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An LTCC Interference Cancellation Device for Closely Spaced Antennas Decoupling

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ABSTRACT A compact interference cancellation device (ICD) offering a great decoupling for a pair of closely overlapped antennas and enhancing the throughput of the multi-input-multi-output (MIMO) system is proposed. The device is implemented using semi-lumped components with a compact size of 1.6 mm $\times$ 0.8 mm $\times$ 0.6 mm with the help of the low temperature co-fired ceramics multilayer fabrication technology. The proposed topology is applied to enhance the overall data throughput of a MIMO system with two overlapped antennas sharing a reduced clearance region. A MIMO antenna system consisting of two conventional coupled antennas locating at the same plane, and its counterpart containing two overlapped antennas integrated with the ICD chip are fully investigated. The experimental results demonstrate that around 10% overall throughput improvement of the MIMO system is obtained across the 2.4 GHz band while the ground clearance area of the antennas has been shrunk by 50%. It is also proved that the presented ICD device is a good candidate in applications of mobile terminals and wireless communication devices with very compact volumes.

INDEX TERMS Overlapped antennas, mutual coupling, antenna decoupling, MIMO system, throughput enhancement.

I. INTRODUCTION

As the highly increasing demands on higher data rate and larger average throughput of wireless communication systems, the multiple-input multiple-output (MIMO) technology has attracted huge attention in both industrial and academic community due to its promising advantages in terms of providing better transmission quality and enhancing coverage [1]. Therefore, extensive studies have been performed on MIMO antennas which are suitable for various multi-functional high-speed mobile terminals with compact size and wideband characteristics [2]–[5]. It is remarkable that with consideration of the increasing frequency bands and the limited spatial space among mobile terminal devices, the most challenging part exists in realizing MIMO capability within the compact volume of a mobile device. Since good channel throughput can be achieved when the correlations among MIMO antenna elements are sufficiently low [6]–[8], the envelope correlation coefficient (ECC), which is directly affected by the isolation of the multi-element antenna, is one of the key factors for the MIMO systems. However, with the limited size and the number of antenna element increasing, the spatial correlation and the mutual coupling among antennas become worse, which further deteriorates the ECC, lowers the radiation efficiency, and reduces the channel capacity [9]. All of the abovementioned shortcomings degrade the merits of a MIMO system and worsen its performance. Hence, a critical consideration in designing MIMO antennas for wireless communications is providing sufficiently good antenna isolation [10]–[12]. A printed ultra-wideband MIMO antenna system operating in 3.1-10.6 GHz is proposed in [10], which applies a tree-like structure on the ground plane so as to block the current from one radiator flowing to the other one. In this design, the isolation between the two antenna elements is better than 16 dB in the wide operating bandwidth.

In [11], a directional slot antenna utilizing a two-element array structure is firstly introduced with a high front-to-back ratio of up to 19.2 dB. Subsequently, the proposed slot antenna is adopted to construct a compact four-element MIMO array which obtains a good isolation of over 22 dB across the bandwidth of 5.0-6.0 GHz. Besides, a four-port reconfigurable MIMO antenna designed for IEEE 802.11 applications is proposed in [12]. With different states of the radio-frequency (RF) micro-electromechanical system (MEMS) switches, the antenna is able to work as either a four-port antenna operating at 5 GHz band or a two-port antenna operating at 2.4 GHz band together with another two-port antenna working at 5 GHz band. Both configurations provide good isolations between the antenna ports. Recently, a passive network topology is proposed for two closely located antennas in [13]–[15], which provides an efficient way to eliminate the leakage current between two antennas, thus improve the isolation between them. All the above-mentioned solutions are able to realize good antenna isolation; however, these topologies are not practical enough to be placed in a size-limited mobile communication terminal.

Meanwhile, it should be noted that, compared with the authors' previous work [15], the proposed ICD has a different topology which makes it more suitable for extremely strong mutual coupling between two overlapped antennas sharing a common clearance region, while the previous one only deals with the case that two antennas are placed side-by-side in the same plane. Besides, although the upgraded ICD contains two more resonant cells, the volume has greatly reduced from 3.2 mm×2.5 mm×1.2 mm to 1.6 mm×0.8 mm×0.6 mm, which would be more practical to be used in a compact modern communication terminal.

As Massive MIMO and Carrier Aggregation (CA) have become key technologies for 4.5G and 5G wireless systems [16] [17], an increasing number of multiband antennas will be coexisted in one modern compact communication device in order to increase the overall transmission bandwidth and realize considerably higher data rate. In this case, the mutual coupling and interference problem among the antenna elements will inevitably become more severe. Therefore, developing an effective antenna decoupling technology with sufficiently compact volume has become a focused research area in recent years.

In this paper, an integrated general solution, whose core part is a miniaturized interference cancellation device (ICD), is proposed to reduce the strong mutual coupling between MIMO antennas, and accordingly enhance the system throughput. The basic underlying principle of the ICD is that using a 2$^{\text{nd}}$ or higher order coupling resonator network with its admittance opposite to that of the closely located antennas, the mutual coupling effect can be greatly reduced within the band of interest by connecting the ICD to the adjacent antennas in shunt. Remarkably, unlike conventional planar MIMO antenna elements reported in other works, the coupled antennas in this work are placed at the two sides of the same clearance region, i.e., antennas overlapping, to simulate an extremely compact condition. In this case, it is known that although whole antenna area can be greatly reduced by about 50%, it also makes the mutual coupling between the antennas much stronger than those of planar placed ones. However, by using the ICD with two adjustable elements, not only the strong coupling between the two overlapped antennas can be largely reduced, but also the channel throughput of the test MIMO system is improved. In other words, high isolation between the antenna elements and enhanced throughput of the MIMO system can be achieved simultaneously in an extremely compact volume due to the merit of this integrated solution, which will be very suitable for modern wireless portable terminal device [18]. In addition, the proposed ICD can handle various form factors in realization, such as low temperature co-fired ceramics (LTCC) and integrated passive devices (IPD), which could render the whole size more compact. Note that the work is of a great improvement and difference from our previous one [19]. The chip topology in this paper has been optimized and modified to be more suitable for applying in strongly coupled environments (e.g., isolation lower than 5 dB). Furthermore, the proposed decoupling chip can not only be applied to planar coupled antennas but also suitable for overlapped antennas (sharing the same clearance). At the same time, an obvious improvement on the throughput of the MIMO system has also been demonstrated. In a word, the proposed interference cancellation device technology can effectively solve the problem of antenna interference caused by multi-antenna system in wireless communication terminals.

II. DESIGN THEORY

The correlation of the terminal antennas has been studied in [20], as well as its impact on MIMO channel capacity. According to [21], the channel capacity of a point to point MIMO system can be expressed as below,

$$C = \log_2 \left[\det \left(I_{Nr} + \frac{\rho}{N_t} H H^H \right) \right] \tag{1}$$

where ρ is the average signal noise power ratio (SNR), I_{Nr} is an $N_r \times N_r$ identity matrix, and H is the channel matrix. In addition, based on [22], it is also shown that antenna parameters, for instance, ECC and antenna isolation, have great effects on MIMO system capacity and diversity performance. In other words, higher antenna isolation means lower ECC, which leads to better channel capacity and diversity gain. Therefore, an interference cancellation network is proposed in this paper to enhance the isolation between two closely placed antennas and improve the throughput of the MIMO system simultaneously.

As shown in Fig. 1, two coupled antennas can be represented by a 2×2 admittance matrix $[Y^A]$ with complex entries, and their mutual coupling/interference is reduced by an interference cancellation network (ICN) which consists of a consolidated LTCC ICD, Match network 3, Match network 4 and two adjustable components (J_{11} and J_{22}). As the ICN is directly connected to the antennas network in shunt with its admittance matrix $[Y^N]$, the admittance of the whole topology is the superposition of the two individual admittance

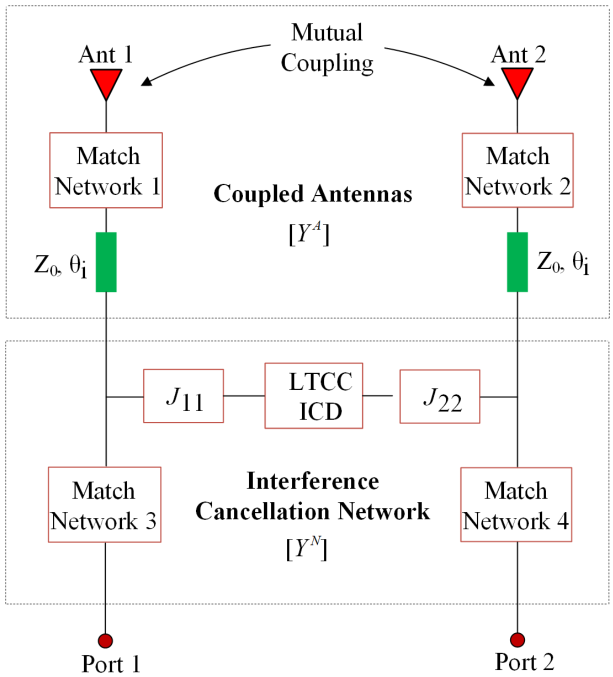


FIGURE 1. The proposed interference cancellation circuit topology.

matrices as:

$$\mathbf{Y} = \begin{bmatrix} Y_{11}(f) & Y_{12}(f) \\ Y_{21}(f) & Y_{22}(f) \end{bmatrix} = \begin{bmatrix} Y_{11}^A(f) + Y_{11}^N(f) & Y_{12}^A(f) + Y_{12}^N(f) \\ Y_{21}^A(f) + Y_{21}^N(f) & Y_{22}^A(f) + Y_{22}^N(f) \end{bmatrix} \tag{2}$$

Where the parameter f is the band-pass frequency variable.

Assuming the ICN is lossless, the entries of the admittance matrix $[Y^N]$ can be considered as purely imaginary. Nevertheless, the admittance matrix $[Y^A]$ for the antenna networks is complex in general. The entire network demonstrated in Fig. 1 can be produced from an S-to-Y matrix transformation [23]. Therefore, high isolation between Port 1 and Port 2 could be realized within the interfering frequency band if:

$$\mathrm{Re}\left\{Y_{21}^A(f)\right\} \approx 0, \quad f \in [f_1, f_2] \tag{3a}$$

$$\mathrm{Im}\left\{Y_{21}^A(f)\right\} + \mathrm{Im}\left\{Y_{21}^N(f)\right\} \approx 0, \quad f \in [f_1, f_2] \tag{3b}$$

Condition (3a) can be satisfied by introducing a portion of matching conversion transmission line as clarified in [13], and (3b) is related to ICD's admittance characteristic.

Besides, it is also important that the total impedance matching performance of the antenna system should not be degraded after the decoupling process. Thus, the impedance matching conditions is able to rewrite as:

$$\mathrm{Re}\left\{Y_{kk}^A(f)\right\} \approx Y_0, \quad f \in [f_1, f_2], \ k = 1, 2 \tag{4a}$$

$$\mathrm{Im}\left\{Y_{kk}^A(f)\right\} + \mathrm{Im}\left\{Y_{kk}^N(f)\right\} \approx 0, \quad f \in [f_1, f_2], \ k = 1, 2 \tag{4b}$$

When the coupled antennas are assumed to be well-matched at the original resonant frequency, (4b) can be simplified to:

$$\mathrm{Im}\left\{Y_{kk}^N(f)\right\} \approx 0, \quad f \in [f_1, f_2], \ k = 1, 2 \tag{4c}$$

III. DESIGN DEMONSTRATION

To verify the proposed concept, an interference cancellation network is designed and applied to decouple two closely overlapped monopole antennas resonating at Wi-Fi 2.4 GHz (2.4 $\sim$ 2.483 GHz) band. Fig. 2 shows the geometry and dimensions of the antennas to be decoupled before employing the decoupling network. The two monopole antennas are located face-to-face at the opposite sides of a FR-4 PCB substrate, and the total occupied area is 20×11 mm^2. The coupled antennas are tuned to be well-matched at the designed resonant frequency with input impedances of about 50 ohms. Fig. 3 presents the configuration of the decoupled antenna system. As can be seen, Antenna 1, Matching Network 1, Matching Network 2 and the Interference Cancellation Network are located on the top side, while Antenna 2 is located on the bottom side, which is connected to the Matching Network 2 through a metal via.

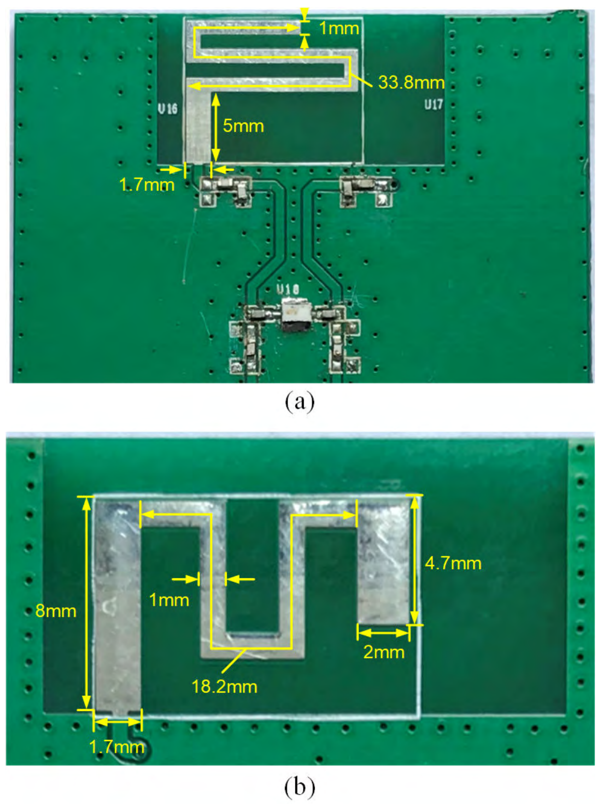
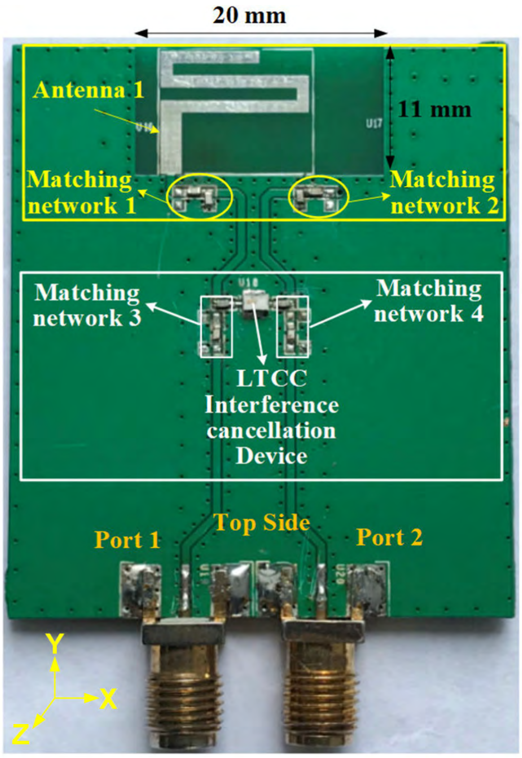
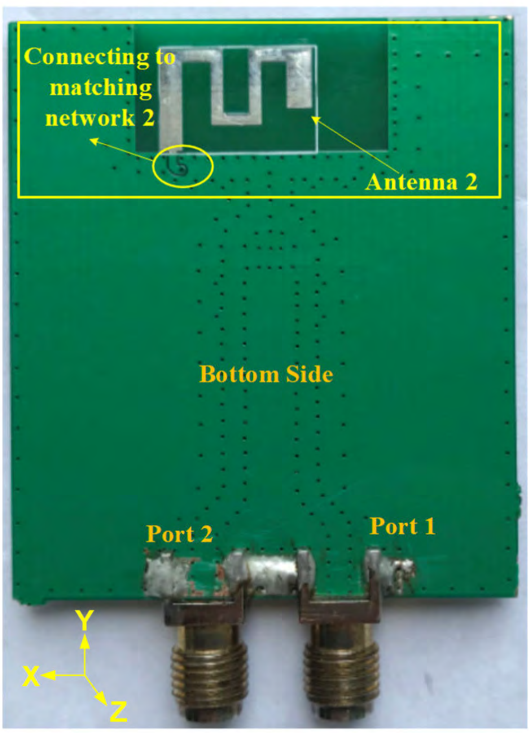


FIGURE 2. The geometry and dimensions of the coupled antennas. (a) Antenna 1. (b) Antenna 2.

The initial coupling between the two antennas is extremely strong because of the small common clearance region and close spacing between the antennas. Fig. 4 shows the LTCC electromagnetic (EM) model and circuit model of the ICD.



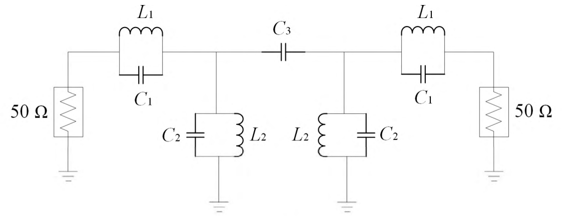
(a)



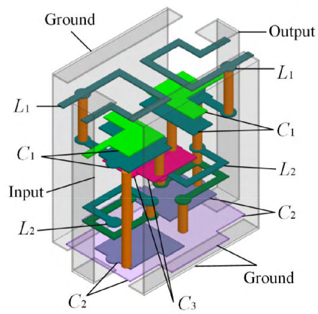
(b)

FIGURE 3. (a) Top side of the decoupled overlapped antennas. (b) Bottom side of the decoupled overlapped antennas.

Generally, it is a π-network consisting of two L-C resonant tanks. To further satisfy the decoupling condition (3) and matching condition (4) simultaneously, the components



(a)



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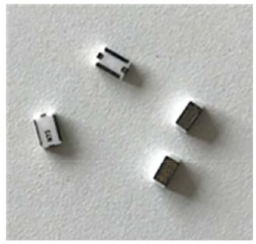

(c)

FIGURE 4. (a) Circuit model of the LTCC ICD. (b) EM model of the LTCC ICD. (c) Proposed ICD with LTCC technology.

C_1, C_2, L_1 and L_2 are optimized with the help of simulation. Thereafter, the whole circuit can be realized by using LTCC technology. The optimal parameters of the lumped components presented in Fig. 4 (a) are: $L_1 = 2.29$ nH, $L_2 = 2.4$ nH, $C_1 = 1.15$ pF, $C_2 = 2.15$ pF, and $C_3 = 0.79$ pF. The proposed ICD consists of 12 layers of silver conductors totally, which are implanted in a ceramic substrate with relative permittivity of 9.8 and loss tangent of 0.0035. After plating with tin/nickel electrode, the final device has a very small volume of 1.6×0.8×0.6 mm^3, as shown in Fig. 4(c).

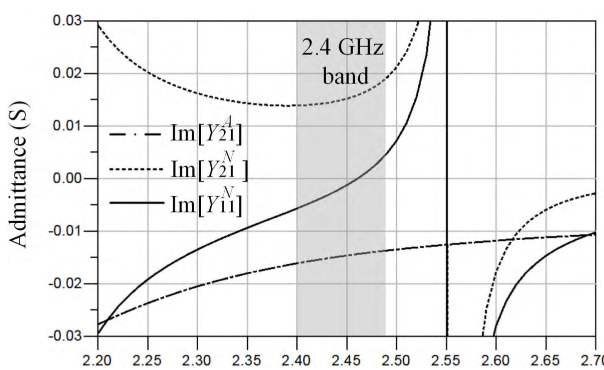

FIGURE 5. Measured Y-parameters of the antennas shown in Fig. 2.

The measured Y-parameters of the decoupled antenna system at 2.45 GHz is shown in Fig. 5. As can be seen, the $\mathrm{Im}(Y_{21}^N)$ is a positive admittance about 0.015 S, which just neutralizes the $\mathrm{Im}(Y_{21}^A)$ with a negative admittance about −0.015 S. Furthermore, the decoupled antennas are well matched as $\mathrm{Im}(Y_{11}^N)$ is near zero.

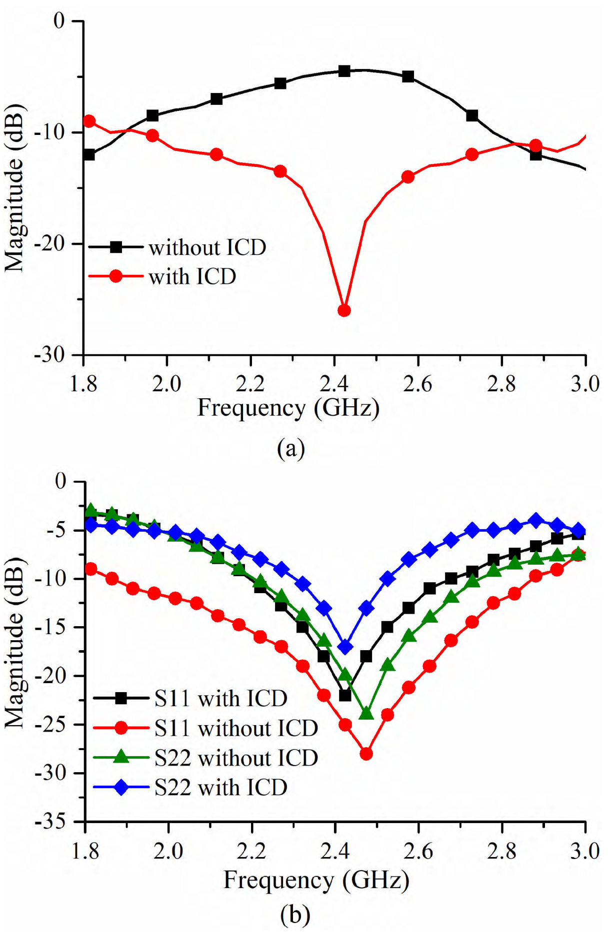

FIGURE 6. Measured S-parameters of the overlapped antennas with and without the ICD. (a) Isolation. (b) Reflection coefficient.

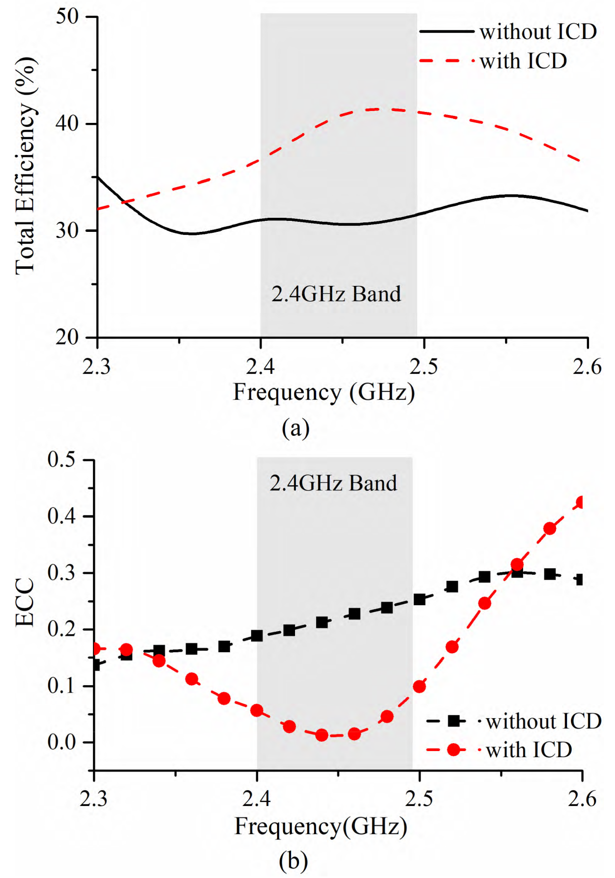

FIGURE 7. (a) Measured total efficiency of the overlapped antennas with and without the ICD at 2.4 GHz band. (b) Measured ECC at 2.4 GHz band.

The measured S-parameter of the antennas with and without LTCC ICD circuit is shown in Fig. 6. It is clear that, without the ICD, although the antennas are well matched at 2.4 GHz band, the isolation of the coupled antennas is no more than 5 dB within the working band due to the vertical coupling structure. However, with the help of the proposed decoupled antenna with ICD circuit, the isolation has been improved by better than 12 dB in 100 MHz bandwidth, while the impedance matching performance at 2.4 GHz band is still satisfactory. It is also observed that the matching bandwidths of both antennas decrease when the interference cancellation network is utilized. The main reason for this phenomenon is that the antennas with poor isolation have lower quality factor (Q) values than those have higher isolation, thus one could understand that the matching bandwidth for an antenna with lower Q value is wider.

In order to verify the performance of the proposed device in terms of radiation characteristics, the antennas with and without the interference cancellation network are measured by a SATIMO near-field test chamber. Fig. 7(a) shows the measured total efficiency, which is the averaged efficiency of the two antennas. It can be seen that the total efficiency of the overlapped antennas has been improved by more than 8% within the 2.4 GHz band after applying the decoupling technique.

As mentioned, another important figure of merit in MIMO systems is the ECC, which can be derived from the experimental complex radiation patterns as described in [24]:

$$\rho_e = \frac{\left| \iint_{4\pi} [\mathbf{E}_1(\theta,\phi) \cdot \mathbf{E}_2(\theta,\phi)] d\Omega \right|^2}{\iint_{4\pi} |\mathbf{E}_1(\theta,\phi)|^2 d\Omega \iint_{4\pi} |\mathbf{E}_2(\theta,\phi)|^2 d\Omega} \tag{5}$$

The ECC performance of the antennas with and without the ICD are plotted in Fig. 7(b) based on (5). A great ECC improvement can be observed between the one without ICD (around 0.2) and with ICD (around 0.05).

To further prove the practical merit of the proposed ICD, an experimental comparison of throughput capacity between MIMO systems using conventional coupled antennas without ICD and overlapped antennas with ICD is carried out. It can be seen from Fig. 8(a) that the conventional coupled antennas occupied a clearance region of 40 mm×11 mm, while that of the overlapped antennas (shown in Fig. 3) has shrunk by 50%. Fig. 8(c) shows the experimental antenna isolation of the two topologies. Although the conventional solution has

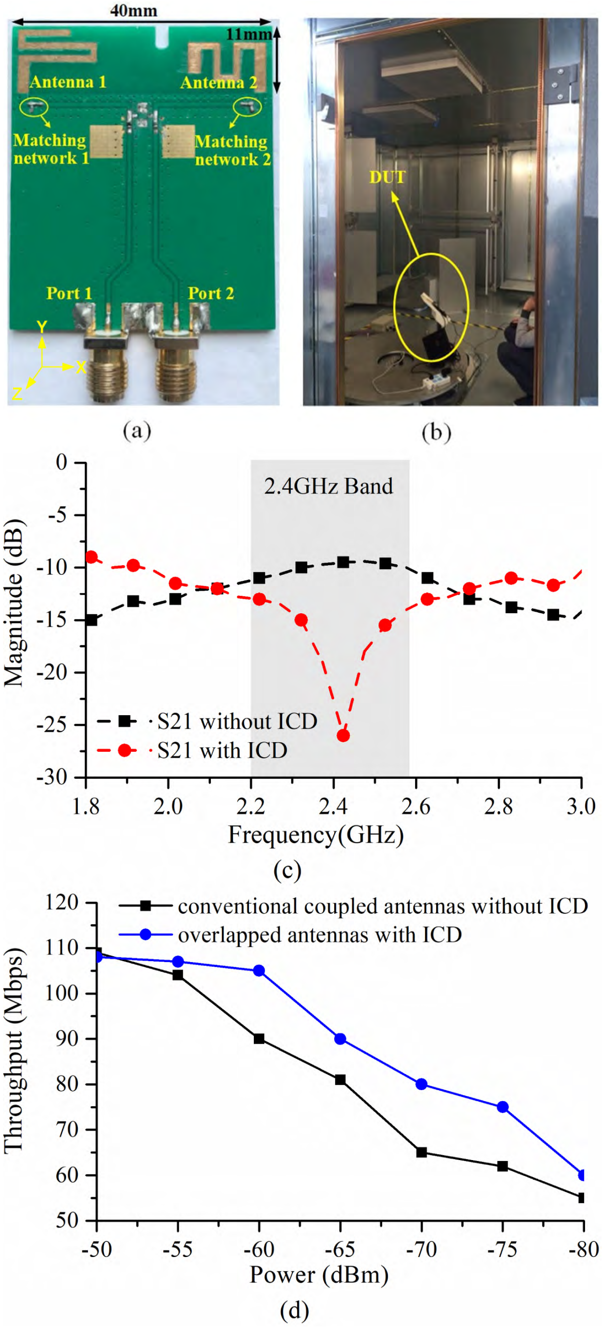

FIGURE 8. **(a) Conventional coupled antenna array. (b) Throughput measurement in a RTS60 reverberation chamber. (c) Measured isolations of the conventional coupled antennas and the decoupled overlapped antennas. (d) Measured data throughput comparison.**

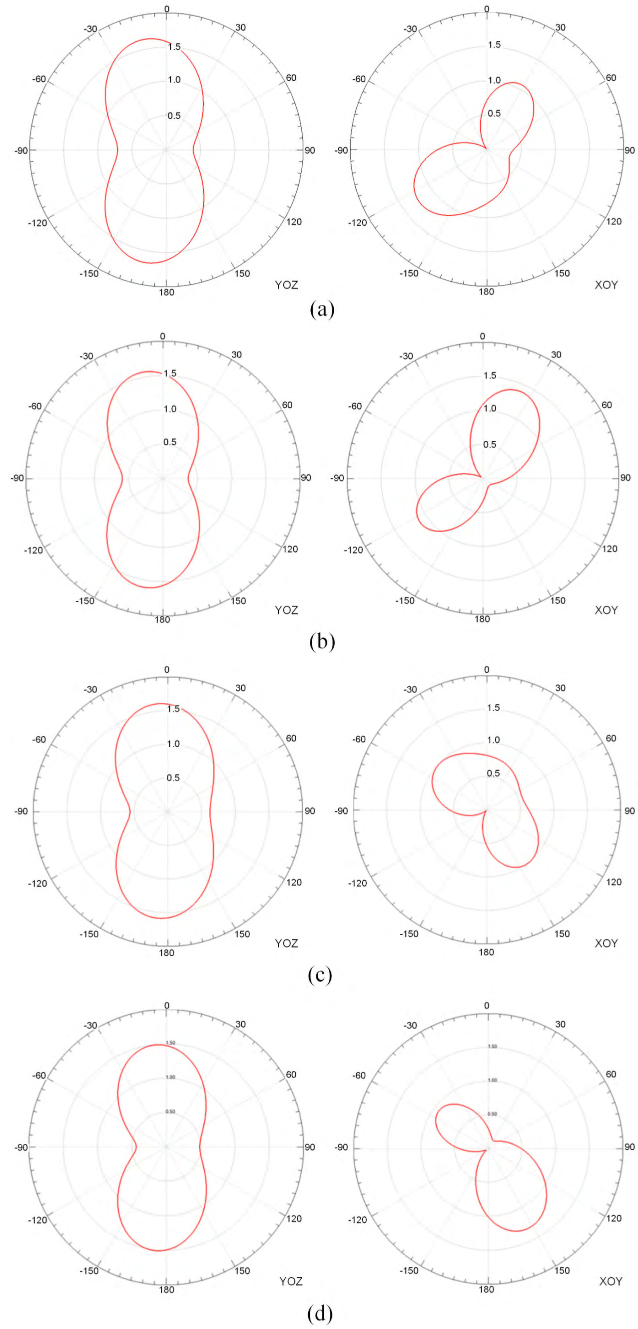

FIGURE 9. **Radiation patterns under different scenarios: (a) Antenna 1 without the proposed ICD device (measured at 2.45 GHz). (b) Antenna 1 with the proposed ICD device (measured at 2.45 GHz). (c) Antenna 2 without the proposed ICD device (measured at 2.45 GHz). (d) Antenna 2 with the proposed ICD device (measured at 2.45 GHz).**

a relatively larger space between the antennas, the isolation is hard to exceed more than 10 dB within the operating bandwidth. On the contrary, by adopting the ICD decoupling mechanism, the isolation between the overlapped antennas, whose coupling effect is much stronger than the conventional one, can achieve more than 18 dB while the occupied clearance is only 20 mm×11 mm. The overall data throughput is measured in a Bluetest's RTS60 reverberation chamber as shown in Fig. 8(b). The system is able to measure the downlink performance by using four reference antennas at the AP (Access Point) end, while the antennas with and without the interference cancellation network are used as the client. The tested bandwidth is 20 MHz under the IEEE 802.11n protocol. The measured results are averaged over channel 1, 7 and 12 in the 2.4 GHz Wi-Fi bands. Throughput comparison

TABLE 1. Performance comparison between this work and other existing structures.

Indicator	The proposed ICD	Decoupling device in [13]	Decoupling device in [14]	Decoupling device in [15]
Occupied area or volume	1.6×0.8×0.6mm^3	1.0×0.5×0.5 mm^3	12.8×9.5mm^2	3.2×2.5×1.2 mm^3
20dB decoupling bandwidth	85 MHz	40 MHz	500 MHz	110 MHz
Clearance area of the antennas	Half of the normal one	Normal	Normal	Normal
Decoupling frequency band	2.4 GHz band	2.4 GHz band	2.4 GHz band	2.4 GHz band
Complexity of the method	Ordinary	Low	Ordinary	Ordinary

is illustrated in Fig. 8(d). One can observe that the throughput has been improved by around 10% while taking all power levels into consideration. Furthermore, measured radiation patterns of the antennas under different scenarios are plotted in Fig. 9. It can be seen though there are small discrepancies existent between the antenna with and without the proposed ICD device, the overall radiation performance is acceptable. Finally, a table of comparing this work with other existing structures is shown in Table 1. One could identify that the proposed ICD is very compact and suitable for MIMO system of modern wireless communication devices with miniaturized ground plane and volume.

IV. CONCLUSION

An integrated interference cancellation network realized by multilayered structure was presented to reduce the mutual coupling between the closely placed antennas, lower down the ECC, and improve the throughput of MIMO system accordingly. The planar coupled antennas and the overlapped antennas with the integrated ICD have been designed and tested to verify the practical effectiveness of the interference cancellation network. It is shown that around 10% overall throughput improvement of the MIMO system can be achieved while the ground clearance area of antennas has been reduced by 50% simultaneously. The proposed topology is very suitable for MIMO system in modern wireless communication device with miniaturized ground plane and compact volume.

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