Multimode Decoupling Technique With Independent Tuning Characteristic for Mobile Terminals

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***Abstract*—The isolation between antenna elements is a key metric in some promising fifth generation technologies such as beamforming and in-band full-duplex. However, the multimode decoupling technology remains a great challenge, especially for mobile terminals. One difficulty in achieving multidecoupling modes is that the operating modes of closely packed decoupling elements have very strong mutual effect, which makes the tuning complicated and even unfeasible. Thus, in physical principle, a novel idea of achieving the stability of the boundary conditions of decoupling elements is proposed to solve the mutual effect problem; in physical structure, a metal boundary is adopted to realize the stability. One distinguished feature of the proposed technique is that the independent tuning characteristic can be maintained even if the number of decoupling elements increases. Therefore, wideband/multiband high isolation can be achieved by using multidecoupling elements. To validate the concept, two case studies are given. In a quad-mode decoupling design, the isolation is enhanced from 12.7 to >21 dB within 22% bandwidth by using a $0.295\lambda_0 \times 0.059\lambda_0 \times 0.007\lambda_0$ decoupling structure. The mechanism of the decoupling technique and the mutual effect between decoupling elements are investigated.**

***Index Terms*—Fifth generation (5G) communication, multimode decoupling elements, mutual coupling, wideband decoupling.**

I. Introduction

THE next generation of the mobile wireless technology, i.e., fifth generation (5G) wireless systems, will be able to deliver multigigabit-per-second data and efficiently support a much larger and more diverse set of devices than fourth generation wireless systems [1]. Beamforming and in-band full-duplex (IBFD) are very promising technologies for 5G [1]–[3]. One common feature of these technologies is the requirement of high isolation between antenna elements, because the strong mutual coupling among antenna elements will cause blind spot in wide-angle beam scanning array (beamforming) and severe self-interference (the major problem in an IBFD system) [3]–[5]. However, it is a great challenge to achieve good isolation in mobile terminals due to the limited space. Scientists have spent a lot of efforts on this problem.

Manuscript received October 31, 2016; revised August 17, 2017; accepted September 11, 2017. Date of publication September 19, 2017; date of current version November 30, 2017. This work was supported by Huawei Technologies Ltd., China. *(Corresponding author: Hang Xu.)*

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Digital Object Identifier 10.1109/TAP.2017.2754445

Recently, some isolation enhancement methods have been reported including defected ground structure (DGS) [6], orthogonal polarization [7], characteristic mode [8], decoupling network [9], neutralization line [10], and decoupling element [11]. However, the multimode decoupling technology remains a great challenge in compact application scenarios. DGS is bulky for mobile terminals such as smart phones [12]–[15]. A compact antenna array with orthogonal polarization is proposed for smart phones; acceptable isolations and good system performance are obtained [16]. Characteristic mode can achieve good isolation below 1 GHz [8], but it is difficult to manipulate the frequency of multicharacteristic modes, because the freedom of modifying the radiator, i.e., the chassis, is very limited. Most decoupling networks are filter-like structures [17]–[20], so multidecoupling modes can be realized by referring to the design theory of multimode filter. Nevertheless, if the number of the decoupling modes rises, the design difficulty may become unacceptable due to the increased complexity of the corresponding matrix. Reference [21] shows a design of three neutralization lines, but the layout is not flexible because the design needs to connect to specific locations of the antenna elements, and the neutralization lines affect each other.

To some extent, decoupling element can be identified as a wireless decoupling technology, so multidecoupling modes can be achieved by conveniently arranging a multimode decoupling element or multisingle-mode decoupling elements between antenna elements or anywhere available. In [22], a tree-like multimode decoupling element was reported and achieved wideband isolation, but it is still bulky and does not show an easy-tuning feature; in theory, a miniaturized multimode resonator (decoupling element) is difficult to tune because of extremely complicated electromagnetic (EM) environment. Then another choice is to use multisingle-mode decoupling elements, but the strong mutual effect between closely packed decoupling elements is a large problem (it will be explained in Section II-B).

In this paper, a novel idea of achieving the stability of the boundary conditions of decoupling elements is proposed to solve the problem of strong mutual effect; a metal boundary is adopted to realize the stability by using its total-reflection feature. Benefiting from the achieved stability of the boundary conditions, the operating modes of different decoupling elements can achieve independent tuning even if the edge-to-edge distance between these decoupling elements is only 3 mm ($0.035\lambda_0$ at 3.5 GHz and $0.024\lambda_0$ at 2.45 GHz). Besides, there is no limit for the number of the decoupling elements in this technique; in other words, $N-1$ metal boundaries can be inserted between N decoupling elements ($N = 2, 3, 4, \ldots$). A distinguished feature of the proposed technique is that the independent tuning characteristic can still be maintained in the case of more decoupling elements (the key of the arrangement will be explained in Section III-B). As a result, wideband/multiband high isolation can be achieved by using multidecoupling elements. Two case studies are given to validate the concept. In a quad-mode decoupling design, the isolation is enhanced from 12.7 to >21 dB within 22% bandwidth by using a $0.295\lambda_0 \times 0.059\lambda_0 \times 0.007\lambda_0$ decoupling structure. The mechanism of the decoupling technique and the mutual effect between decoupling elements are investigated.

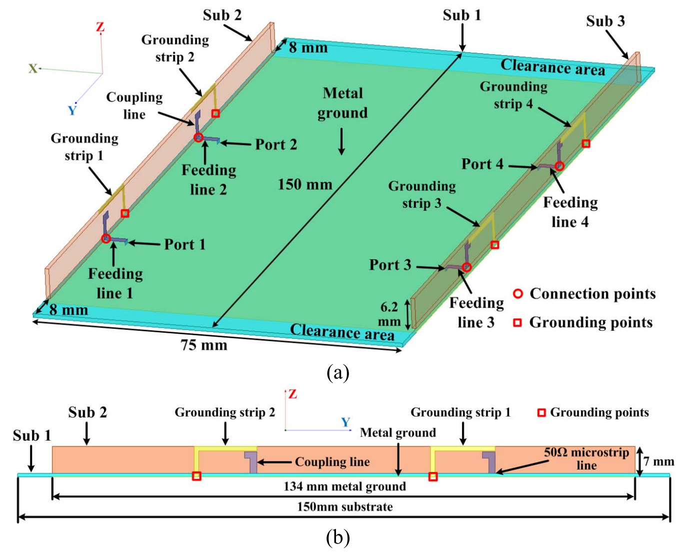

Fig. 1. Configuration of an antenna array. (a) Overall view. (b) Side view.

II. Methodology of Decoupling Elements Isolation Technique

In Section II-A, the configuration of an antenna array is introduced as the research scene. The mutual effect between decoupling elements is investigated and analyzed in Section II-B. In Section II-C, a novel physical idea and the corresponding physical structure are proposed to solve the mutual effect problem. The proposed idea is demonstrated in Section II-D. In Section II-E, some discussion is given.

A. Configuration Specification

A smart phone side-edge antenna array is shown in Fig. 1. There are three PCBs including Sub 1, Sub 2, and Sub 3. All the PCBs are 0.8 mm thick and double-sided FR4 ($\varepsilon r =$ 4.4 and loss tangent = 0.02). The dimension of Sub 1 is $150 \times 75 \times 0.8$ mm^3 with 134×75 mm^2 metal ground on the bottom layer and 50 Ω microstrip lines on the top layer. There are two 75×8 mm^2 clearance areas. Sub 2 and Sub 3 ($134 \times 6.2 \times 0.8$ mm^3 for each) are perpendicularly placed on the top of Sub 1. Hence, the whole dimension of the antenna array is $150 \times 75 \times 7$ mm^3. The antenna elements including their feeding lines are symmetrically arranged along the two long edges of Sub 1.

The antenna elements in this paper are grounding strips, coupled fed by coupling lines [23]. The grounding strips on Sub 2 and Sub 3 are grounded to the metal ground on Sub 1 through grounding points, and the coupling lines on Sub 2 and Sub 3 are connected to the 50 Ω microstrip lines on Sub 1 at connection points. In Fig. 1(b), the grounding strips are on the top layer of Sub 2 and the coupling lines are on the bottom layer. All the decoupling structures (not shown in Fig. 1) in this paper are on the same layer as the grounding strips. The antenna array in Fig. 1 is for explaining the configuration, and the detailed dimensions will be given in each example.

B. Mathematical and Physical Analysis of Mutual Effect Between Decoupling Elements

In order to explain the problem of mutual effect, two decoupling elements, i.e., Strips 1 and 2, are arranged between two antenna elements operating at 3.5 GHz in Fig. 2(a). The distance between strips 1 and 2 is only 3 mm. The decoupling elements in this paper are grounding strips without feeding lines. Because there are only 50 Ω microstrip lines and metal ground on Sub 1, only the structures on Sub 2 are shown for simplicity. The simulated S21 between Ants 1 and 2 is shown in Fig. 2(b) and (c). To improve the isolation bandwidth, the resonant frequency of Strips 1 and 2 needs to be tuned together. However, from the results in Fig. 2(b), when the resonant frequency of Strip 1 decreases from 4.045 to 3.925 GHz (0.12 GHz), the resonant frequency of Strip 2 declines from 3.470 to 3.370 GHz (0.1 GHz) as well. As a result, it is difficult to achieve wider isolation bandwidth by arranging the resonant frequency of two decoupling elements together. In such a small distance ($0.035\lambda_0$ at 3.5 GHz), the strong mutual effect seems unsolvable. To the author's knowledge, how to reduce the mutual effect between decoupling elements is still a blank field.

In this section, the investigation is on the basis of the solution property of Maxwell's equations [24]. In a solution region, the solution should contain all the EM information including the electrical characteristics of resonators. Obviously, the resonant frequency of resonators is one of the electrical characteristics. Thus, the essence of the resonant frequency variation of the decoupling elements is that the solution of Maxwell's equations has changed in the corresponding solution region. Based on this analysis, there are three steps for the research: first, figure out in which solution region the solution can represent the main electrical characteristics of a decoupling element (Section II-B1); second, in the chosen solution region, investigate the reason of the solution change (Section II-B2); and last, propose some ideas to keep the solution stable (Section II-C).

1) Where Is Solution Region: An assumption will be used here: if in a solution region, the solution can represent the electrical characteristics of a decoupling element, most EM energy of the operating mode(s) of the decoupling element

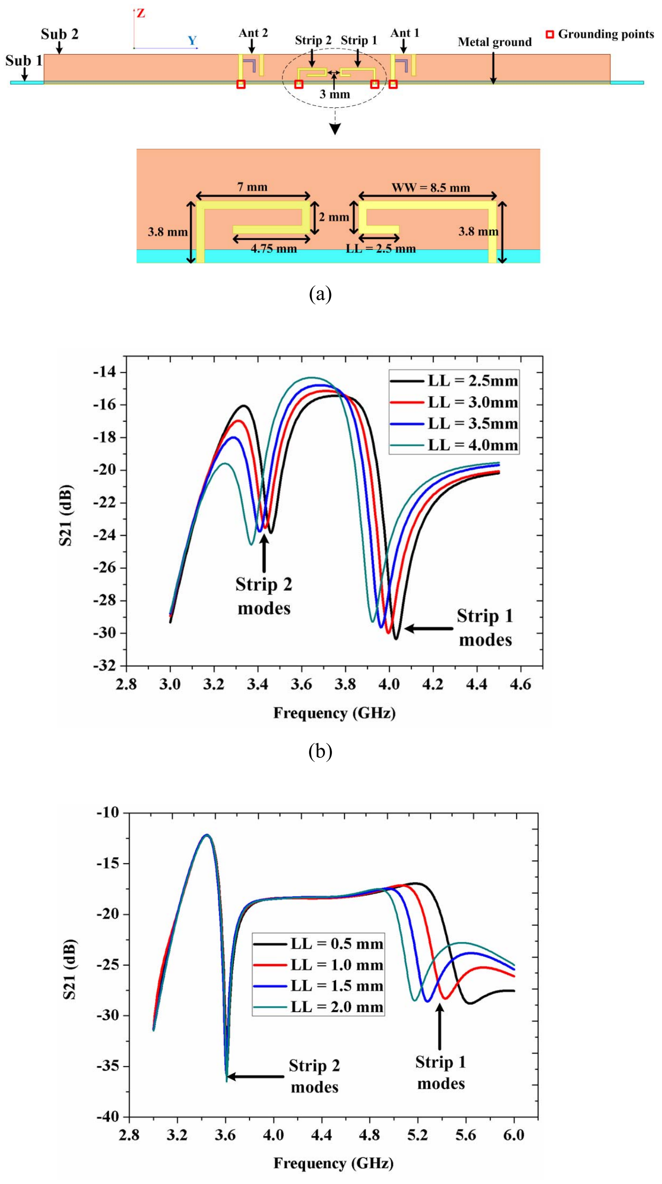

Fig. 2. Example for mutual effect. (a) Configuration. (b) S21 when WW = 8.5 mm. (c) S21 when WW = 5 mm.

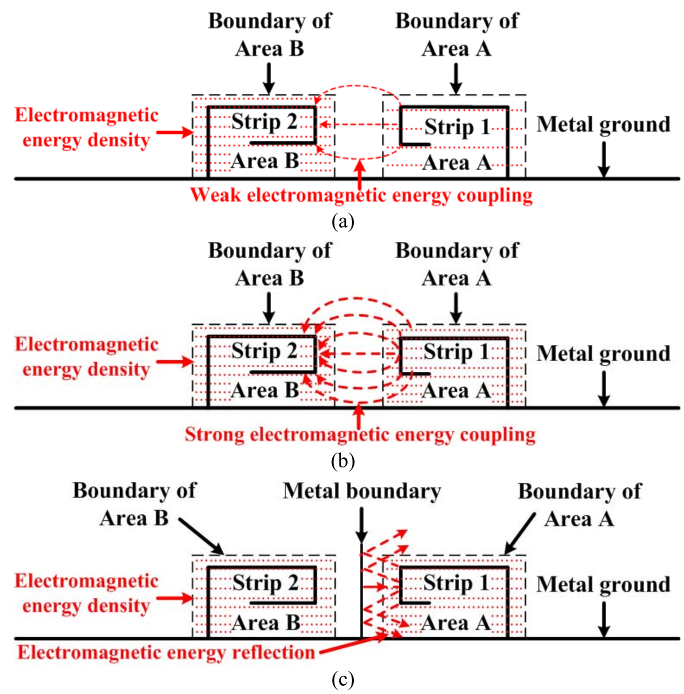

Fig. 3. Investigation model of mutual effect. (a) Weak coupling and (b) strong coupling without metal boundary. (c) Reflection effect of metal boundary.

should distribute in that solution region. The decoupling elements used here are microstrip resonators that operate at standing-wave modes. Standing wave means that the EM field seems to stand on the metal track of a decoupling element itself without spreading, so the majority of the EM energy concentrates in the vicinity region of the decoupling element. The following is a demonstration for this conjecture.

All the discussion in this paragraph processes at the resonant frequency of Strip 2. Let us assume that the EM energy of Strip 2 distributes in a wide region, so there should be strong EM energy from Strip 2 distributing in the region of Strip 1 due to the very small distance (3 mm). Thus, even if the resonant frequency of Strip 1 is far from that of Strip 2 (this means that the energy from Strip 1 is very weak at the resonant frequency of Strip 2), the metal dimension change of Strip 1 should still have strong influence on Strip 2 because metal can greatly affect the EM field distribution. However, in Fig. 2(c), it can be seen that Strip 1 has little influence on Strip 2 when their resonant frequency is far from each other. The same phenomenon can be observed when Strip 1 is located on the left side of Strip 2. Therefore, even in the region very close to Strip 2, the EM energy from Strip 2 is still weak or null. Hence, the EM energy of Strip 2 should concentrate around itself instead of a wide distribution. The conclusion is the same for Strip 1.

Since the majority of the EM energy concentrates around a decoupling element itself, the solution in the vicinity region of the decoupling element should be able to represent its main electrical characteristics. For the ease of description, abstract models are extracted for Strips 1 and 2 from Fig. 2(a) and shown in Fig. 3. Area A is the solution region of Strip 1 and Area B is the solution region of Strip 2. The solution in Area A and Area B can represent the main electrical characteristics of Strips 1 and 2, respectively.

2) Why Does Solution Change: In order to investigate the reason of the solution change for Strip 2, a comparison between two situations is carried out: the first situation is that the resonant frequency of Strip 1 is far from that of Strip 2 and the second situation is that the resonant frequency of Strip 1 is near that of Strip 2. The discussion in the following processes still at the resonant frequency of Strip 2 and on the base of the models in Fig. 3.

According to the uniqueness theorem [24], in a fixed solution region, the solution can only be changed by varying the source and/or boundary conditions. However, in the solution region of Strip 2, i.e., Area B, there is no source. Therefore, the solution in Area B can only be altered by changing the boundary conditions. In the first situation, Strip 1 does not resonate, so the EM energy from Strip 1 is very weak on the boundary of Area B, as shown in Fig. 3(a). When the resonant frequency of Strip 1 changes (still far from that of Strip 2), the EM energy from Strip 1 also changes on the boundary of Area B. Nevertheless, because the EM energy from Strip 1 is too weak compared to the energy of Strip 2, the energy fluctuation from Strip 1 cannot disturb the boundary conditions of Area B. As a result, the solution in Area B does not change, and thus the resonant frequency of Strip 2 remains the same. The results in Fig. 2(c) support the above analysis. In the second situation, the EM energy from Strip 1 is relatively strong on the boundary of Area B, which is shown in Fig. 3(b). When the resonant frequency of Strip 1 changes (still near that of Strip 2), the EM energy from Strip 1 also changes on the boundary of Area B. Because the EM energy from Strip 1 is comparable to the energy of Strip 2 in this case, the energy fluctuation from Strip 1 disturbs the boundary conditions of Area B. As a result, the solution in Area B changes, and hence the resonant frequency of Strip 2 varies. The results in Fig. 2(b) also support the above analysis well.

Therefore, the mutual effect between decoupling elements should not be caused by the metal dimension change because the metal track of one decoupling element is out of the solution region of other decoupling elements in general. From the analysis in last paragraph, the essence of the mutual effect between decoupling elements is that the resonant frequency variation of one decoupling element leads to disturbing the boundary conditions of the adjacent decoupling elements, so the solutions of Maxwell's equations vary in the corresponding solution regions. The solution change means the resonant frequency deviation of the adjacent decoupling elements.

C. Mechanism of Decoupling Elements Isolation Technique

Since the reason of the solution change is that the boundary conditions are disturbed, the key is to achieve the stability of the boundary conditions. Basically, there should be two kinds of thoughts including active methods and passive methods. The active methods are to initiatively compensate the EM field fluctuation on the boundary, for instance, similar to signal compensation technology, another excitation source might be introduced to provide an antifluctuation, but it would increase the complexity and the cost, and it should be difficult to provide accurate compensation in such complicated EM coupling environment. The passive methods are to block the EM energy from the adjacent regions through absorption or reflection: absorption methods seem unfeasible because it is difficult to find such small absorption material ($<7 \times 3 \times 0.8$ mm^3, i.e., $0.082\lambda_0 \times 0.035\lambda_0 \times 0.009\lambda_0$ at 3.5 GHz), and therefore, reflection methods should be the proper choice. For reflection methods, there are also two different ways: one is to use different dielectrics with the permittivity of great difference so the EM field should reflect on the interface and the other is to use metal boundary which can be simply printed with PCB technology. Apparently, the first reflection method is more difficult to realize and its reflection effect should not be better than using metal boundary because metal boundary means total reflection. As a result, metal boundary is adopted in this paper.

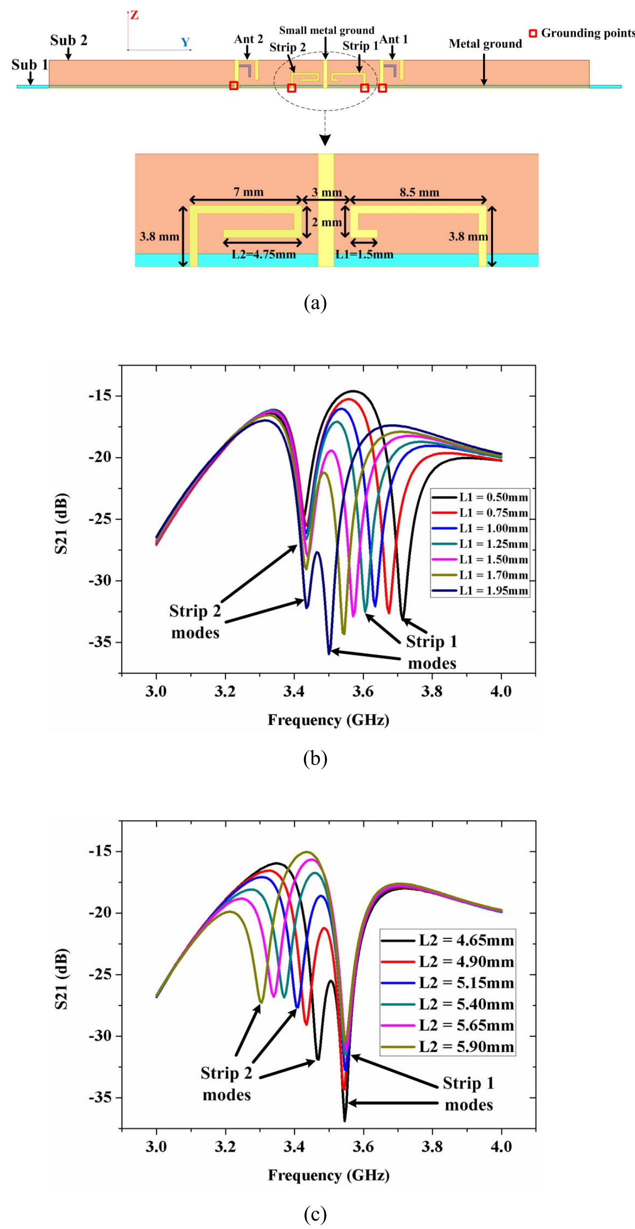

Fig. 4. Demonstration example. (a) Configuration. The resonant frequency of (b) Strip 1 and (c) Strip 2 changes.

To explain how a metal boundary can achieve the stability of the boundary conditions explicitly, an abstract model with a medal boundary between Strips 1 and 2 is shown in Fig. 3(c); the metal boundary is connected to the metal ground. The discussion processes at the resonant frequency of Strip 2. When the resonant frequency of Strip 1 is near that of Strip 2, the EM energy from Strip 1 is relatively strong in Area A but very weak in Area B, because the metal boundary can reflect the majority of the EM energy, as can be seen in Fig. 3(c). When the resonant frequency of Strip 1 changes (still near that of Strip 2), the EM energy from Strip 1 also fluctuates. However, because the EM energy from Strip 1 is much weaker

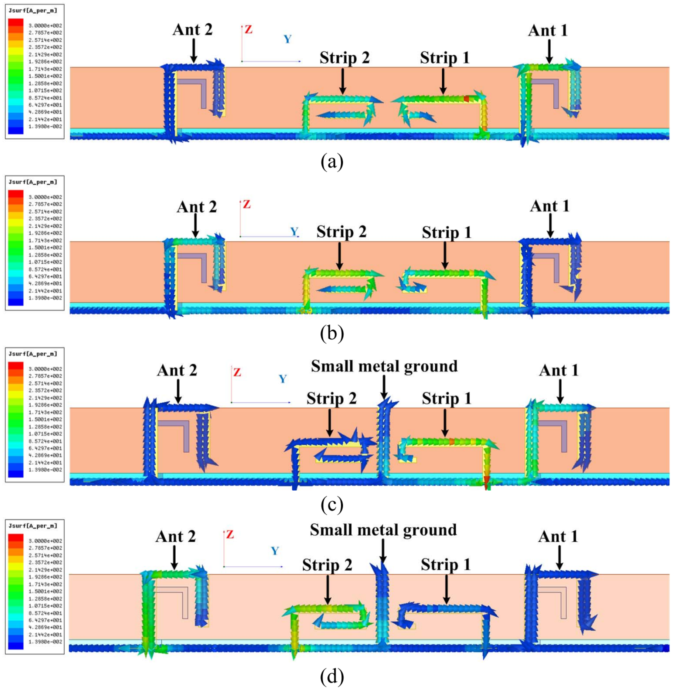

Fig. 5. Current distributions. (a) Strip 1 and (b) Strip 2 resonates without small metal ground. (c) Strip 1 and (d) Strip 2 resonates with small metal ground.

than Strip 2 in Area B, the energy fluctuation cannot disturb the boundary conditions of Area B. Thus, the solution in Area B remains steady, so the resonant frequency of Strip 2 stays the same.

In terms of the analysis above, benefiting from the reflection effect of the metal boundary, the resonant frequency change of one decoupling element cannot disturb the boundary conditions of the adjacent decoupling elements anymore. The stability of the boundary conditions implies steady solutions, which mean consistent resonant frequency for the decoupling elements.

D. Demonstration Example

In order to demonstrate the proposed idea, a new model with a small metal ground acting as the metal boundary between Strips 1 and 2 is shown in Fig. 4(a). The newly created metal ground that only occupies 7×1 mm^2 is on the same surface of the PCB as Strips 1 and 2.

From the simulation results in Fig. 4(b) and (c), it can be clearly seen that the resonant frequency of Strips 1 and 2 can be tuned separately; compared to the results in Fig. 2(b), the mutual effect between Strips 1 and 2 has been eliminated successfully. For further certification and comparison, in Fig. 5(a) and (b), vector current distributions are plotted for the model in Fig. 2(a). The figures show that at the resonant frequency of Strip 1 [Fig. 5(a)], there is a strong energy coupled from Strip 1 to Strip 2; similarly, at the resonant frequency of Strip 2 [Fig. 5(b)], there is also strong energy coupled from Strip 2 to Strip 1; thus, the EM energy fluctuation of one strip can transmit to the other strip, which leads to the disturbance of the EM boundary conditions. In Fig. 5(c) and (d), vector current distributions are drawn for the model in Fig. 4(a). The results clearly prove that at the resonant frequency of Strip 1 [Fig. 5(c)], there is only very weak or null energy coupled from Strip 1 to Strip 2, which means that the small metal ground has blocked the energy of Strip 1 for Strip 2; at the resonant frequency of Strip 2 [Fig. 5(d)], the phenomenon is similar; hence, the EM energy fluctuation of one strip cannot transmit to the other strip anymore, so the EM boundary conditions of each strip can keep stable now. Additionally, from the vector current distributions, it can be concluded that the decoupling elements operate at 0.25λ mode like monopole antennas.

E. Discussion

Some researchers may think of other applications for the proposed idea. When an antenna element is close to a decoupling element, the decoupling element usually has large impact on the performance of the antenna element. By inserting a metal boundary, the influence of the decoupling element might be eliminated. However, the decoupling principle of decoupling elements is to utilize the energy coupling between decoupling elements and antenna elements to create a new coupling path; the energy from the new coupling path can cancel the original coupling energy. Hence, if the decoupling elements and the antenna elements are isolated with the metal boundary, the energy coupling between them should be weakened, so the decoupling effect of the decoupling elements may become extremely weak or even disappear.

Another possible thought is to reduce the mutual coupling between antenna elements by using the metal boundary directly. It should be emphasized that the elimination of the mutual effect between decoupling elements does not mean that there is no mutual coupling between them. The condition of weak or null mutual effect is that the energy from mutual coupling is not strong enough to disturb the EM boundary conditions of the decoupling elements. Therefore, the mutual coupling still exists. For instance, the mutual coupling between two decoupling elements is -13 dB, so only 5% energy is coupled between them. The 5% energy should not be strong enough to affect the resonant frequency of the decoupling elements, but 13 dB is not a good isolation level. Thus, null mutual effect does not mean good isolation. As a result, the proposed idea can effectively eliminate the mutual effect between decoupling elements, but the metal boundary itself may not be able to reduce the mutual coupling to a very low level. The meaning of the proposed idea is to achieve the multimode decoupling technique which can realize wideband/multiband high isolation.

Besides, the proposed small metal ground, which acts as the metal boundary, seems similar to the protruded metal ground in [25]. However, the protruded metal ground is actually a kind of resonant structure because there is obvious resonant feature in [25, Fig. 9]. The decoupling elements in this paper can also be considered as a kind of slim protruded metal ground. Thus, the dimension of the protruded metal ground is relevant to its operating frequency. On the contrary, the dimension of the proposed small metal ground is independent of its operating

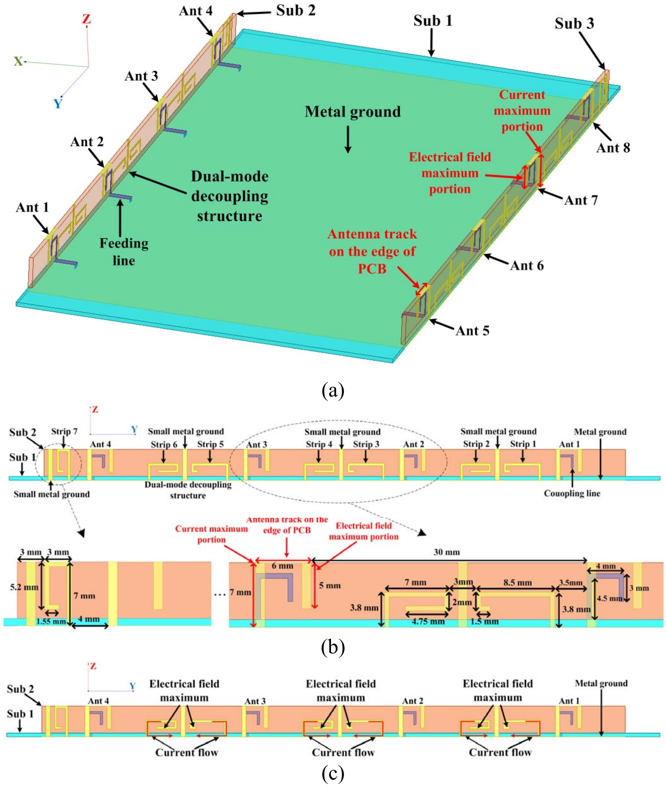

Fig. 6. Configuration of the eight-antenna array. (a) Overall view. (b) Detailed dimensions. (c) Arrangement of the energy maximum portions.

frequency; in other words, a small metal ground with a fixed dimension can be applied to any frequency as long as its volume is big enough to block the EM energy. For instance, the same small metal ground is applied to 3.5 and 2.45 GHz in Section III. As a result, the principle of the small metal ground is completely different from that of the protruded metal ground.

III. Multimode Decoupling Technique

By inserting $N-1$ metal boundaries between N decoupling elements ($N = 2, 3, 4, \ldots$), multidecoupling modes can be achieved. Two case studies are shown in this section and the configuration is similar to the antenna array in Fig. 1. The detailed dimensions are shown just for Sub 2, because there are only 50 Ω microstrip lines and metal ground on Sub 1, and the structures on Sub 3 are symmetric with that of Sub 2. Besides, the simulation and measured results are only shown for the antenna elements in Sub 2 as well. All the small metal grounds have the same dimension of 7×1 mm^2.

A. Dual-Mode Decoupling Design for a Smart Phone Side-Edge Eight-Antenna Array at 3.5 GHz

The configuration is shown in Fig. 6. There are four antenna elements on Sub 2, so three dual-mode decoupling structures ($18.25 \times 7 \times 0.8$mm^3 for each, i.e., $0.213\lambda_0 \times 0.082\lambda_0 \times 0.009\lambda_0$ at 3.5 GHz) are inserted between them. All the dual-mode decoupling structures have the same dimension in detail. In Fig. 6(b), the current maximum portion of Ants 1–4 is on the top layer of Sub 2, while the electrical field maximum portion is on the bottom layer of Sub 2; on the edge of Sub 2, there is a 0.8 mm wide copper track connecting the two portions. The uniform width of the other antenna tracks is 1 mm, and the uniform width of the coupling lines and the decoupling elements is 0.5 mm.

In Fig. 6(c), the consideration for the special layout can be seen clearly: the electrical field maximum portions of the decoupling elements face to the adjacent decoupling elements but not the antenna elements; although the current maximum portions are close to the antenna elements, the currents do not flow to the antenna elements because of the mirror currents on the metal ground and the current continuity theorem. In this way, the influence of the decoupling elements on the antenna elements can be minimized. The mutual effect between the decoupling elements can be eliminated with the proposed small metal ground. As a result, even if there are ten resonators in a volume of $114 \times 7 \times 0.8$ mm^3 ($1.330\lambda_0 \times 0.082\lambda_0 \times 0.009\lambda_0$ at 3.5 GHz, i.e., $0.133\lambda_0 \times 0.082\lambda_0 \times 0.009\lambda_0$ for each resonator on average), they can still operate properly.

The simulated S-parameter, antenna efficiency, and antenna pattern results are shown in Fig. 7. Comparing the results in Fig. 7(a) and (b), it can be clearly observed that the reflection coefficients are even enhanced due to the dual/multiresonance feature. According to our simulation, the resonance at around 3.58 GHz for Ants 1–3, and Ant 4 benefits from Strips 1, 3, 5, and 7, respectively. Take Ant 1 and Strip 1 as an example. The current maximum portions of Strip 1 and Ant 1 are close and parallel, so Strip 1 can be coupled fed by Ant 1 as a parasitic element. Therefore, one extra resonance is generated by Strip 1. Strip 7 is added also for the extra resonance of Ant 4.

The results in Fig. 7(a) and (b) show that the isolation between Ant 1 and Ant 2, Ant 2 and Ant 3, and Ant 3 and Ant 4 is improved from 13.5 to >20 dB in the frequency band of 3.4–3.6 GHz (5.7% fractional bandwidth). The isolation between Ant 1 and Ant 3, Ant 1 and Ant 4, and Ant 2 and Ant 4 is not shown because it is much better. According to our simulation, Strips 1–7 can still be tuned separately. For simplicity, the results are not shown. From the results in Fig. 7(c) and (d), the decoupling structures reduce the radiation efficiency (RE) to >39%, but the total efficiency (TE) remains >38% within 3.4–3.6 GHz owe to the enhanced reflection coefficients. For verification of the RE and TE with decoupling elements obtained from HFSS, the results from CST is shown in Fig. 7(e). In terms of the comparison, it is evident that the results of the RE from HFSS and CST agree quite well. The results of the TE have a little bigger difference, because the simulated reflection coefficients from CST are worse than HFSS (not shown).

After adding the decoupling elements, the antenna patterns also change due to the scattering effect. According to our simulation, Strips 1, 3, 5, and 7 have greater influence on the patterns than Strips 2, 4, and 6, because the radiation currents of these four decoupling elements are closer to that of the antenna elements. Thus, the 3-D patterns of Ants 1–4 with and without the decoupling elements are shown in Fig. 7(f)–(i) at 3.55 GHz, which is the resonant frequency of Strips 1, 3, 5, and 7. From the results, it is evident that the

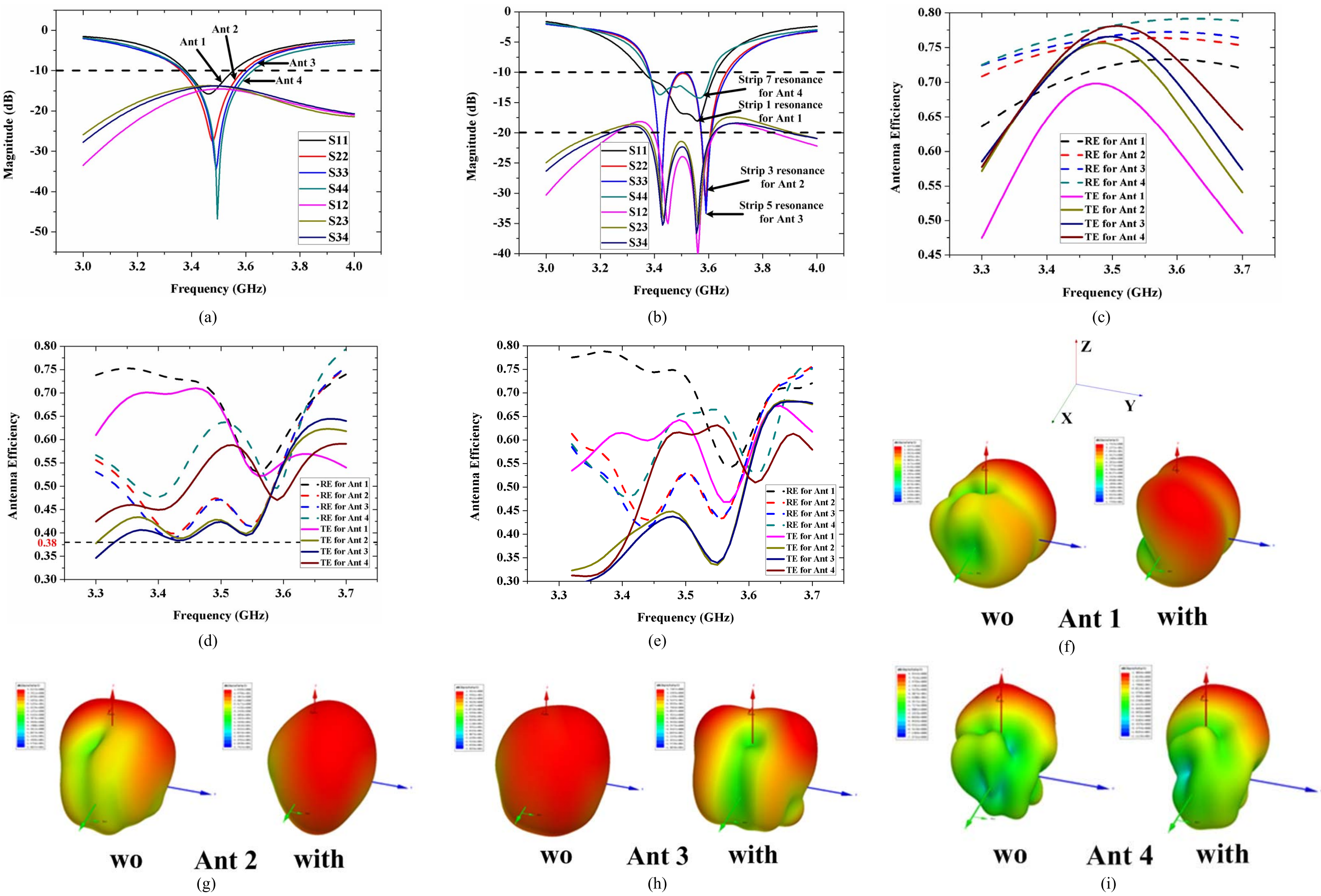

Fig. 7. Simulation results. S-parameter (a) without and (b) with decoupling elements obtained from HFSS. RE and TE (c) without and (d) with decoupling elements obtained from HFSS. (e) RE and TE with decoupling elements obtained from CST. 3-D antenna patterns of (f) Ant 1, (g) Ant 2, (h) Ant 3, and (i) Ant 4 at 3.55 GHz with and without decoupling elements obtained from HFSS.

decoupling elements significantly affect the radiation patterns due to the small distance. Although it is not shown, the pattern variation becomes weaker and weaker as the frequency decreases.

This eight-antenna array has been fabricated and measured. The prototype and the measured S-parameter results are shown in Fig. 8(a) and (b), respectively. The resonant frequency of the antenna elements and the decoupling elements deviates a little due to the rough handmade prototype. The measured S12, S23, and S34 are < -20 dB in the frequency band of 3.47–3.69 GHz (6.1%), 3.42–3.66 GHz (6.8%), and 3.42–3.67 GHz (7.1%), respectively. Thus, the measured results still demonstrate the good decoupling effect of the design. In addition, this antenna array can be extended by simply duplicating the antenna elements and the decoupling elements, so it is promising for the arrays with multiantenna elements. Table I shows a decoupling comparison between the proposed and the reported smart phone side-edge eight-antenna array at 3.5 GHz.

TABLE I

DECOUPLING COMPARISON

Ref. (3.5 GHz)	Proposed	[12]	[14]	[15]
Isolation (dB)	≥ 20	≥ 10	≥ 10	≥ 12
Isolation bandwidth (%)	6.1	5.7	5.7	5.7
Decoupling mode(s)	Dual-mode	None	None	Single-mode
Tuning difficulty	Easy Independent tuning	-	-	Need to design two different structures
Potential	Infinite elements in theory	-	-	Four closely-packed elements

B. Quad-Mode Decoupling Design for a Smart Phone Side-Edge Four-Antenna Array at 2.45 GHz

Since there have been tri-mode decoupling designs such as [21], a quad-mode decoupling design is presented directly to show the advantage of the proposed technique. The configuration is shown in Fig. 9. There are two antenna elements on Sub 2, so one quad-mode decoupling structure ($35 \times 7 \times 0.8$ mm^3, i.e., $0.295\lambda_0 \times 0.059\lambda_0 \times 0.007\lambda_0$ at 2.526 GHz) is inserted between them. The uniform width of the coupling lines, the antenna tracks, and the decoupling elements is 1.5, 1, and 0.5 mm, respectively.

Although the independent tuning feature has been demonstrated in Section II-D, when more decoupling elements are placed together, the mutual effect could still deteriorate because the EM coupling environment would become more

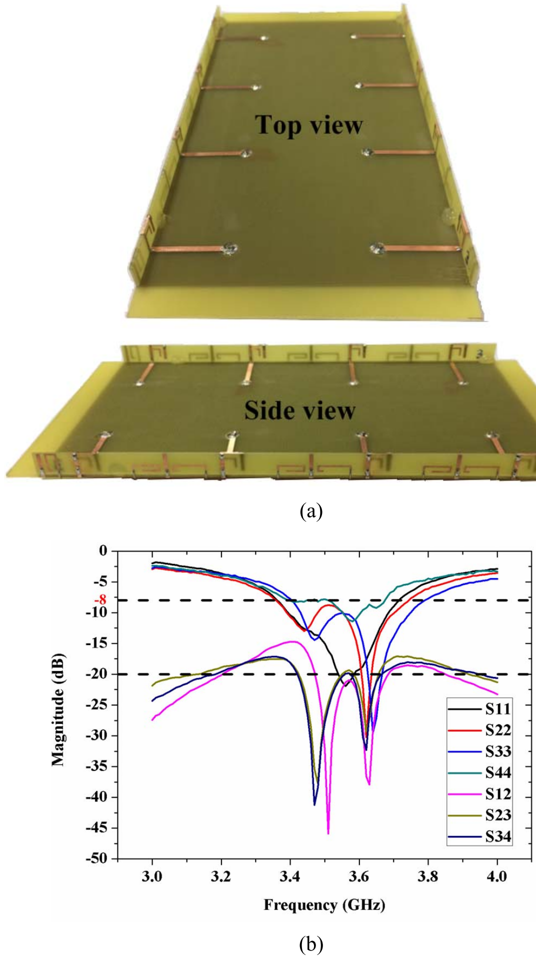

Fig. 8. (a) Fabricated prototype. (b) Measured S-parameter.

TABLE II
WIDEBAND-DECOUPLING COMPARISON

Ref.	Enhanced isolation	Enhanced bandwidth	Volume (λ_0^3)	Design difficulty	Processing technology
[18]	13 dB	11%	0.026× 0.020× 0.010	Not easy	LTCC
[21]	7 dB	20.1%	0.390× 0.050× 0.006	Not easy	PCB
[22]	7 dB	109%	0.622× 0.183× 0.018	Not shown	PCB
This paper	8.3 dB	22%	0.295× 0.059× 0.007	Easy tuning	PCB

complicated. According to our simulation, the mutual effect between Strips 1 and 2, and Strips 3 and 4 is still weak, but the mutual effect between Strips 2 and 3 is relatively strong when their resonant frequency is close to each other. In order to reduce the mutual effect between Strips 2 and 3, the resonant frequency of the four decoupling elements can be arranged as Strips 3, 4, 1, and 2 (the frequency increases from left to right). In this way, the resonant frequency of Strips 2 and 3 is far from each other, so their mutual effect can be reduced

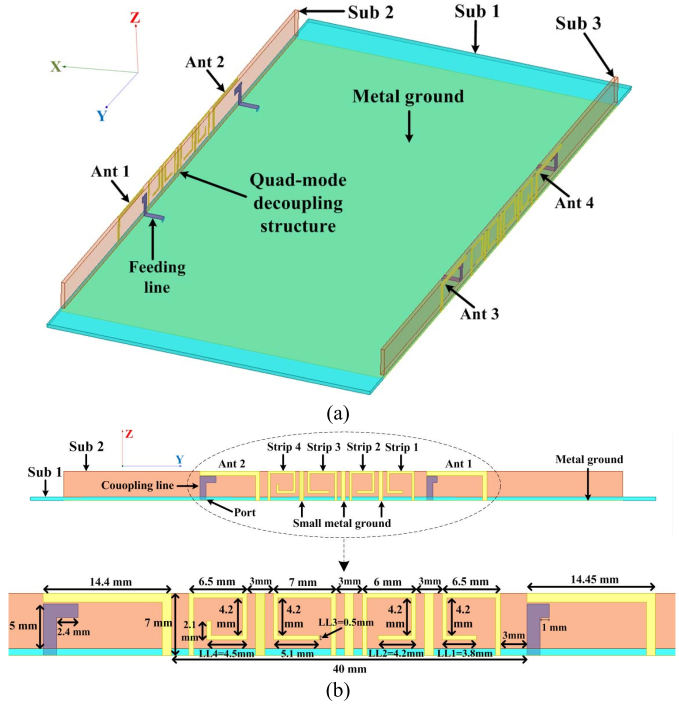

Fig. 9. Configuration of the four-antenna array. (a) Overall view. (b) Detailed dimensions.

effectively; the resonant frequency of Strips 1 and 4 is close to each other, but their position is far from each other, and Strips 2 and 3 can actually act as the decoupling elements between them, so the mutual effect between Strips 1 and 4 is extremely weak. As a result, even if the decoupling modes are doubled, these four decoupling modes can still be tuned independently. If more decoupling elements are added, the same method can be applied.

The simulated S-parameter, antenna efficiency, and antenna pattern results are in Fig. 10. In Fig. 10(b), the results clearly reveal that the isolation between Ants 1 and 2 is improved from 12.7 to >21 dB in the frequency band of 2.248–2.805 GHz (22% fractional bandwidth).The results in Fig. 10(c) show that the decoupling structure reduces the RE to >43%, but the TE is still >40% within 2.4–2.5 GHz. It can also be noticed that in the frequency band of 2.2–2.3 GHz, the TE of the Ant 2 with the decoupling elements is higher than that of the Ant 2 without the decoupling elements; this profits from the enhanced S22. For verification of the RE and TE with decoupling elements obtained from HFSS, the results from CST is shown in Fig. 10(e). According to the comparison, the results of the RE from HFSS and CST agree quite well. The results of the TE have a little bigger difference, because the simulated reflection coefficients from CST are worse than HFSS (not shown). From the results in Fig. 10(f)–(i), the independent tuning characteristic of Strips 1–4 is still good owe to the proper arrangement of their resonant frequency.

The scattering effect of the decoupling elements exists as well. In terms of the simulation, Strips 1 and 2 have greater influence on the patterns of Ant 1 than Strips 3 and 4 because Strips 1 and 2 are closer to Ant 1; among all the decoupling

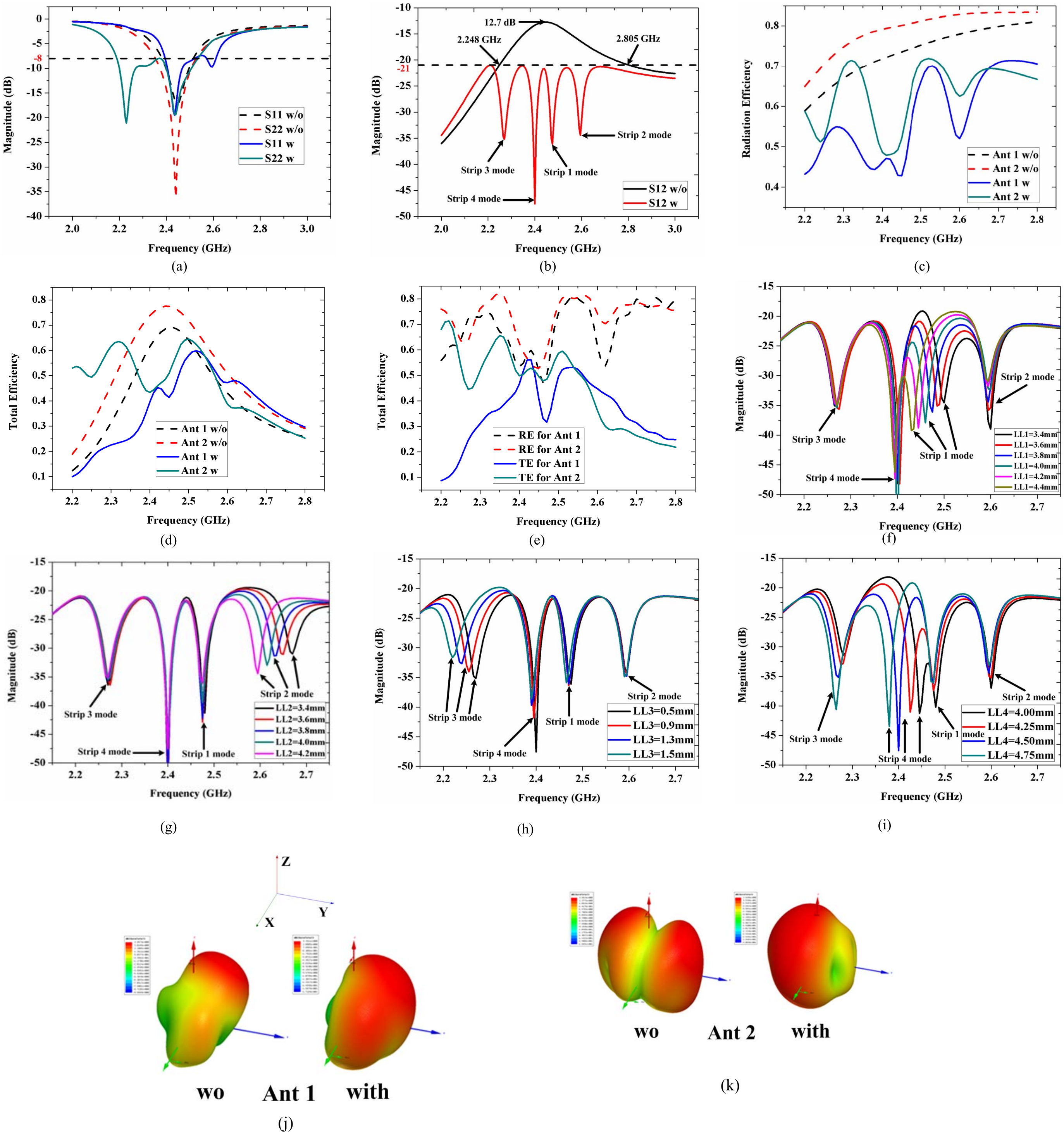

Fig. 10. Simulation results. (a) S11/S22 and (b) S12 with/without decoupling elements obtained from HFSS. (c) RE and (d) TE with/without decoupling elements from HFSS. (e) RE and TE with decoupling elements from CST. Resonant frequency of (f) Strip 1, (g) Strip 2, (h) Strip 3, and (i) Strip 4 changes obtained from HFSS. 3-D antenna patterns of (j) Ant 1 at 2.5 GHz and (k) Ant 2 at 2.4 GHz with and without decoupling elements obtained from HFSS.

elements, Strip 4 has the largest impact on Ant 2, because their radiation currents are the nearest. Therefore, the 3-D patterns of Ant 1 (at 2.5 GHz which is between the resonant frequency of Strip 1 and Strip 2) and Ant 2 (at 2.4 GHz which is the resonant frequency of Strip 4) with and without the decoupling elements are shown in Fig. 10(j) and (k), respectively.

This four-antenna array has been fabricated and measured. The prototype and the measured S-parameter results are shown in Fig. 11(a) and (b), respectively. The resonant frequency of the antenna elements and the decoupling elements deviates a little due to the fabrication error, but the measured isolation still agrees with the simulated value well. As a result,

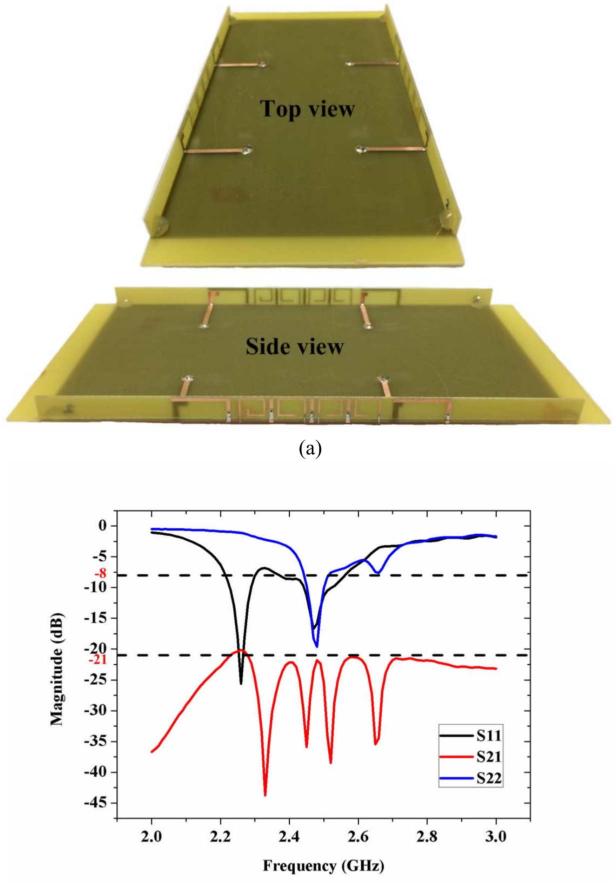

Fig. 11. (a) Fabricated prototype. (b) Measured S-parameter.

although the bandwidth of the antenna elements is not as wide as the decoupling bandwidth, this application example still demonstrates the excellent wideband-decoupling power of the proposed decoupling technique in a compact volume. Multiband decoupling can be achieved with the same method. Table II shows a comparison between the proposed and other reported wideband-decoupling designs in mobile terminals.

C. Impact of Smart Phone Components

The impact of some smart phone components at different distance from the antenna arrays is researched. All the components are imitated by using metal blocks. When a battery ($70 \times 40 \times 3$ mm^3) is placed in the middle of the smart phone, the performance has little degradation except 4% reduction of the TE, so the results are not shown for simplicity.

In Fig. 12(a), a USB connector ($10 \times 8 \times 3$ mm^3) and a metal housing (120 mm $\times$ (75 mm$-DD1/DD2$) $\times$ 3 mm) are put on the top of Sub 1 for each antenna array. One rectangular block is removed from the whole metal housing for each feeding port to ensure normal excitation. The simulated S-parameter and TE are presented in Fig. 12(b)–(d). There are loads of data, so only some typical antenna elements were adopted for analysis and explanation.

For the eight-antenna array, the performance change of Ant 2 is shown. At DD1 = 3, 4, and 5 mm, the reflection coefficient of Ant 2 has little deterioration, but the TE decreases to 30%

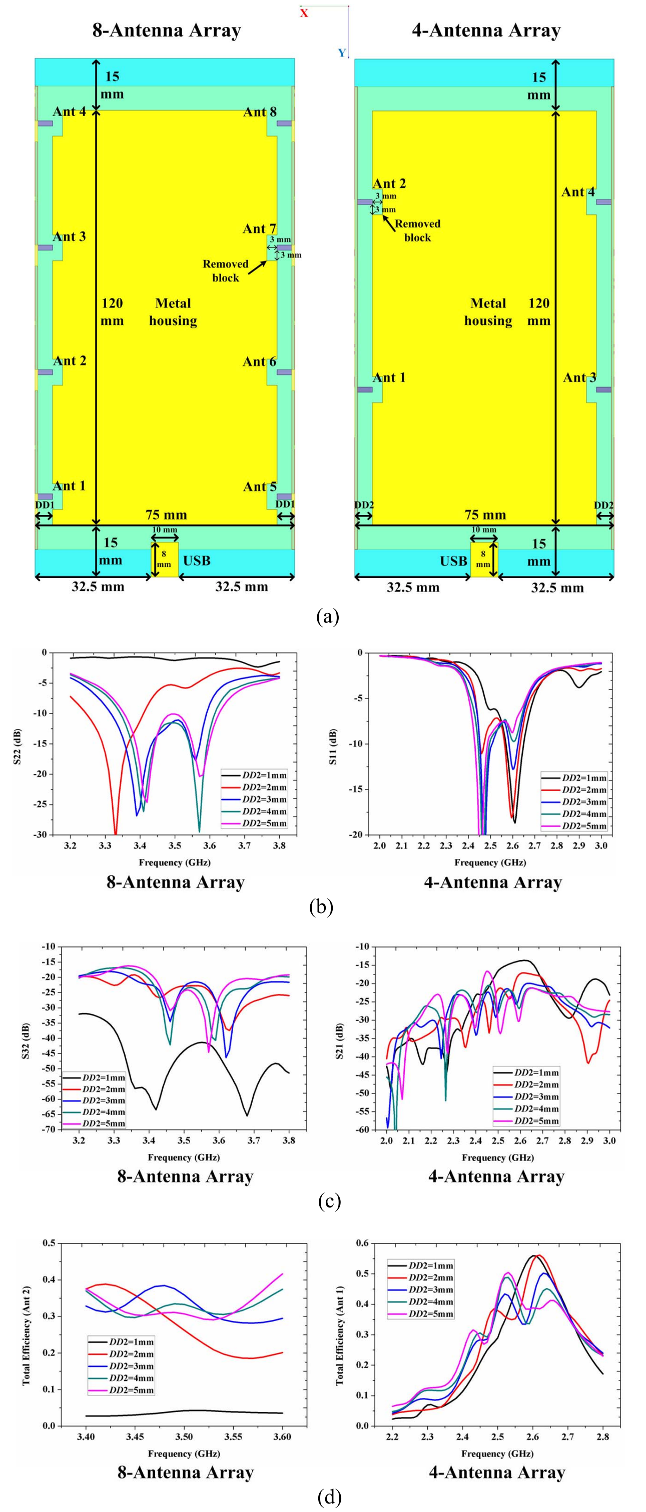

Fig. 12. Impact of a metal housing and a USB connector. (a) Simulation models. (b) Reflection coefficients, (c) mutual coupling, and (d) TE of Ant 2 in the eight-antenna array and Ant 1 in the four-antenna array.

due to the absorption effect of the metal housing. At DD1 = 2 mm, the resonant frequency of Ant 2 decreases obviously, because the metal housing is close to the open-end of the antenna and thus provide a capacitive loading. At DD1 = 1 mm, the performance of the antenna has been destroyed. At all the parameters, the isolation between Ants 2 and 3 keeps a

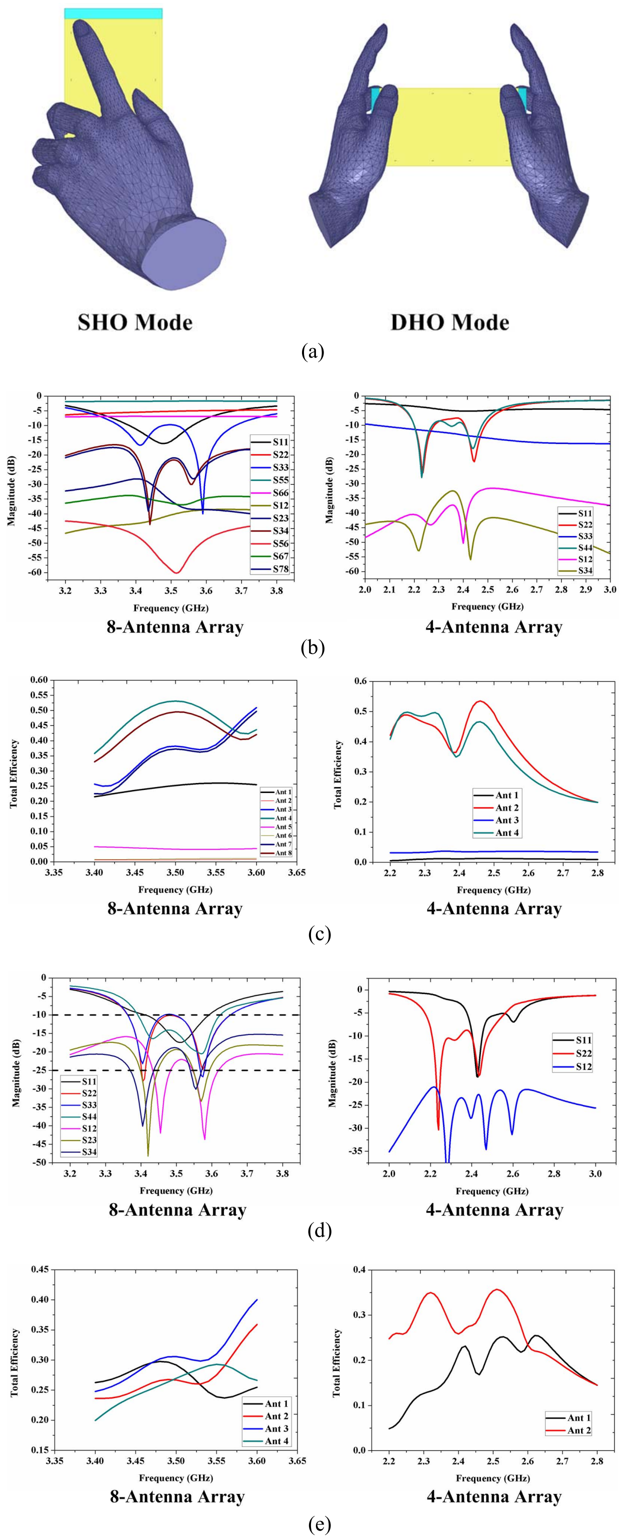

Fig. 13. Effect of a user's hand(s). (a) Two typical usage scenarios. (b) S-parameter and (c) TE of the eight-antenna array and four-antenna array at SHO mode. (d) S-parameter and (e) TE of the eight-antenna array and four-antenna array at DHO mode. All the results were obtained from HFSS.

good level of >19 dB within 3.4–3.6 GHz. The phenomena are similar in other antenna elements.

The situation is better in the four-antenna array, because the open-end of the antenna elements is somewhat far from the metal housing so the capacitive-loading effect is relatively weak. Ant 1 was adopted as the example. At DD2 = 3, 4, and 5 mm, there is little degradation in the reflection coefficient, but the isolation between Ants 1 and 2 declines to 16 dB at DD2 = 5 mm due to the resonant frequency variation of the decoupling elements. At DD2 = 1 and 2 mm, the resonant frequency of Ant 1 actually increases rather than decreases, so the frequency point of the worst S21 rises as well. The peak point of the TE varies along with the resonant frequency of Ant 1. The phenomena are similar in other antenna elements.

D. User's Hand Effects

The effect of the user's hand(s) on the antenna performance is investigated including single-hand operation (SHO) and dual-hand operation (DHO), which are depicted in Fig. 13(a). The antenna arrays at 2.45 and 3.5 GHz normally operate at data mode, so the effect of a user's head is not considered.

For SHO mode, the simulated S-parameter and TE are shown in Fig. 13(b) and (c). For the eight-antenna array, Ants 2, 5, and 6 are directly contacted by the hand, so their performance has the largest degradation: the reflection coefficients are influenced dramatically, and the efficiency declined to <10% due to the absorption effect of the hand. Ant 1 is not contacted but very close to the hand, so its efficiency is lower than the other four antenna elements. The isolation between Ants 3 and 4, and Ants 7 and 8 remains consistent, but the isolation between other antenna elements actually becomes much better, because much EM energy has been absorbed. The phenomena are similar in the four-antenna array. The performance of Ants 1 and 3 deteriorates the most because of the direct contact of the hand, and the isolation between antenna elements increases to >30 dB owe to the absorption of the EM energy.

For DHO mode, the situation is better, because the hands do not contact the antenna elements directly. The simulated S-parameter and TE are shown in Fig. 13(d) and (e). For the eight-antenna array, the reflection coefficients have little deterioration, but the resonant frequency of the decoupling elements varies a little. However, the isolation is still >18 dB within the operating frequency band. The efficiency decreases due to the absorption effect of the hands. The change is analogous in the four-antenna array. The S-parameter has minute degradation and the efficiency declines.

IV. Conclusion

The essence of the strong mutual effect between closely packed decoupling elements has been explained from the perspective of mathematical physics. A novel idea of achieving the stability of the boundary conditions of decoupling elements has been proposed and solved the mutual effect problem simply and effectively; in physical structure, a metal boundary has been adopted to realize the stability.

By isolating multidecoupling elements, the multimode decoupling technique has been achieved for mobile terminals. The proposed technique can accomplish wideband/multiband high isolation and easy-tuning feature in a compact volume.

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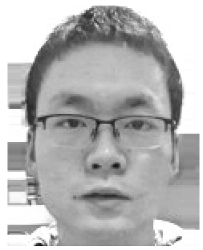

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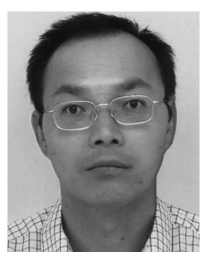

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