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# A Quad-antenna System Operating at the 2.4/5.2/5.8 GHz WLAN Bands for Laptop Computers

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**Abstract**—In this paper, a quad-antenna system for laptop computers is studied. Because two dual-antenna systems can construct a quad-antenna system, the dual-antenna systems in the open literature are utilized. The mutual coupling between the two dual-antenna systems is analyzed and reduced. To validate the design of a quad-antenna system, the quad-antenna system, consisting of two dual-antenna systems proposed in the open literature and a decoupling element, is fabricated and tested. Its measured $-10$ dB impedance bandwidths are 200 MHz (2.33–2.52 GHz) and 1.62 GHz (4.5–6.12 GHz). The measured mutual couplings are below $-15.5/-19$ dB at the 2.4- and 5.2/5.8-GHz WLAN bands, respectively. The measured gains are better than 2.4/3.9 dBi with efficiencies higher than 70%/72% at the two bands, respectively. The envelop correlation coefficient is evaluated based on the measured results.

## 1. INTRODUCTION

Wi-Fi has become a necessary function for computers as it provides a convenient way to access the internet. To guarantee a high throughput for better experience, the multiple-input multiple-output (MIMO) technology has been adopted in the IEEE 802.11 standard [1, 2]. The MIMO technology employs multiple antennas on the transmitter and receiver to improve the communication quality and increase the system capacity without using additional spectrum and power [3–6]. To achieve a good performance of the MIMO system, the mutual couplings between the multiple antennas should be low. However, it is still an open issue to integrate multiple antennas with low mutual coupling in the laptop computers [7].

In [8–11], dual-antenna systems operating at the 2.4 (2400–2484 MHz)/5.2 (5150–5350 MHz)/5.8 (5725–5875 MHz) GHz WLAN bands for laptop computers have been well studied. These dual-antenna systems adopted a parasitic element [8], a dual-band strip resonator [9], a protruded ground with an embedded spiral slot [10], and a protrude ground with an embedded T-shaped slot [11] to reduce the mutual coupling. These dual-antenna systems [8–11] with small sizes and good performances are suitable for practical applications. In the future, $4 \times 4$ or $8 \times 8$ MIMO system will be in demand [12]. In [13], it has been demonstrated that the $4 \times 4$ MIMO system has a theoretical 4 times the capacity of a single antenna system. Nevertheless, researches on integrating four, six, or eight antennas in the laptop computers are one of the less explored areas. In this paper, we will draw our attention on this aspect. In [14], an antenna system with six elements for the 2.4 GHz WLAN band was proposed. For seamless wireless connectivity, designing a quad-, six-, or eight-antenna system for 2.4/5.2/5.8 GHz WLAN bands is promising.

In this paper, a quad-antenna system for 2.4/5.2/5.8-GHz WLAN bands is studied. Because two dual-antenna systems can construct a quad-antenna system, the dual-antenna systems, which were

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proposed in the literature, are utilized to construct a quad-antenna system. Thus, the proposed dual-antenna systems in the open literature could be taken full advantage to reduce the design circle. To reduce the occupying space, two dual-antenna systems are required to be located at the same side of the laptop display which would lead to strong mutual coupling between them. To study the quad-antenna system in depth, the dual-antenna system proposed in [11] is selected to construct the quad-antenna system. It should be noted that the dual-antenna system can be any proposed dual-antenna systems in the open literature. The coupling mechanism between the two selected dual-antenna systems is analyzed and the decoupling methods are proposed to address it. Finally, a quad-antenna system with low mutual coupling for 2.4/5.2/5.8-GHz WLAN bands is achieved.

## 2. ANTENNA GEOMETRY AND DESIGN CONSIDERATIONS

Figure 1 shows the overall view of the proposed quad-antenna system which consists of two symmetric dual-antenna systems and a decoupling element. To reduce the occupying space, the two dual-antenna systems and the decoupling element are located along the top edge of the supporting ground of the laptop display. The dual-antenna system and the decoupling element have their own ground to be easily installed. In the experiment, the grounds of the dual-antenna system and the decoupling element are covered by the supporting ground. The two dual-antenna systems, the decoupling element, and their grounds are printed on three single-layer printed circuit boards (PCBs). All the PCBs are fabricated on the 0.8-mm-thick FR4 substrate with a relative permittivity of 4.4 and a loss tangent of 0.02. The

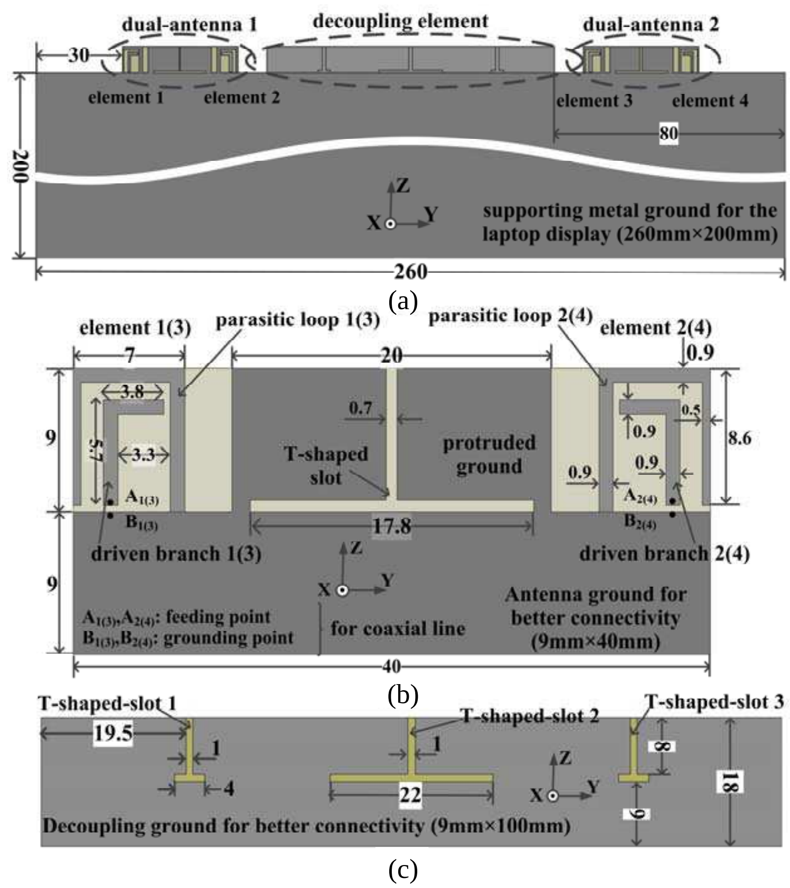



**Figure 1.** Geometry of the proposed quad-antenna system with dimensions in millimeters. (a) Installation positions of the two dual-antenna system and the decoupling element with their grounds connecting to the supporting ground. (b) Detailed dimensions of the dual-antenna system and its ground on the PCB. (c) Detailed dimensions of the decoupling element and its ground on the PCB.

positions of the two dual-antenna systems, affecting the impedance characteristics of the antennas, are selected based on the layout of the laptop computer. This effect can be handled by adjusting the parameters of the antenna approximately. The supporting ground is made of a 0.2-mm-thick copper plate with a dimension of $260 \times 200\,\mathrm{mm}^2$, which is a suitable size for a 13-in display.

Figure 1(b) shows the geometry with detailed dimensions of the two dual-antenna systems. The dual-antenna system, which was proposed in [11], consists of two symmetric elements and a protruded ground with an embedded T-shaped slot. The antenna element of the dual-antenna system in [11] is a coupled-fed loop antenna with a driven branch and a parasitic loop. The couple-fed technique is a common method to reduce the antenna size [15] or widen the bandwidth [16]. Thus, due to the coupled-fed technique, the parasitic loop generates a quarter-wavelength loop resonant mode at the 2.4 GHz WLAN band and the driven branch contributes a quarter-wavelength monopole resonant mode at the 5.2/5.8 GHz WLAN bands. The protruded ground and the embedded T-shaped slot reduce the mutual coupling between the two antenna elements at the 5.2/5.8 GHz and 2.4 GHz WLAN bands, respectively. Finally, dual-antenna system with good impedance matching and low mutual coupling for 2.4/5.2/5.8-GHz WLAN bands is achieved.

By installing two of the dual-antenna systems along the top edge of the supporting ground, a quad-antenna system is achieved. However, the mutual coupling between the two dual-antenna systems is strong. To reduce the mutual coupling, a decoupling element is applied. The decoupling element, located at the middle of the top edge of the supporting ground, consists of a protruded ground with three T-shaped slots. The geometry with detailed dimensions of the decoupling element is shown in Figure 1(c). To better understand the proposed quad-antenna system, the coupling between the two dual-antenna systems and the decoupling methods will be analyzed in the following section. Finally, four 26-cm-long hard coaxial lines (SFT50-1), with their inter conductors and outer conductors connecting to the A1 (A2, A3, A4) and B1 (B2, B3, B4), respectively, are employed to feed the quad-antenna system.

## 3. ANALYSES OF THE PROPOSED QUAD-ANTENNA SYSTEM

In this section, the coupling between the two dual-antenna systems is analyzed at first. Then, the decoupling methods are proposed to address it. Also, the effect of the keyboard ground on the $S$-parameters is studied. At last, a design methodology of the quad-antenna system is summarized to conclude this section. The electromagnetic simulations in this paper are all carried out using a commercial electromagnetic solver ANSYS HFSS 15, which is based on the finite element method (FEM).

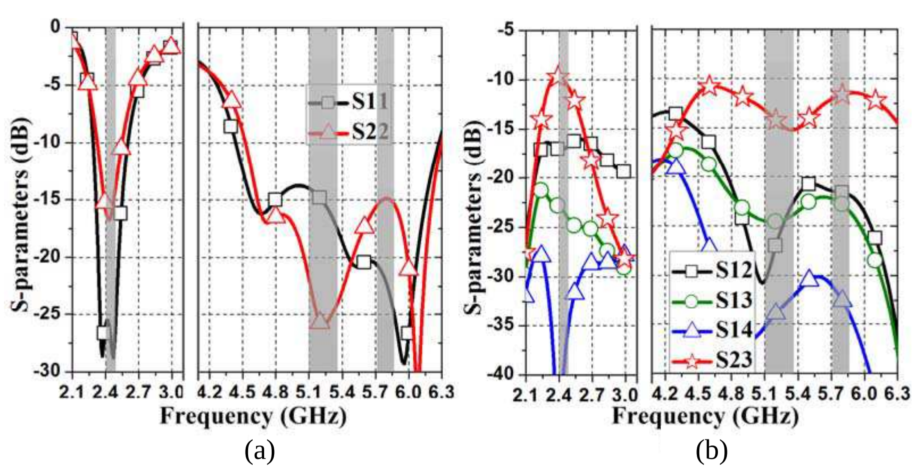



**Figure 2.** Simulated $S$-parameters of the quad-antenna system without the decoupling element. (a) Reflection coefficient. (b) Mutual coupling.

### 3.1. Mutual Couplings between the Two Dual-antenna Systems

To quantify the mutual couplings between the two dual-antenna systems, the simulated $S$-parameters of the proposed quad-antenna system without the decoupling element are shown in Figure 2. For the symmetry of the quad-antenna system, only $S_{11}$, $S_{12}$, $S_{13}$, $S_{14}$, $S_{22}$, and $S_{23}$ are shown. From Figure 2, it could be observed that, the coupling between the elements 2 and 3 is strong while the couplings between the other elements are weaker at the 2.4/5.2/5.8-GHz WLAN bands. Although the distance between the two dual-antenna systems is as far as 120 mm ($\sim 1\lambda$ at 2.4 GHz or $\sim 2.2\lambda$ at 5.5 GHz), the mutual coupling ($S_{23}$) between them is still higher than $-15$ dB. In addition, increasing the distance between the two dual-antenna systems does not decrease the mutual coupling significantly. Since the near-field coupling between the two dual-antenna systems is weak for the large distance, it infers that the mutual coupling mainly comes from the coupling of the surface wave on the ground plane. When element 2 (3) is excited, the surface wave will travel between elements 2 and 3 along the top edge of the supporting ground. When element 1 (4) is excited, the surface wave will be trapped by the embedded T-shaped slot of the dual-antenna system and thus is not able to travel to the other elements. And this is the reason why only the mutual coupling between the elements 2 and 3 is strong. So, due to the effect of the surface wave, the quad-antenna system with low mutual coupling cannot be achieved by simply installing two dual-antenna systems at the top edge of the supporting ground.

### 3.2. The Method to Reduce the Mutual Coupling

To construct a quad-antenna system with low coupling using two dual-antenna systems, the surface wave on the ground between them should be suppressed. Many methods, including introducing an electromagnetic band gap (EBG) or a defected ground structure (DGS), could be applied to suppress the surface wave. In this paper, T-shaped slots are applied. A resonating T-shaped slot can trap the surface wave and prevent the surface wave from travelling [11]. It should be noted that selecting the T-shaped slots as the decoupling element is just to validate the design of the quad-antenna system. The methods, which can suppress the surface wave flowing between the two dual-antenna systems, can be applied as the decoupling element. To suppress the surface wave at the 2.4/5.2/5.8-GHz WLAN bands, three T-shaped slots are embedded in a protruded ground as shown in Figure 1(c). T-shaped-slot 2 resonates at 2.442 GHz and T-shaped-slots 1 and 3 resonate at 5.5 GHz. Consequently, the T-shaped-slot 2 and T-shaped-slots 1 and 3 can suppress the surface wave at the 2.4- and 5.2/5.8-GHz WLAN bands, respectively. The simulated $S$-parameters of the proposed quad-antenna system without the T-shaped-slot 2 and the T-shaped-slots 1 and 3 are shown in Figure 3 and Figure 4, respectively. Figure 3 shows that the T-shaped-slots 1 and 3 are mainly used to reduce the mutual coupling between the elements 2 and 3 at the 5.2/5.8-GHz WLAN bands. Figure 4 shows that the T-shaped-slot 2 reduces the mutual

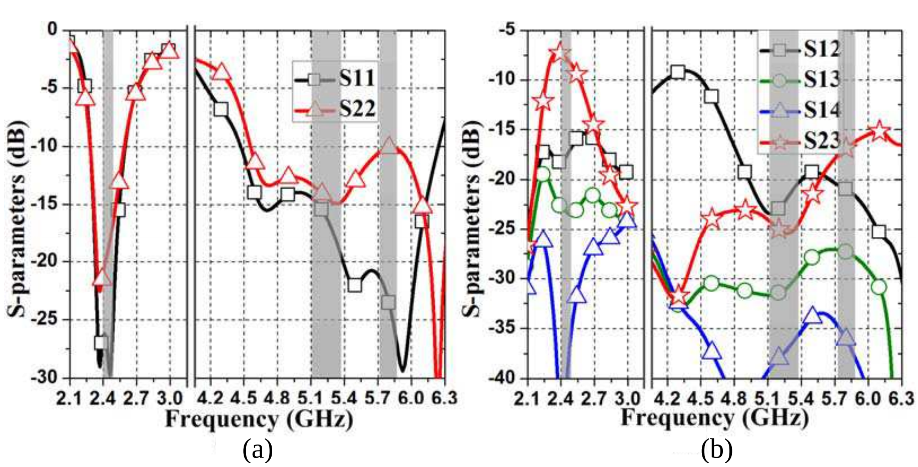



**Figure 3.** Simulated $S$-parameters of the quad-antenna system without the T-shaped-slot 2. (a) Reflection coefficient. (b) Mutual coupling.

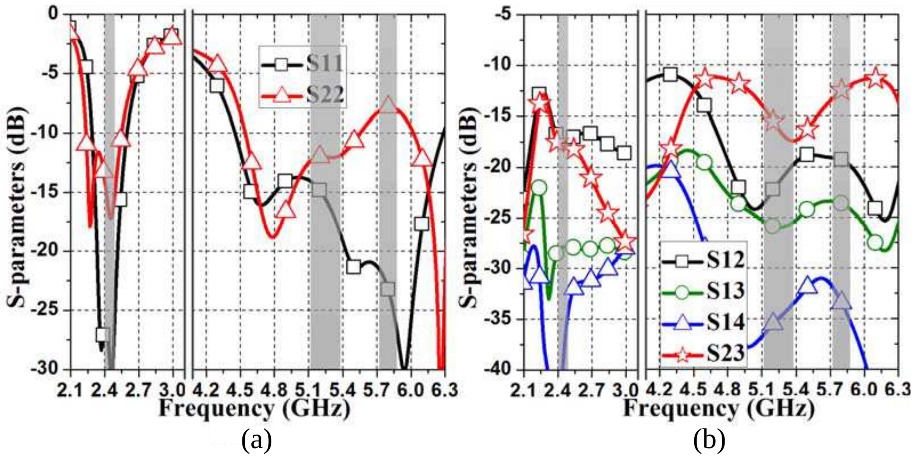



**Figure 4.** Simulated $S$-parameters of the quad-antenna system without the T-shaped-slots 1 and 3. (a) Reflection coefficient. (b) Mutual coupling.

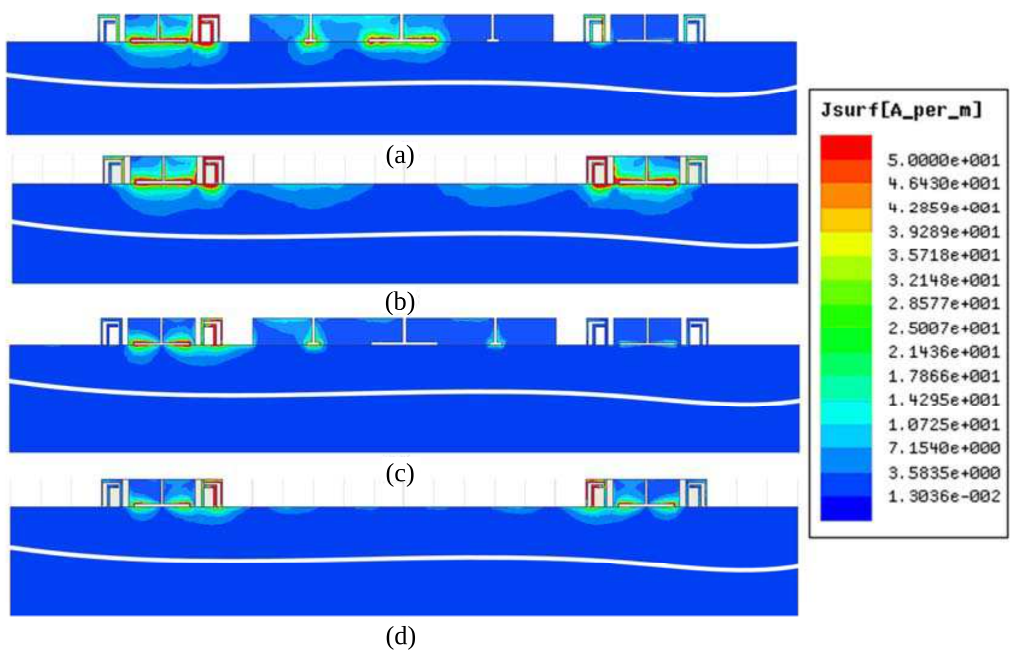



**Figure 5.** Simulated surface current distributions on the proposed antenna with and without the decoupling element at 2.442 GHz and 5.5 GHz. (a) With the decoupling element at 2.442 GHz. (b) Without the decoupling element at 2.442 GHz. (c) With the decoupling element at 5.5 GHz. (d) Without the decoupling element at 5.5 GHz.

coupling at the 2.4-GHz WLAN band. To better understand the function of the decoupling element, the simulated surface current distributions on the proposed antenna with and without the decoupling element at 2.442 and 5.5 GHz are shown in Figure 5. It should be noted that the Figure 5 is got under the condition that the element 2 is excited while the other three elements are terminated to a matching load, respectively. It is shown in Figures 5(b) and (d) that the induced currents on the element 3 without the decoupling element are strong at 2.442 and 5.5 GHz. From Figures 5(a) and (c), one can find that, with the help of the decoupling element, the induced currents on the element 3 are reduced. Also, one can find that the T-shaped slot 2 resonates at 2.442 GHz while the T-shaped slots 1 and 3 resonate at 5.5 GHz. So, the T-shaped slot 2 and T-shaped slots 1 and 3 can prevent the surface current (wave) travelling between the two dual-antenna systems at 2.442 GHz and 5.5 GHz, respectively. As the three

T-shaped slots are employed simultaneously, the surface wave at the 2.4/5.2/5.8-GHz WLAN bands can be suppressed simultaneously. The simulated $S$-parameters of the proposed quad-antenna system are shown in Figure 6. Figure 6 shows that, with the help of the decoupling element, the quad-antenna system with low mutual coupling operating at the 2.4/5.2/5.8-GHz WLAN bands is achieved.

### 3.3. Effect of the Keyboard Ground on the $S$-Parameters

To better emulate the effect of the laptop computer on the antenna performances, the laptop keyboard ground should be considered. The laptop display ground and the laptop keyboard ground should be considered simultaneously to emulate the laptop computer. So, the display ground and the keyboard ground form an angle of 90 degrees (as a common professional standard) with the same size of $260 \times 200\,\text{mm}^2$ is used to emulate a 13 inch laptop computer. The installation environment of the quad-

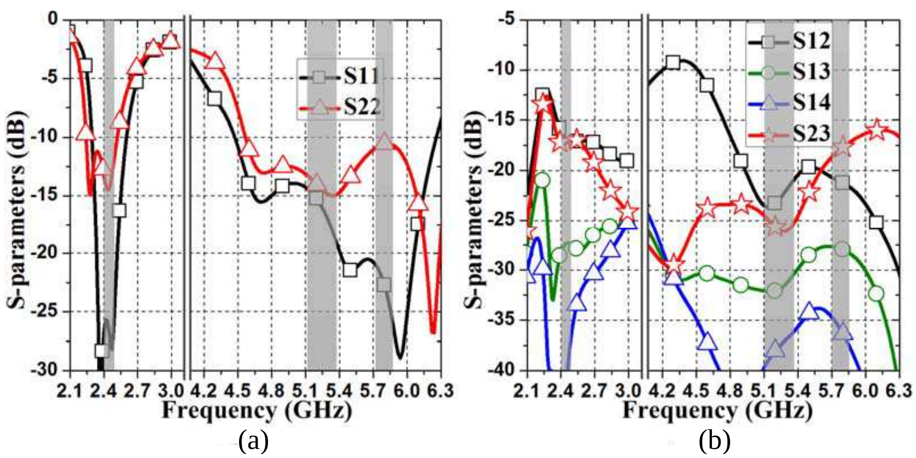



**Figure 6.** Simulated $S$-parameters of the proposed quad-antenna system. (a) Reflection coefficient. (b) Mutual coupling.

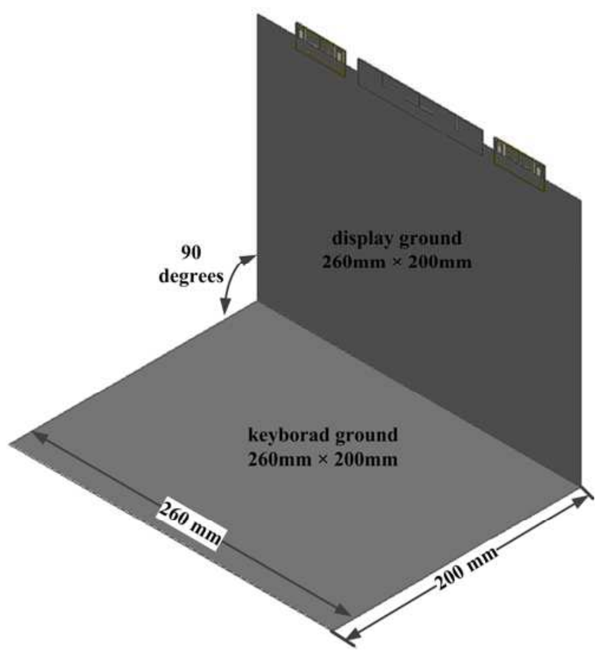
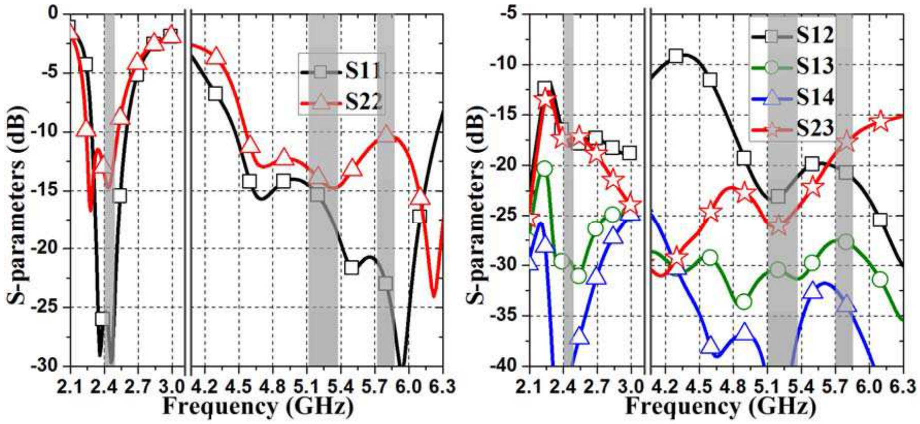



**Figure 7.** The installation environment of the quad-antenna system on the laptop computer with keyboard ground.




(a) (b)

**Figure 8.** Simulated $S$-parameters of the quad-antenna system on the laptop computer with keyboard ground.

antenna system on the laptop computer with keyboard ground is shown in Figure 7. The simulated $S$-parameters of the quad-antenna system on the laptop computer are shown in Figure 8. From Figure 8, we can find that the effect of the laptop keyboard ground on the $S$-parameters is weak and can be ignored. So, only the laptop display ground is used to emulate the laptop computer in this paper.

### 3.4. Design Methodology of a Quad-Antenna System

According to the above analyses, to construct a quad-antenna system with two dual-antenna systems, a decoupling element should be applied to suppress the surface wave on the ground. The design methodology of the quad-antenna system is summarized as follows.

a) Installing two dual-antenna systems at the top edge of the supporting ground.
b) Applying a decoupling element between the two dual-antenna systems to suppress the surface wave on the ground.
c) Fine-tuning the parameters of the quad-antenna system to obtain the desired performance.

## 4. EXPERIMENTAL RESULTS AND DISCUSSIONS

To validate the above simulated results, a prototype based on the dimensions in Figure 1 is fabricated and measured. The photo of the fabricated quad-antenna system is shown in Figure 9. The $S$-parameters are tested by an Agilent E5071B vector network analyzer (VNA) and the radiation performances are measured in an ETS-Lindgren AMS-8500 anechoic chamber where the 3D radiation pattern can be measured. The total radiation power is calculated using the discrete integral in the 3D space with a step of 5 degrees. The antenna efficiency is achieved by comparing the total radiation power with the antenna input power. The envelop correlation coefficient is calculated using the measured results.

### 4.1. *S*-Parameters

The simulated and measured $S$-parameters of the proposed quad-antenna system are shown in Figure 6 and Figure 10, respectively. The $S_{ii}$ and $S_{ij}$ $(i, j = 1, 2, 3, 4, i \neq j)$ are measured under the condition that the related port(s) are connected to the VNA while the rest ports are terminated by a matching load, respectively. For the symmetry of the quad-antenna system, only $S_{11}$, $S_{12}$, $S_{13}$, $S_{14}$, $S_{22}$, and $S_{23}$ are shown. The simulated overlapped $-10$ dB impedance bandwidths of the four elements are 220 MHz (2.29∼2.51 GHz) at 2.4-GHz WLAN band and 1.68 GHz (4.58–6.26 GHz) at the 5.2/5.8-GHz WLAN bands, respectively. The simulated mutual couplings are below $-16$ dB and $-17$ dB at the 2.4- and 5.2/5.8-GHz WLAN bands, respectively. The measured $-10$-dB impedance bandwidths are 200 MHz


**Figure 9.** Photo of the fabricated quad-antenna system.

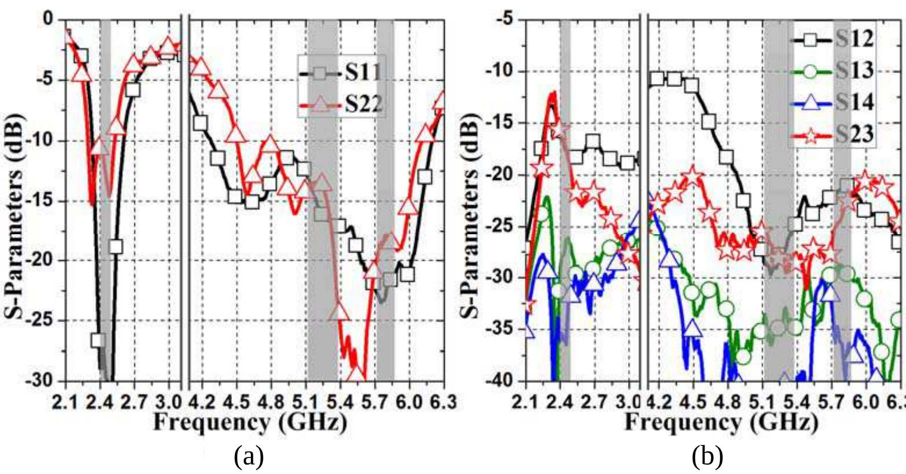



**Figure 10.** Measured $S$-parameters of the proposed quad-antenna system. (a) Reflection coefficient. (b) Mutual coupling.

(2.33–2.52 GHz) and 1.62 GHz (4.5–6.12 GHz), respectively. The measured mutual couplings are lower than −15.5 and −19 dB at the 2.4- and 5.2/5.8-GHz WLAN bands, respectively. The slight differences between the measured and simulated results may come from the manufacturing error.

### 4.2. Radiation Performances

The measured 3-D radiation patterns of the quad-antenna system at 2.442, 5.25, and 5.8 GHz are shown in Figure 11. The patterns are obtained under the condition that one element is excited while the other three elements are terminated to a matching load, respectively. Figure 11 shows that the radiation patterns of the four elements have complementary characteristics in the space.

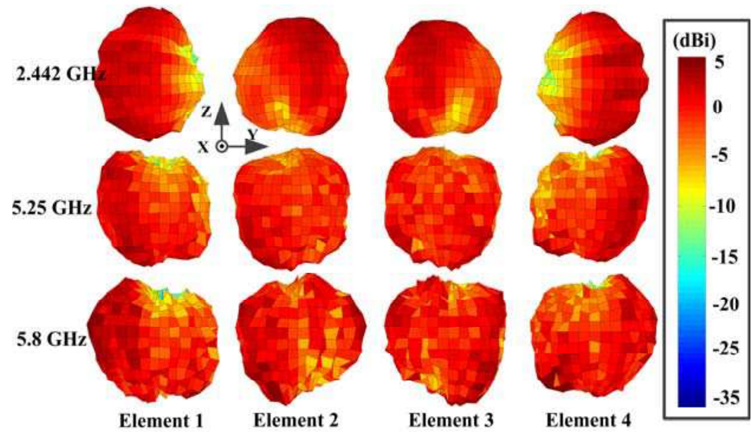



**Figure 11.** Measured 3-D radiation patterns at 2.442, 5.25, and 5.8 GHz.

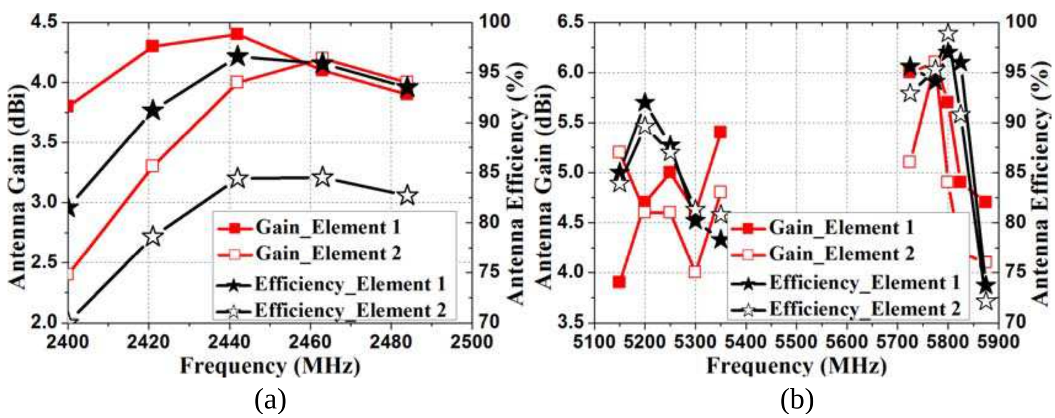



**Figure 12.** Measured gains and efficiencies of the proposed quad-antenna system. (a) 2.4-GHz WLAN band. (b) 5.2/5.8-GHz WLAN bands.

Figure 12 shows the measured gains and efficiencies of the quad-antenna system at 2.4/5.2/5.8-GHz WLAN bands. The antenna efficiency includeds the effects of the mismatching, dielectric loss, and metal loss. For the symmetry of the quad-antenna system, only the gains and efficiencies of the elements 1 and 2 are shown. Figure 12(a) shows that the gains are better than 2.4 dBi and the efficiencies are higher than 70% at the 2.4 GHz WLAN bands. Figure 12(b) shows that the gains are better than 3.9 dBi and the efficiencies are higher than 72% at the 5.2/5.8-GHz WLAN bands. The differences of the gains and efficiencies of the four elements may come from the different positions of the antenna elements.

### 4.3. Envelop Correlation Coefficient (ECC)

The envelop correlation coefficient (ECC) is the correlation of the signals received by two different elements. It is a figure of merit to evaluate the diversity performance of a multi-antenna sytem. Under the condition that the reflection and diffraction are rich and the channel response is Rayleigh-distributed, the ECC, shown in Table 1, is calculated using the measured 3-D radiation patterns with the method proposed in [17]. In Table 1, the $\rho_{ij}$ is the ECC of the element $i$ and element $j$. $\Gamma$ is the cross-polarization discrimination (XPD) (ratio of vertical to horizontal power density) of the incident field. And the $\Gamma$ of 0 dB and 6 dB, which are the average in an indoor and an urban fading environment, respectively, are assumed [17]. Table 1 shows that the ECC between the four elements are low enough which is promising for good antenna diversity.

**Table 1.** ECC of the proposed quad-antenna system.

| Frequency (GHz) | Γ (dB) | $\rho_{12}$ | $\rho_{13}$ | $\rho_{14}$ | $\rho_{23}$ |
|---|---|---|---|---|---|
| 2.442 | 0 | 0.0228 | 0.0031 | 0.0003 | 0.0010 |
| | 6 | 0.0165 | 0.0022 | 0.0002 | 0.0006 |
| 5.25 | 0 | 0.0003 | 0.0002 | 0.0006 | 0.0002 |
| | 6 | 0.0034 | 0.0001 | 0.0012 | 0.0002 |
| 5.8 | 0 | 0.0004 | 0.0003 | 0.0002 | 0.0039 |
| | 6 | 0.0003 | 0.0001 | 0.0004 | 0.0031 |

## 5. CONCLUSIONS

In this paper, a quad-antenna system covering the 2.4/5.2/5.8-GHz WLAN bands has been proposed. Two dual-antenna systems in [11] are utilized to construct the quad-antenna system. The mutual coupling between the two dual-antenna systems is studied. A decoupling element, consisting of a protruded ground with three T-shaped slots, is applied to reduce the mutual coupling. The function of the decoupling element is studied based on the $S$-parameters. A prototype shows that it covers the 2.4/5.2/5.8-GHz WLAN bands with measured mutual couplings below $-15.5$ dB and $-19$ dB at the 2.4- and 5.2/5.8-GHz WLAN bands, respectively. The measured 3D patterns of the four elements cover complementary spatial regions. The measured gains are better than 2.4/3.9 dBi and the measured efficiencies are higher than 70%/72% at the 2.4- and 5.2/5.8-GHz WLAN bands, respectively. The envelop correlation coefficient of the four elements are low which is promising for good antenna diversity.

## ACKNOWLEDGMENT

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