3. In theory, the DG value of the MIMO antenna system for smartphones should be around 10 dB within its operating bandwidth. However, these results are within the acceptable range.

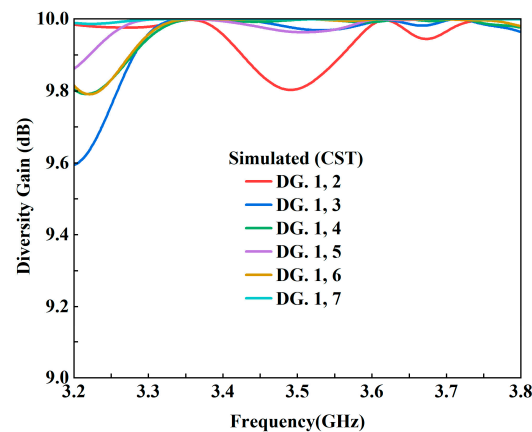


Figure 15. DG of the designed antenna array.

In addition, Table 1 provides a comprehensive analysis comparing the bandwidth, isolation degree, and ECC values of the designed 12-element MIMO antenna array with those of several other MIMO antenna arrays mentioned in the relevant references. In contrast to the results in Reference [25], the designed antenna reduces the antenna size relative to the operating wavelength, while the -6 dB bandwidth of the antenna array is increased to 500 MHz. Each antenna element has the same dimensions and can be mounted in the limited space of a smartphone. As evident from Table 1, the proposed MIMO antenna array exhibits a wider bandwidth, while maintaining relatively low ECC values.

Table 1. Comparison of MIMO antennas.

Ref.	Frequency (GHz)	BW (GHz)	Isolation (dB)	ECC	Elements	Radiating Element Size (mm ²)
[12]	3.6	3.4–3.8	<−10	<−0.1	10	NG
[13]	3.5	3.4–3.6	<−10	<−0.3	16	19 × 2 (0.22λ × 0.023λ)
[15]	3.5	3.4–3.6	<−15	<−0.1	8	17.4 × 6 (0.203λ × 0.07λ)
[17]	3.5	3.4–3.6	<−10	<−0.15	8	10 × 7 (0.12λ × 0.082λ)
[25]	3.5	3.4–3.6	<−10	<−0.1	10	13.45 × 6 (0.157λ × 0.07λ)
[30]	3.5	3.4–3.6	<−10	NG	8	40.8 × 3 (0.476λ × 0.035λ)
Proposed	3.3 and 3.6	3.2–3.7	<−12	<−0.065	12	12.95 × 6 (0.151λ × 0.07λ)

Abbreviations: BW = -6 dB Bandwidth; NG = not given.

4. Conclusions

In this work, a 12-element wideband antenna array is presented that was designed to operate at a 3.3 GHz frequency in smartphones and to be utilized in 12×12 MIMO systems. The wideband antenna array is arranged along a vertical substrate on bilateral smartphones. The results of the designed antenna array show a wider working bandwidth of 500 MHz, a higher isolation degree better than 12 dB with acceptable antenna efficiencies, and DG

values close to 10 dB. Additionally, the antenna elements exhibit nearly omnidirectional radiation patterns and good gain characteristics, while maintaining ECCs below 0.065. These results suggest that the designed 12-element MIMO array holds significant potential for applications in future 5G massive mobile communication systems.

Author Contributions: Conceptualization, H.Y.; Methodology, H.Y.; Software, Y.L.; Validation, J.W.; Formal analysis, H.Y.; Investigation, X.S.; Resources, Q.X.; Data curation, W.L.; Writing—review & editing, Q.X. and J.W.; Supervision, Q.X.; Funding acquisition, H.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Yuanzhe Luo was employed by the company Beijing Zhongchao Weiye Information Security Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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