Compact Double Shorted Loop Sub-6-GHz Dual-Band MIMO Quad-Antenna System

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ABSTRACT This paper presents the design of a compact double-loop sub-6-GHz dual-band MIMO quad-antenna system for 5G laptops. To meet the market demand for laptops with a high screen-to-body ratio, the sub-6-GHz dual-band MIMO quad-antenna system is realized to have a low-profile height of only 3 mm. To make the MIMO quad-antenna system suitable for laptops with a narrow bezel, the four antenna elements are printed on the same FR4 substrate, which is mounted on the upper edge of and coplanar with the display ground plane of a laptop. The four antenna elements have the same double shorted loop structure and the same size of \(15 \times 3 \text{ mm}^2\). In the loop structure, a meandered path is embedded in one of the two shorted-end sections, and a series chip capacitor is embedded in the other. The low-frequency resonance mode can be adjusted by varying the meandered path, and the high-frequency resonance mode can be tuned using the meandered path and the series chip capacitor. The four antenna elements are aligned in the same direction with an end-to-end gap of 5 mm so that satisfactory isolation can be achieved without any additional isolation elements. The MIMO quad-antenna system, although measuring only \(75 \times 3 \text{ mm}^2\) with the three gaps included, can cover 3400–3800 and 4800–5000 MHz for 5G dual-band operations. The measured isolations between the four antenna elements are larger than 10 dB, the envelope correlation coefficient (ECC) values calculated from the measured radiation patterns are all below 0.27, and the measured radiation efficiencies of all four antenna elements are over 42%.

INDEX TERMS Laptop antennas, multi-input multi-output (MIMO) antennas, loop antennas, 5G antennas.

I. INTRODUCTION The fifth-generation (5G) mobile communications require high transmission rates and use multiple-input multiple-output (MIMO) technology to boost transmission rates and provide high throughputs. With the current trend towards large screens with narrow bezels for laptops, the biggest challenge in antenna design for 5G mobile communications is how to closely configure multiple low-profile antennas in limited space while maintaining good isolation of the MIMO antenna system to sustain a high data transmission rate. Although it is easier to design low-profile MIMO antenna systems for 5G than for 4G, how to make multiple antennas tightly configured while keeping good isolation is still very challenging for 5G MIMO antenna design. In recent years, there have been several designs for tight configurations of multiple antennas [1]–[12], in which various methods have been proposed to optimize the isolation between multiple antennas closely placed in limited space available for mobile communication devices. In some 5G MIMO multi-antenna systems [1]–[3], the isolations between individual antenna elements have been optimized by arranging these antenna elements at appropriate intervals, with a spacing of about 15–30 mm between adjacent antenna elements. Several isolation optimization techniques have also been introduced for closely spaced two-antenna systems, including adding a chip inductor at the branch ends of the two antennas [4], [5], adding a chip capacitor at the common short-circuit end of the two loop antennas [6], and using distributed capacitive and inductive designs at the common short-circuit end of the two antennas [7] to improve the isolation between them without reserving additional spacing. In [8], two different excitation mechanisms are employed to produce good isolation between the two antenna elements of the MIMO.
antenna system that has a profile height of 4 mm and a length of 30 mm and that can cover the 3400–3800 MHz band of 5G. There are also 5G MIMO antenna arrays deployed on the bezel of a mobile phone [9]–[11], where in each array two closely spaced antenna elements are cleverly grouped as a unit for good isolation and the compact two-antenna unit is used as a building block for constructing a MIMO antenna system consisting of multiple two-antenna units. In [9] and [10], the two antenna elements in the same unit on the bezel are asymmetrically mirrored with respect to the system ground plane. An employed short-circuit decoupling technique results in excellent intra-unit isolation. In [11], the two antenna elements in the same unit are mirrored of each other and are on the same side of the system ground plane. Although the end-to-end gap between the two antenna elements is only 3 mm, good intra-unit isolation has also been obtained using a similar short-circuit decoupling technique. Although the two-antenna units in [9]–[11] are very compact, their corresponding MIMO antenna systems consisting of two or four units are not. This is because the gap between adjacent two-antenna units must be sufficiently large to obtain a good enough inter-unit isolation. Note that in [4]–[8] each MIMO antenna system is also a tightly packed two-antenna unit; if these arrays are to be expanded to contain more units, the large inter-unit gaps required will also cause the resulting MIMO antenna systems to occupy a large circuit area.

In [12], two mirrored compact two-antenna units are used to construct a four-element MIMO antenna system (or called MIMO quad-antenna system). This system is also very compact, since the two units are connected by only two isolation chip inductors. If desired, the MIMO antenna system can be expanded to contain three or more than three two-antenna units, in which adjacent units can also be connected by two isolation chip inductors. Although having the advantage of compactness, the structure of the antenna elements in [12] is complicated and not easy to fabricate. Not only are the antenna patterns printed on a T-cross-sectioned substrate, making the structure three-dimensional, but a bending sheet not printed on the substrate is also needed for each antenna element. In addition, the main antenna structure is perpendicular to, not coplanar with, the display ground plane, causing this MIMO quad-antenna system not suitable to be implemented on laptops whose bezels are very narrow (or laptops that are very thin).

In this paper, we propose for 5G another dual-band MIMO quad-antenna system that is suitable for thin laptops with a large screen-to-body ratio. This MIMO quad-antenna system measuring only $75 \times 3$ mm$^2$ is mounted on the upper edge of the display ground plane. The substrate holding the four antenna elements is coplanar with the display ground plane of a laptop, and thus is suitable for thin laptops. Also, the profile height of the quad-antenna system is only 3 mm; hence it is suitable for laptops with a large screen-to-body ratio. The four antenna elements in the quad-antenna system have the same double shorted loop structure and the same size of $15 \times 3$ mm$^2$. They are oriented in the same direction and are aligned in tandem with an end-to-end gap of 5 mm along the same axis so that satisfactory isolation can be achieved without any additional isolation elements. If additional antenna elements are required to be added to the original quad-antenna system to form a new MIMO antenna system with more than four antenna elements, these additional antenna elements do not have to be placed far away from the original four elements. They can be configured in the same manner and be separated from the original quad-antenna system by the same gap of 5 mm. The implemented quad-antenna system can support the 5G dual-band operation in the 3400–3800 and 4800–5000 MHz bands. The measured isolations between the four antenna elements exceed 10 dB, the envelope correlation coefficient (ECC) values calculated for the measured radiation patterns all fall below 0.27, and the measured radiation efficiencies of all four antennas are over 42%.
of the loop, and a series 0.3 pF chip capacitor is embedded in the other shorted-end section. For distinction, the loop containing the former is called Loop 1, and the latter Loop 2. Loop 1 is the path from feeding point A through the meandered shorted-end section to ground point G2 (ABDG2); Loop 2 is the path from feeding point A through the chip capacitor to ground point G3 (ABDG3). Point A in the diagram is the signal feeding point, which is connected to the inner conductor of the 50-Ω mini coaxial line, while the outer conductor of the 50-Ω mini coaxial line is connected to ground point G1 on the display ground plane.

B. EXPERIMENT AND MEASUREMENT RESULTS

Figure 3 shows a zoom-out photo of the overall 5G dual-band MIMO quad-antenna system (with the laptop included), and Figure 4 shows a photo of the FR4-supported 5G dual-band MIMO quad-antenna system itself. The full-wave software tool ANSYS HFSS (Version 15) [13] is employed for simulation in this study. The criterion chosen for the impedance band is that the reflection coefficient must be less than –6 dB (i.e., VSWR < 3), which is also frequently adopted in the literature on multiple antennas for 5G mobile communication devices [1]–[12], while satisfactory in-band transmission coefficients between individual antenna elements must be less than –10 dB (see [10]–[12]).

Figure 5 shows the simulated and measured reflection coefficients of the 5G dual-band MIMO quad-antenna system. From this figure, we can see that the quad-antenna system can generate two resonance modes, one at low and the other at high frequencies; that the simulated and measured data are in good agreement; and that the proposed quad-antenna system can provide two operating bands of 5G, i.e., 3400–3800 and 4800–5000 MHz. Figure 6 demonstrates the simulated and measured transmission coefficients between the four antenna elements of the quad-antenna system. Although the measured transmission coefficients are all less than –10 dB, the simulated ones in the low-frequency band are only below –8 dB, so special attention needs to be paid to the antenna efficiency for practical applications. If the mutual coupling between two adjacent antenna elements needs to be further reduced, the area of 5 × 3 mm² between...
FIGURE 6. Transmission coefficients (a) simulated and (b) measured for the 5G dual-band MIMO quad-antenna system.

the two antenna elements should be fully utilized. For that purpose, the display ground plane can be protruded into that area [1]. Alternatively, a thin meandered line section shorted to the ground can be inserted into that area so that its quarter-wavelength resonance can offer the wave-trapping function to reduce the mutual coupling around the low-frequency band.

In addition to the isolation between antenna elements, the ECC, mean effective gain (MEG), and total active reflection coefficient (TARC) are also important reference parameters for MIMO antenna systems. For conciseness, TARCs will not be presented here. In general, an ECC of less than 0.5 [14] and an MEG difference of less than 3 dB between antenna elements [3], [15] are criteria that can be adopted in practice.

Figure 7 presents the ECC values calculated from the radiation patterns measured for the 5G quad-antenna system. The ECC values from the radiation patterns measured in the 3400–3800 MHz and 4800–5000 MHz bands of the 5G quad-antenna system are both less than 0.27, and the ECC values are generally smaller for antenna elements that are farther apart. We also note that the ECC values for Ants 2–3 are much higher than the ECC values between the other two antennas. The reason for that can be explained in what follows. Because Ant 2 (Ant 3) is sandwiched by Ant 1 (Ant 2) and Ant 3 (Ant 4), Ants 2 and 3 can “see” similar environments since they are both next to two antenna elements. On the other hand, for example, Ant 1 has Ant 2 on its right side but without any antenna element on its left side, indicating that Ant 1 is next to only one antenna element. The environments around Ant 1 and Ant 2 are quite different. This causes the ECC values for Ants 2–3 to be larger than those for Ants 1–2. Nevertheless, these ECC values are all less than 0.27, meeting the criterion for practical applications and thus confirming good channel independence between antenna elements in the MIMO quad-antenna system. Figure 8 shows the measured mean effective gains (MEGs) for the 5G MIMO quad-antenna system. The difference between the MEGs of the four antenna elements is within 2.85 dB in the operating bands, which is also small enough for practical applications.

FIGURE 7. ECCs calculated from the complex E-field radiation patterns measured for the 5G MIMO antenna system.

FIGURE 8. Measured mean effective gains (MEGs) for Ants 1–4 in the 5G MIMO quad-antenna system.

Figure 9 presents for the MIMO quad-antenna system the measured antenna efficiencies, which range from 42% to 72% for the low-frequency band and from 48% to 69% for the high-frequency band. Observe that the two inner antenna elements (Ants 2 and 3) are less efficient than the two outer ones (Ants 1 and 4), primarily in that each of the former is next to two antenna elements and each of the latter is next to only one antenna element.
Next, we present and explain the radiation pattern characteristics of these four antenna elements. Figure 10 shows the 3D measured radiation patterns of the four antenna elements operating at 3600 MHz and 4800 MHz. These patterns are unnormalized, and hence are the patterns for the realized gain [16]. Although the four antenna elements are identical in structure, they “see” different environments. Hence, they produce different radiation patterns, and cause the ECC values to be less than 0.27, as given in Figure 7.

The surface current distribution of one single antenna element at 3600 and 4800 MHz is illustrated in Figure 11. It can be observed that there is a clear current distribution in the Loop 1 (ABDG2) path when the antenna is operating at 3600 MHz and there are two current nulls in the path, thus suggesting that the low-frequency mode is contributed by the full-wavelength resonance of Loop 1. When the antenna is operating at 4800 MHz, the electric currents are distributed in both the Loop 1 (ABDG2) and Loop 2 (ABDG3) paths. In short, the 3600 MHz resonance mode of the antenna is mainly associated with the Loop 1 (ABDG2) path, while the 4800 MHz resonance mode pertains to both the Loop 1 (ABDG2) and Loop 2 (ABDG3) paths.

To further look at the isolation between the four antenna elements in the quad-antenna system, we have also performed an analysis of the electric surface currents on the four antenna elements and the ground plane. These surface currents at 3600 and 4800 MHz are illustrated in Figure 12. From this figure, it can be seen that at both 3600 and 4800 MHz no significant ground-plane current flows from the activated antenna element to the other silent antenna elements, regardless of which antenna element is excited. Therefore, the four antenna elements have good isolation and ECC performance, which may be related to the structural design of the antennas. For example, the Loop 1 path for the low-frequency mode is in full-wavelength resonance, causing the currents exterior to the resonance path much weaker than those inside the resonance path. The ground plane for our design can be regarded as outside the resonance path, and hence the weak ground-plane currents lead to weak coupling and high isolation to the neighboring antenna elements. Since the electric length of the separation distance between the ports of adjacent antenna elements is larger at the high-frequency band than at the low-frequency band, the isolation at the high-frequency band is larger than that at the low-frequency band. This phenomenon can also be inferred from the current distributions in
Figure 12, where the transverse ground-plane current flowing from the excitation port to the neighboring silent port decays faster at 4800 MHz than at 3600 MHz.

**C. PARAMETRIC STUDY**

Next, in order to better understand the operation mechanism of the antenna element, three different structures are analyzed here: the structures for Ant 1 (called the Proposed antenna) and two reference antennas (called the Reference1 and Reference 2 antennas). From the inset of Figure 13, we can see that the Reference 1 antenna has the Loop 1 (ABDG2) path of Ant 1 without the meandered path and instead with a direct short-to-ground structure, while the Reference 2 antenna possesses the proposed structure of Ant 1 but without the meandered path as in the Reference 1 antenna. Figure 13 shows the reflection coefficient comparison, from which it can be seen that the simple loop structure of Reference 1 with a direct shorted-end section can produce a resonance mode at 3850 MHz. This resonance mode occurring at 3850 MHz is still present when a parallel shorted-end section with 0.3 pF chip capacitance is added to the Reference 1 antenna to form the Reference 2 antenna. For the Reference 2 antenna, an additional resonance mode can be generated at the high frequency of 5950 MHz. Finally, we added the meandered path to the direct shorted-end section in the Reference 2 antenna to form the optimal Ant 1 (the Proposed antenna). As presented earlier, the electric current is mainly distributed in the Loop 1 path for the low-frequency mode and in both the Loop 1 and Loop 2 paths for the high-frequency mode. We expect that the lengthened Loop 1 path will lower the resonance frequencies of both the low- and high-frequency modes. Hence, the meandered path inserted in the shorted-end section of Loop 1 can lower the resonance frequencies (3850 and 5950 MHz) of the Reference 2 antenna to those (3600 and 4800 MHz) of the proposed Ant 1. As shown in Figure 13, these two frequency bands can cover the dual bands required for sub-6-GHz 5G applications.

To gain a further understanding of the contribution to each mode, the following three parameters are analyzed for the Ant 1 structure. First, we analyze the parameters for the partial meander section length $m$ on the Loop 1 (ABDG2) path. A comparison of the simulated reflection coefficients for three different values of $m$ is exhibited in Figure 14, which indicates that when the partial meander section length increases from 1 to 4 mm, the two resonance modes display a downward trend in frequency, thereby proving that the Loop 1 (ABDG2) path can affect both the low- and high-frequency resonance modes. Next, we perform a parametric analysis of the partial common section length $d$ for the Loop 1 (ABDG2) and Loop 2 (ABDG3) paths. The simulated reflection coefficients for three different values of $d$ are presented in Figure 15. When this partial common section length of Loop 1 and Loop 2 increases from 11 to 15 mm, both the low- and high-frequency resonance modes exhibit a significant downward trend in frequency, as expected.

**FIGURE 13.** Structure and reflection coefficient comparison of three antennas: reference 1, reference 2 and proposed (Ant 1).

**FIGURE 14.** Simulated reflection coefficients for three values of $m$ related to the meandered path of the loop.

**FIGURE 15.** Simulated reflection coefficients for three values of the path parameter $d$ of the loop.

Finally, we will study the effect of the capacitance $C$ on the reflection coefficient. Since the chip capacitor exists in the Loop 2 path, we expect that the high-frequency resonance mode will be affected more pronouncedly than the
low-frequency one. Figure 16 shows the simulated reflection coefficients for three different values of $C$ (0.2, 0.3, and 0.4 pF). These results verify that the high-frequency mode has an obvious trend of frequency downshift as the value of $C$ increases. At this point, we can also observe that the low-frequency mode has a slight tendency of frequency downshift as the value of $C$ increases. This is because the electric current in the shorted-end section of the Loop 2 path for the low-frequency mode is only much weaker than that in the shorted-end section of the Loop 1 path, but not identically zero (see Figure 11).

**TABLE 1.** Performance comparison of MIMO antenna systems.

| Ref. | size (width $\times$ length) (mm) | operating bands (MHz) | spacing between two antennas (mm) | Isolation (dB) | efficiency | ECC | compact four-antenna unit |
|------|---------------------------------|-----------------------|-----------------------------------|----------------|------------|-----|--------------------------|
| 3    | $3 \times 16$                  | 3400–3800             | $\geq 19.5$                       | $\geq 10$      | $\geq 42\%$ | $\leq 0.15$ | N/A                      |
| 4    | $4 \times 9.5$                 | 3400–3800             | $\leq 17.5$                       | $\geq 50\%$   | $\leq 0.05$ | N/A            |                          |
| 5    | $5 \times 20.5$                | 2400–2480             | $\leq 17$                        | $\geq 48\%$   | N/A        | N/A            |                          |
| 7    | $8 \times 16.1$                | 2300–6000             | without spacing                   | $\leq 12$      | $\geq 50\%$ | $\leq 0.1$ | N/A                      |
| 8    | $4 \times 14.5$                | 3400–3800             | without spacing                   | $\leq 12$      | $\geq 57\%$ | $\leq 0.1$ | N/A                      |
| 9    | $3.1 \times 10$               | 3400–3600             | $0.8$                             | $\geq 10$      | $\geq 50\%$ | $\leq 0.1$ | N/A                      |
| 12   | $1.7 \times 30$               | 3300–2600             | $\leq 10$                        | $\geq 55\%$   | $\leq 0.3$ | achieved         |                          |
| this work                                  | 3400–3800             | $5$                             | $\geq 10$      | $\geq 42\%$ | $\leq 0.27$ | achieved         |                          |

*Compact four-antenna unit here means that two two-antenna units can be separated by less than 5 mm.

**FIGURE 16.** Simulated reflection coefficients for three values of capacitance $C$.

**III. CONCLUSION**

This paper proposes a compact double shorted loop sub-6-GHz dual-band MIMO quad-antenna system with only 5 mm apart between adjacent antenna elements without the need for any isolation elements. The two operating bands of the proposed MIMO quad-antenna system can be easily tuned by adjusting a meandered path and a series chip capacitor embedded in the two shorted-end sections of the loop structure. The generated two operating bands can cover 3400–3800 and 4800–5000 MHz that are required by sub-6-GHz 5G applications. The quad-antenna system is printed on an FR4 substrate of $75 \times 3 \text{ mm}^2$, which is mounted on the upper edge of and coplanar with the display ground plane. Such a small profile height and such a simple configuration, along with the good ECC and isolation performance, make the proposed quad-antenna system ideal for laptops with narrow bezels and large screens.

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