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RESEARCH ARTICLE

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Dual-port single-loop MIMO antenna unit for unbroken metal-frame terminals without cutting

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Abstract

In this study, a simple and efficient dual-port single-loop antenna unit, intended for full metal-frame terminals, is presented as the first of its kind. The proposed multiple-input and multiple-output (MIMO) antenna unit is constructed within a loop resonator, inserted between the metal frame and the ground plane without any slits or cuttings. Two voltage ports are utilized to simultaneously excite the shared loop resonator as radiators; however, the strong mutual coupling is induced from one port to another because of the shared loop resonator. Herein, a simple and efficient decoupling capacitor is loaded at the center of the loop resonator, decoupling and decorrelating the two-port loop resonator. In this way, a dual-port single-loop antenna unit is accomplished for 5G MIMO applications. Two units are constructed, forming 4 × 4 MIMO antennas, which are validated in both simulation and measurement.

KEYWORDS

5G, antenna unit, decoupling capacitor, dual-port single-loop, metal-frame, MIMO

1 | INTRODUCTION

Multiple-input multiple-output (MIMO) technology has been widely adopted in 4G LTE applications. With the deployment of 5G, it is required to scale up the number of antenna elements to dramatically increase the channel capacity and meet the desperate demand for ultra-fast speeds, low latency, and outstanding reliability.[1,2] Accordingly, a large-scale antenna array, for example, 4 × 4 MIMO or 8 × 8 MIMO, is a must in current 5G terminals.

For MIMO applications, high isolation and low correlation are important figure-of-merits that can avoid signal interference and efficiency degradation while ensuring diversity performance. The simplest and most straightforward way is the spatial arrangement of the antenna elements, but the dominant drawback of this method is the large distance and long footprint. Besides, there is not sufficient space available for antenna deployment, especially in terminal devices where crowded components are occupying most of the volumes. In this literature, researchers have proposed various decoupling methods to reduce the mutual distance between antenna elements and achieve spatial reuse.[3–14] These methods include neutralization lines, decoupling networks, decoupling structures, pattern or diversity control, and so forth.

Recently, terminals with metal frames, such as smartphones and tablets, are preferred by consumers. Under this circumstance, the introduction of a large-scale MIMO antenna array is a great challenge for antenna engineers, especially in the sub-6 GHz band. The commonly used method in the literature is to introduce cuttings or slits into the metal frames or rims.[15–24] However, their main drawback is the difficult construction process and additional manufacturing cost, not to mention their technical disadvantages, such as complex excitation, matching methods, difficult implementation,

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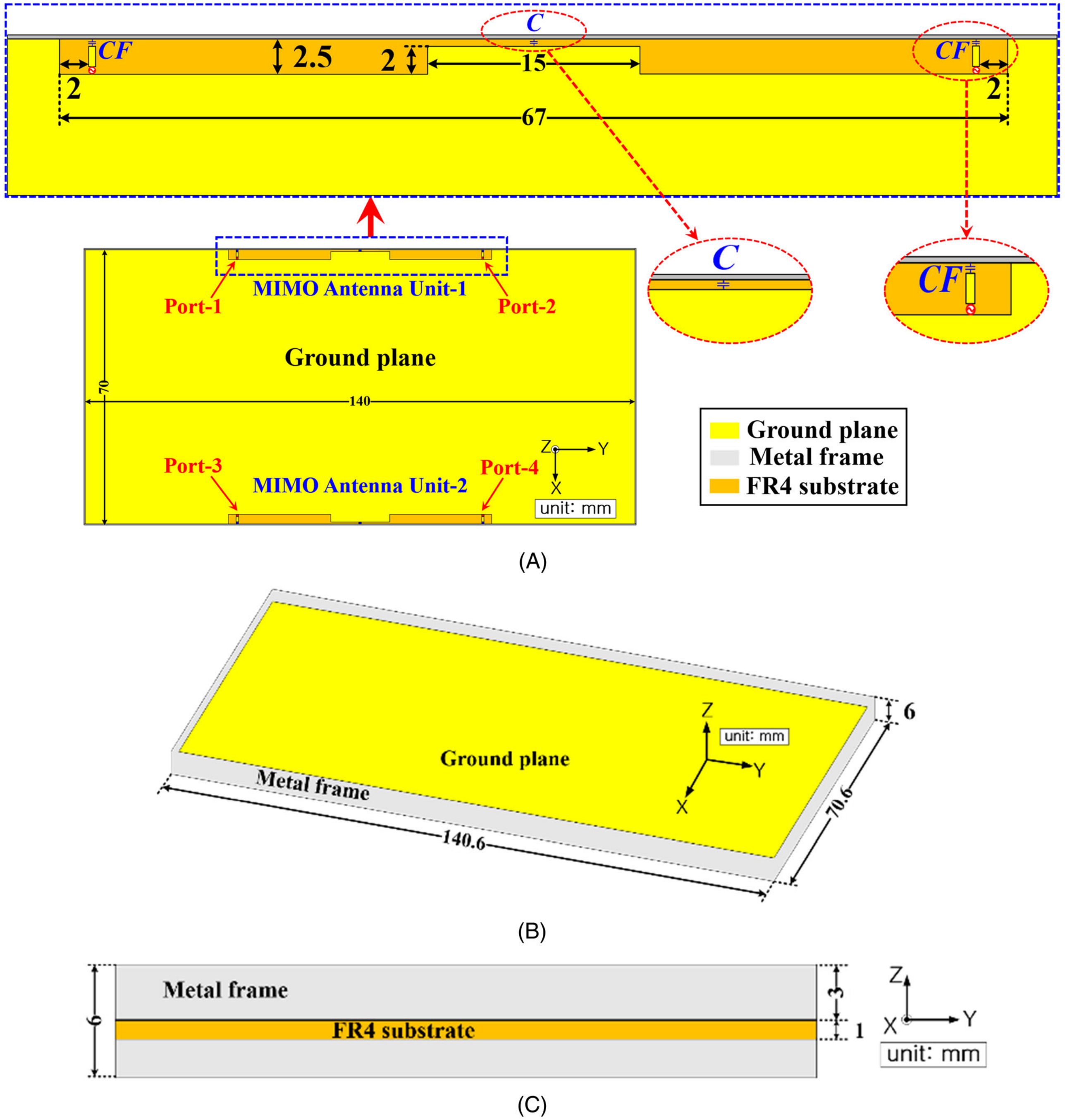

FIGURE 1 Configurations of the proposed MIMO antennas: (A) zoomed view of the MIMO antenna unit, (B) perspective view of the platform, and (C) side view of the metal frame. MIMO, multiple-input and multiple-output.

and low integration level. Especially, none of the reported studies in the literature[3–24] is suitable for current unbroken metal-frame terminals, such as smartphones, laptops, and tablets. Therefore, it is necessary to present a simple yet efficient MIMO antenna integration method for metal-rimmed terminals without any cuttings.

Accordingly, this study presents a new two-in-one MIMO antenna unit that can be simply integrated into the unbroken metal-rimmed terminals. The proposed MIMO antenna unit is formed in a single loop resonator, excited by two voltage sources simultaneously; a decoupling capacitor is utilized at the center of the loop resonator for decoupling and decorrelating the two ports. In this way, a dual-port single-loop MIMO antenna unit is accomplished. The main novelty and contribution of this study lie in two aspects:

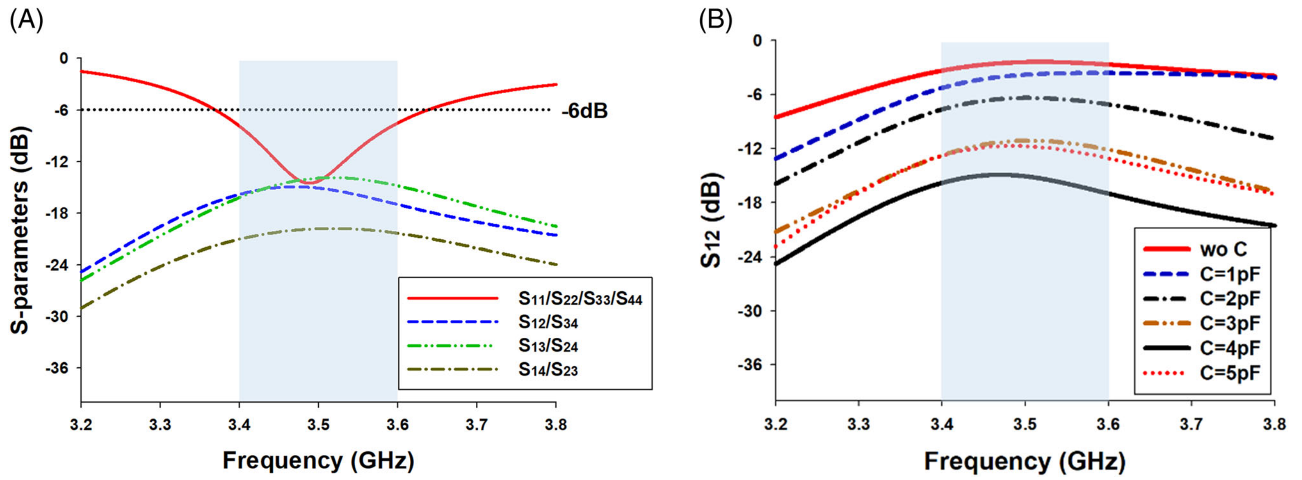

FIGURE 2 Simulation results: (A) S-parameters, (B) isolation performance (S_{12}) with the variation of the decoupling capacitor C

a) A novel and new MIMO antenna unit, intended for the unbroken meal-frame terminals, is presented for the first of its kind.
b) A simple yet efficient decoupling method for loop-type antennas is proposed here, having the advantages of simplicity, easy implementation, and high integration.

This manuscript is organized as follows. In Section 2, the proposed dual-port single-loop MIMO antenna unit operating at the 3.5 GHz band is described, and its operation mechanism is explained. In Section 3, fabrication and measurement were conducted to demonstrate the practicality of the proposed technique for 5G terminals.

2 | DUAL-PORT SINGLE-LOOP MIMO ANTENNA UNIT

2.1 | MIMO configurations

In Figure 1, the configurations of the proposed dual-port single-loop MIMO antenna unit are depicted. The implementation platform is a 140 mm × 70 mm ground plane, surrounded by an unbroken metal frame to model the metal-rimmed smartphone scenario. The ground plane is fabricated on a 1-mm-thick FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) while the height and the thickness of the metal frame are 6 and 0.3 mm, respectively. Meanwhile, the metal frame is connected to the ground plane endlessly, without any cuttings or slits.

As shown in Figure 1A, two sets of the proposed dual-port single-loop MIMO antenna unit with identical dimensions are designed at the center portion along the long sides of the ground plane. Each MIMO antenna unit has a symmetrical structure. Meanwhile, each MIMO antenna unit is constructed by occupying a 67-mm-long (0.79λ) clearance area along the edge side of the ground plane. The maximum gap of the ground clearance is 2.5 mm (0.03λ) and the minimum gap is 0.5 mm. As can be observed, the ground clearance is surrounded by the ground plane and the metal frame, and in this way, a loop-type resonator with an electrical perimeter of two wavelengths is formed around the ground clearance. Two voltage ports are loaded at the right and left ends of the loop resonator to simultaneously excite the shared loop as radiators. Each port is connected with a feeding capacitor *CF* so that the input impedance can be conveniently controlled. A decoupling capacitor *C* is loaded at the center portion of the loop antenna, connected between the ground plane and the metal frame, to improve the port-to-port isolation. Accordingly, both two antenna ports and all the lumped capacitors are enclosed inside the shared loop-type resonator, formed between the metal frame and the ground plane. Detailed information on the dual-port single-loop MIMO antenna unit can be found by referring to Figure 1B,C, and the optimized capacitor values of *CF* and *C* are 0.35 and 4 pF, respectively.

Accordingly, a dual-port single-loop MIMO antenna unit is accomplished by merely utilizing a decoupling capacitor between two coupled ports in a shared loop-type resonator. The method is simple and straightforward, especially suitable for unbroken metal-frame terminals with no need for any cuttings or slits. It is noted that the reference design is designated as the one without the decoupling capacitor *C*. In Figure 1, two sets of the proposed MIMO antenna units are implemented as 4 × 4 MIMO antennas for current metal-frame terminal applications.

Figure 2A presents the simulated scattering parameters (S-parameters) of the proposed MIMO antennas. It is seen that the produced impedance bandwidth of each

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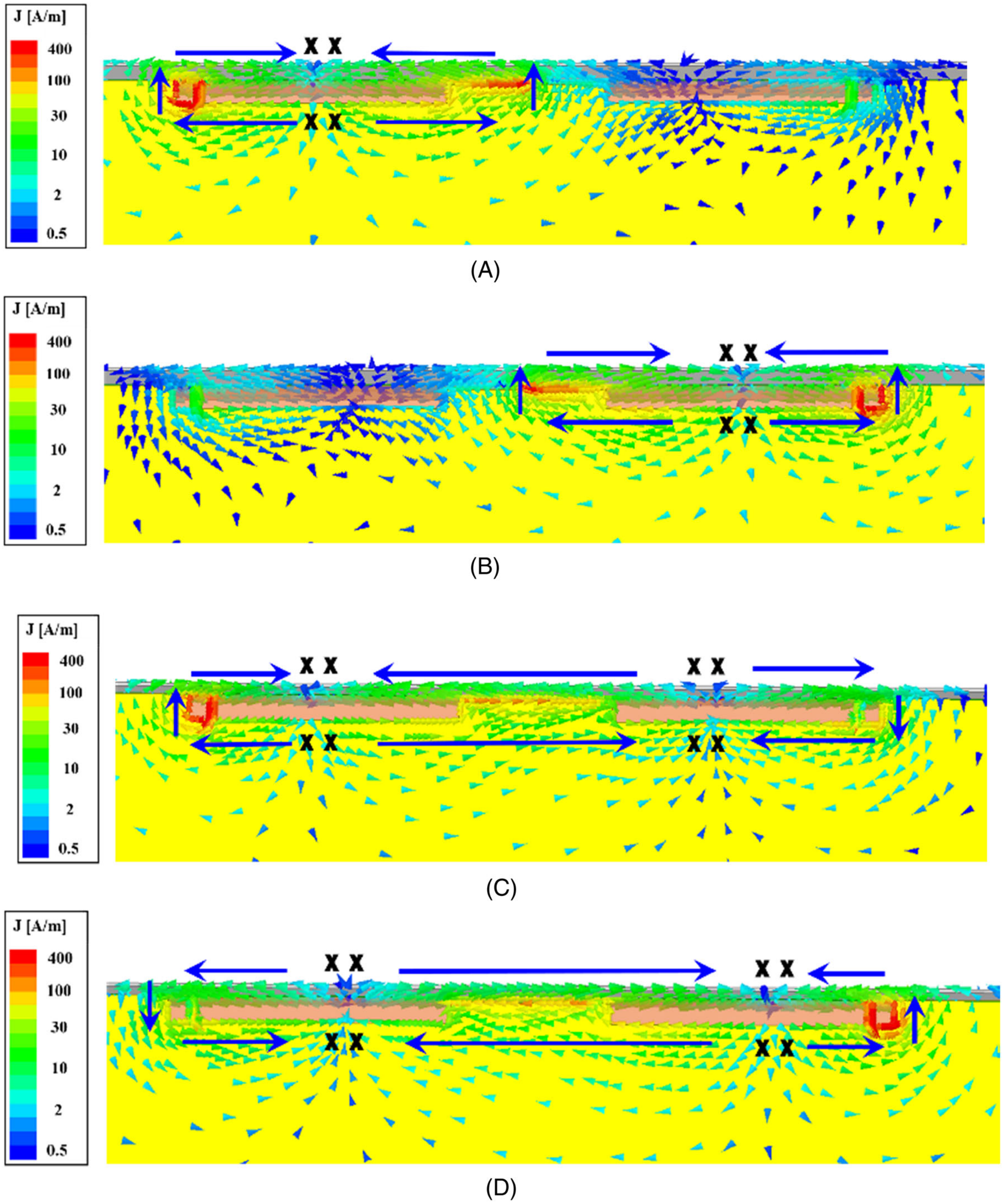

FIGURE 3 Simulated surface current distributions at 3.5 GHz: (A) excitation of Port 1 with the decoupling capacitor, (B) excitation of Port 2 with the decoupling capacitor, (C) excitation of Port 1 without the decoupling capacitor, and (D) excitation of Port 2 without the decoupling capacitor.

antenna can fully cover the 3.5 GHz band. Meanwhile, the port-to-port isolation within the proposed MIMO antenna unit (S_{12} or S_{34}) is higher than 15 dB, and isolation between each two antenna ports is higher than −14 dB.

Since the decoupling capacitor *C* plays a critical role in the proposed technique, a parameter study is discussed here to further understand its operation mechanism. As can be observed in Figure 2B, the mutual coupling (S_{12}) of the reference design without the decoupling capacitor is as high as −2.5 dB, which is attributed to the shared loop resonator. The mutual coupling gradually decreases as the value of the decoupling capacitor *C* increases from 1 to 4 pF. Meanwhile, a further increase of the capacitor

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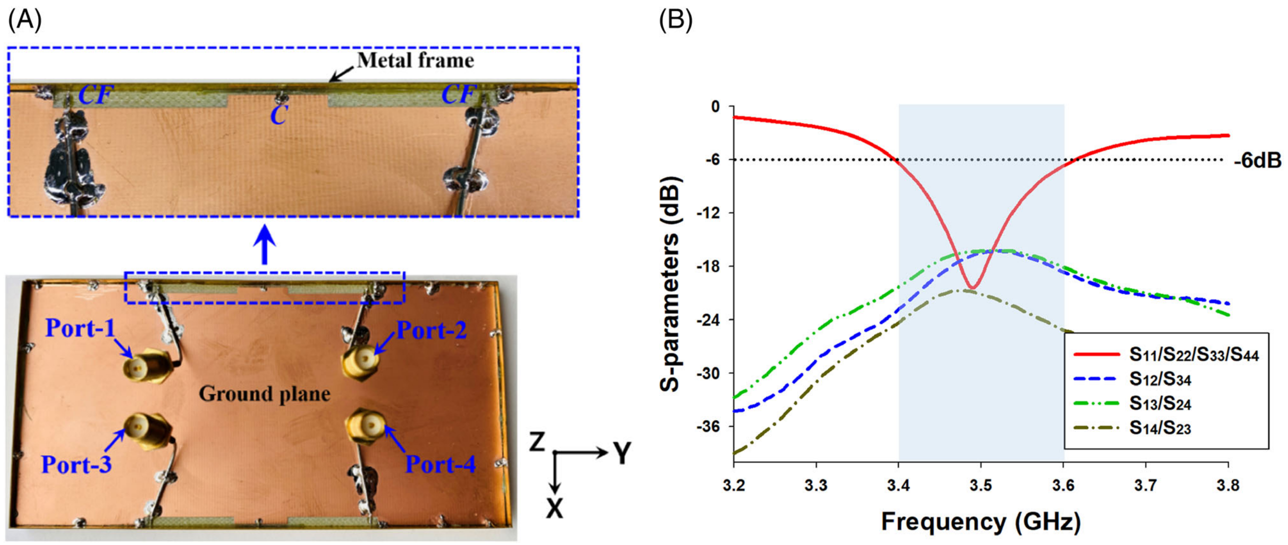

FIGURE 4 Fabrication and measurement: (A) prototype of the proposed 4 × 4 MIMO antennas, and (B) measured S-parameters of the fabricated antennas. MIMO, multiple-input and multiple-output.

value, instead, degrades the decoupling effect. Accordingly, optimization can be obtained when the capacitor value C is 4 pF. Therefore, the decoupling capacitor can significantly improve the isolation from 2.5 dB to above 15 dB.

2.2 | Operation mechanism and parameter study

The simulated surface current distribution over the proposed MIMO antenna unit with and without the decoupling capacitor is plotted in Figure 3 to better understand its operation mechanism. It is noted that the current distribution is generated at 3.5 GHz when one port is excited while the other is terminated with a matched load.

In Figure 3A, where Port 1 is excited and the decoupling capacitor is adopted, the antenna's currents are mainly concentrated on the left side of the MIMO antenna unit, and a wavelength loop-type current mode is produced. In Figure 3B where Port 2 is excited and the decoupling capacitor is deployed, it is seen that the current distribution mainly flows at the right-side of the MIMO antenna unit, producing another wavelength loop-type current mode. In both Figure 3A,B, strong currents are induced to the decoupling capacitor, blocking the current distributions from one side to the other side. More importantly, the induced current from one port to another is extremely weak, indicating the high isolation property between the two ports.

On the contrary, in Figure 3C,D without the decoupling capacitor, the current flow distributes around the ground clearance, and each antenna operates as a two-wavelength resonator (as can be verified from the current modes) by sharing the loop structure. In this case, the induced current from one port to another is high, and the mutual coupling between the two antenna ports is strong. According to Figure 3, the decoupling capacitor can modify the current distributions over the loop, and this is done by adjusting its impedance characteristic, as can be verified from Figure 2B. Therefore, it is obvious that the decoupling capacitor enables the two antenna ports to share a single loop, and the radiation of Port 1 and Port 2 is attributed to the left half (see Figure 3A) and the right half (see Figure 3B) of the loop structure, respectively.

2.3 | Design process

The design process of the proposed dual-port single-element MIMO antenna unit can be summarized as follows:

a) Design a single loop antenna as a two-wavelength resonator, and optimize the loop structure with optimized performance.
b) Symmetrically add another antenna port into the loop-type resonator so that a dual-port MIMO antenna unit is constructed.
c) Insert the decoupling capacitor at the center of the loop resonator, and optimize the isolation performance by sweeping the capacitor value. It is noted that the decoupling capacitor is located at the current

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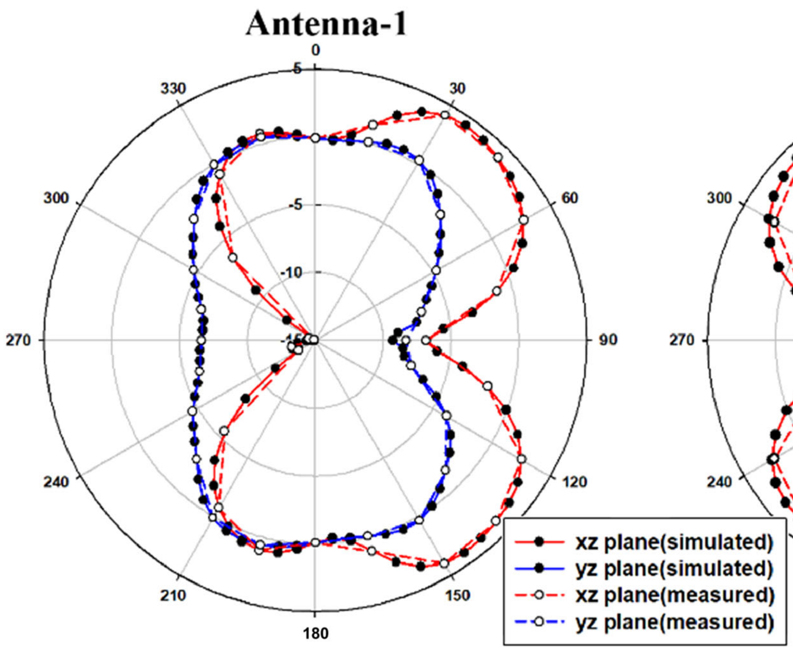

FIGURE 5 Simulated and measured radiation patterns at 3.5 GHz

maximum portion of the two-wavelength resonator, barely affecting the antenna resonance.

d) Optimize the overall performance of the MIMO antenna unit.

3 | FABRICATION AND MEASUREMENT

Based on the previous discussion, the presented 4 × 4 MIMO antennas (see Figure 1) are fabricated, and the prototype of the fabrication is pictured in Figure 4A. Furthermore, the fabrication was tested using a network analyzer and measured in a 6 m × 3 m × 3 m three-dimensional (3D) CTIA OTA anechoic chamber. To verify the adaption of the proposed technique in MIMO applications, some important parameters are investigated here, including mutual coupling, pattern diversity, and correlation.

First of all, the measured S-parameters are given in Figure 4B. As can be observed, the impedance bandwidths can fully cover the 3.5 GHz frequency band, and the mutual coupling between each two antenna ports is lower than −16 dB. Moreover, the measurement in Figure 4B agrees well with the simulation (see Figure 2), and the minor discrepancy may be attributed to the fabrication error. Therefore, the proposed dual-port single-loop MIMO antenna unit is feasible for currently unbroken metal-frame 5 G terminal applications.

In Figure 5, the produced far-field radiation patterns of the proposed MIMO antenna unit at 3.5 GHz are displayed in the *xz*-, *yz*-, and *xy*-planes. Meanwhile, it is verified that the antennas are linearly polarized and have approximately complementary radiation patterns with maximum gains directed against each other, which is an important feature for diversity performance and signal reception. As an important figure-of-merit to evaluate the MIMO performance, the envelope correlation coefficient (ECC) ρ_e is plotted in Figure 6, which is calculated from the vector properties (amplitude, phase, and polarization) of the complex far-field radiation patterns in measurement.[25] The ECC values are all below 0.1, far lower than the acceptable criterion in mobile communications ($\rho_e < 0.5$). Additionally, the measured total efficiencies are also plotted

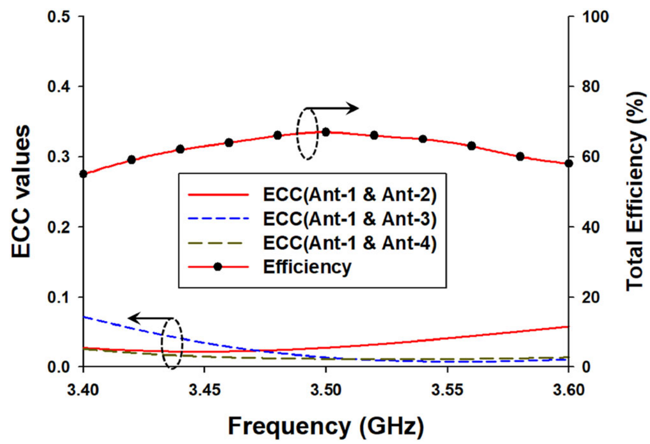

FIGURE 6 Measured ECC values and total efficiencies of the fabricated antennas. ECC, envelope correlation coefficient.

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TABLE 1 Comparisons with the state of the art for metal-frame terminals

Ref.	Decoupling method	Implementation method	−6dB impedance bandwidth	Isolation	Complexity
[15]	Neutralization line	Dual-mode monopole antenna	Dual-band (>200 MHz, >400 MHz)	>10 dB	Need for metal-frame slits; large clearance and large distance
[16]	Orthogonal modes	Shared slot	>200 MHz	>24 dB	Need for metal-frame cutting; complex matching network
[17]	Orthogonal modes	Shared-aperture antenna	>200 MHz	>19 dB	Need for metal-frame slits; difficult installation
[20]	Ungrounded full-wavelength strip resonator	Dual-slot antenna	>200 MHz	>11 dB	Need for metal-frame cuttings; difficult fabrication and low isolation
[24]	Mixed method	Slot antenna	1700 MHz	>10 dB	Need for metal-frame slits; difficult fabrication and low isolation
This work	Decoupling capacitor	Shared loop antenna	>200 MHz	>16 dB	No need for metal-frame slits; simple and new

in Figure 6, and each antenna produced high efficiencies of over 55% within the target band. Accordingly, the proposed dual-port single-loop MIMO antenna unit is demonstrated to have superiority in high isolation, simple implementation, as well as outstanding radiation performance, and good diversity performance, making it especially suitable in unbroken metal-frame terminal devices for 5G applications.

Finally, to further address the novelty of the proposed antenna, a comparison with the state-of-the-art MIMO antennas for metal frame terminals in the literature is conducted in Table 1. It is observed that the proposed dual-port single-loop MIMO antenna unit can produce comparable performances, e.g., impedance bandwidth and isolation. Most importantly, the proposed technique avoids the need for cuttings or slits in the metal frame, which is the first of its kind.

4 | CONCLUSION

This letter presents a novel dual-port single-loop MIMO antenna unit, which is especially suitable for unbroken metal-frame terminals in the 3.5 GHz operation band. The proposed MIMO antenna unit is accomplished within a two-wavelength loop resonator between the ground plane and metal frame. A simple decoupling capacitor at the center of the loop resonator is utilized to isolate two antenna ports. In this way, high port-to-port isolation is obtained even though the two antenna ports share a single loop-type structure. With the utilization of the decoupling capacitor, the isolation of the proposed MIMO antenna unit can be improved from 2.5 dB to 15 dB. 4 × 4 MIMO antennas were fabricated and verified in measurement. The impedance bandwidth can fully cover the operation band, and the isolation between each two antenna ports is higher than 16 dB in measurement. The produced efficiencies are higher than 55% and the calculated ECC values are lower than 0.1. The proposed MIMO antenna unit is feasible for unbroken metal-frame terminals with advantages in easy integration, simple implementation, high isolation, as well as excellent radiation and diversity performances.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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