Research Article

2 × 2 MIMO Asymmetric U-Shaped Nonuniform Slot Antenna for the 4G LTE Metal-Housing Mobile Handsets

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A 2 × 2 MIMO antenna for metal-housing mobile handset application is proposed in this article. The polarization diversity is used to arrange the two antennas’ setup. The asymmetric U-shaped nonuniform slot antenna provides two different resonant bands are designed to be operated in long term evolution (LTE) covers lower band (698 MHz to 960 MHz) and upper band (1710 MHz to 2700 MHz). The modified type III balun is used for upper-operating band, and the open stub is used for lower-operating band, good impedance bandwidth, and radiated pattern and efficiency are shown. The isolation (S21) between the antennas is more than 20 dB, and the envelope correlation coefficient (ECC) is less than 0.02. A prototype of the proposed antenna chiselling in the metal-housing mobile handset (with 160 mm in length, 10 mm in height, and 70 mm in width) is fabricated and experimentally studied.

1. Introduction

Metal-housing mobile handsets are slowly becoming a trend for the fashion industrial design. The demand of increasing panel size has grown dramatically in recent years, at the same time, requires the space reduction of the antenna setup also. Moreover, the rapid increase of wireless communication applications has led to the development of MIMO antennas for 4G LTE terminals. In the scenario of limited antenna space, the antenna performance, such as operating bandwidth, radiated pattern and efficiency, and isolation between antennas, will cause antenna design face a severe challenge. The literature [1] presents by using a stacked rectangular ring slot microstrip antenna with parasitic load for UMTS, LTE, and WiFi applications, and the wide operating bandwidth is shown. This technique is effective in creating an additional resonant path to generate an additional resonant mode for the antenna. This design concept is applied in this study to an open-stub structure. However, the complex fabricated structure needs large space, which excites multimode resonant to cause multilobes in the antenna’s radiated pattern; therefore, it is difficult to use this antenna structure in mobile handsets. In the literature [2, 3] presents by using various slot antenna shape, varying the slot shape of antenna to cause multiresonant path to increase the operating bands and bandwidths are presented. The low-profile feature is suitable to fit in the narrow region between the metal frame and the display panel. Therefore, when the terminal body is larger than the antenna element (especially slot antenna), it is beneficial to enhance the radiated gain and operating bandwidth of the antenna; in other words, the antenna performance is varied due to the influence of the terminal body size that will cause some uncertainty issues. In this article, an asymmetric U-shaped slot antenna is designed, which is chiselled in the metal-housing mobile handset, to achieve 4G LTE full-band (lower-band, 698 MHz to 960 MHz and upper-band, 1710 MHz to 2700 MHz) performance. The feasibility of wide bandwidth operation has been proven by
Figure 1: (a). Geometry of the proposed antenna for $2 \times 2$ MIMO 4G LTE full-band operation. (b). The proposed antenna chiseled in the metal-housing mobile handset (three-dimensional structure). (c). Planar dimensions of the proposed antenna (unit: mm). (d). Implemented prototype of the proposed antenna.
the design structure comprising nonuniform slot, modified type III balun, and open-stub and stepped-fed structure to operate in the dual operating bands. In addition, the 2 × 2 MIMO antennas for the 4G LTE system is the application scenario of the proposed antenna structure. The two antennas are the main antenna and auxiliary antenna. By using the polarization diversity to arrange the two antennas setup, the isolation (S21) between antennas is more than 20 dB. Details of the design considerations and the experimental results of the constructed prototype are presented and discussed in the following sections.

2. Antenna Structure and Design

Figure 1 shows the proposed asymmetric U-shaped slot antenna for 2 × 2 MIMO 4G LTE full-band applications. The polarization diversity is used to setup the two antennas. Because the reference ground-plane is different, the sizes of two antennas, #1 (denoted as auxiliary antenna) and #2 (denoted as main antenna), are slightly different. The presented antennas’ structure is composed of a longer-slot section of length S1, shorter-slot section of length S2, and stepped-fed section of length S3. These sections are all chiseled in the copper metal-plane with size 160 mm by 70 mm. The implemented prototype of the proposed antenna is shown in Figure 1(d). The resonant mode of section S1 is designed to occur at LTE lower band and the section S2 is designed to occur at LTE upper band. The length of radiating slots can be determined from about one half-wave length at the center resonant frequencies. The total length of S2 is designed to one-third S1, so the S2 be an open-stub of S1, for enlarging the bandwidth of lower-operating band. As the slot shape trace was bended, the corresponding resonant frequency of the antenna would decrease as well.

The design parameters and the corresponding characteristics of resonant frequency, input impedance, and bandwidth are functions of the geometrical parameters of the nonuniform asymmetric U-shaped slot structure. Both sections S1 and S2 are nonuniform slot structures. In section S1, the width of longer slot is 3.125 mm, which is one percent wavelength of lower-operating band (@960 MHz), and the width of shorter slot is 1.36 mm, which is one percent wavelength of upper-operating band (@2200 MHz). In section S2, the width of longer slot is 1.75 mm, which is one percent wavelength of upper-operating band (@1710 MHz), and the width of shorter slot is 3.6 mm, which is one percent wavelength of lower-operating band (@825 MHz). The two different slot widths and the bended structure will cause the discontinuity surface current of antenna to induce some proximity resonant frequencies, so the operating bandwidths will increase. Moreover, the end-excited U-shapes slot will lead high-input impedance effect and narrowed bandwidth, and the stepped-fed structure is proposed to be a modified impedance transformer to reduce the input impedance and extend the bandwidth [4]. In addition, because the upper-operating band is produced by the shorter slots, which is sensitive to the metallic environment, to cause frequency detuning. So, to consider the actual applications, the antennas’ performance will be impacted by a LCD condition, because the upper-operating band is produced by the shorter slots, which is sensitive to the metallic environment, to cause frequency detuning. So, to consider the actual applications, the antennas’ performance will be impacted by a LCD panel (which is like a metallic plate); hence, the longer slot of #1 antenna is setup near the middle of the metal back cover and the shorter slot is in the edge of the ground plane.

3. Experimental Results and Discussion

In the experiment, the feed and ground points are connected to 1.13Ω 10 cm minic coaxial cable with 50Ω I-pex connector. By using the described design procedure, a dual-band antenna was constructed to operate at the range of 4G LTE full-band (lower-operating band: 698 MHz–960 MHz and upper-operating band: 1710 MHz–2700 MHz) systems. Figure 2(a) shows the measured and simulated S11 plot of the two antennas. The measured S11 ≤ −10 dB bandwidths are 368 MHz (663 MHz–1031 MHz) and 1338 MHz (1556 MHz–2894 MHz) at lower- and upper-operating band, respectively, in #1 antenna. And the #2 antenna’s bandwidths are 275 MHz (687 MHz–962 MHz) and 1281 MHz (1412 MHz–2693 MHz) at lower- and upper-operating band, respectively. Both of these antennas have same performance. The simulated results are obtained by using the Ansoft HFSS. We can also find a good agreement between the simulation and measurement in the lower-operating band, but there is slight difference in the upper-operating band, which is caused by the high-order mode resonant of the feeding coax because the length of feeding coax is 10 cm, which is near to half-wave length of the upper-operating band. The simulated and measured isolation (S21) between the two antennas is
| Frequency (MHz) | 825 | 960 |
|----------------|-----|-----|
| **Simulated results** | ![Simulated result](image) | ![Simulated result](image) |
| Maximum gain | 3.3 dBi | 4.6 dBi |
| **Measured results** | ![Measured result](image) | ![Measured result](image) |
| Maximum gain | 1.49 dBi | 2.5 dBi |

**Figure 3: Continued.**
Figure 3: Simulated and measured 2D and 3D radiation patterns of #1. (a) Lower-operating band. (b) Upper-operating band.
| Frequency (MHz) | 825   | 960   |
|----------------|-------|-------|
|                | Simulated results |       |
|                | ![Image](image1.png) | ![Image](image2.png) |
| Maximum gain   | 2.6 dBi | 3.3 dBi |
|                | Measured results |       |
|                | ![Image](image3.png) | ![Image](image4.png) |
| Maximum gain   | 1.43 dBi | 1.8 dBi |

**Figure 4: Continued.**
| Frequency (MHz) | 2200 | 2690 |
|----------------|------|------|
| **Simulated results** |     |      |
| Frequency (MHz) | 2200 | 2690 |
| Maximum gain | 4.9 dBi | 5.1 dB |
| **Measured results** |     |      |
| Frequency (MHz) | 2200 | 2690 |
| Maximum gain | 2.98 dB | 2.31 dB |

**Figure 4:** Simulated and measured 2D and 3D radiation patterns of #2. (a) Lower-operating band. (b) Upper-operating band.
shown in Figure 2(b), and more than 20 dB in the lower- and upper-operating band are shown. In the lower-operating band, the longer slot of #1 antenna is setup near the middle of the metal back cover (which is in the $z$-$x$ plane) and the longer slot of #2 antenna is to be bend and setup in the edge of metal-housing (which is in the $y$-$z$ plane); these two longer slots are not in the same plane, as shown in Figure 1(b). In the upper-operating band, the polarization diversity is shown between the two shorter slots. In other words, the good isolation between the two antennas is contributed from adopting a slot antenna structure and polarization diversity arrangement [4–6].

Figures 3 and 4 present the simulated and measured 2D and 3D radiation patterns of #1 and #2 antenna at 825 MHz, 960 MHz, 2200 MHz, and 2690 MHz, respectively. The radiated patterns of simulated and measured results are slightly different, and there is also significant difference between the maximum gains; all of which are caused by the feeding coax issue. In the figures, at the same frequency, the effectiveness of polarization diversity is shown between the two shorter slots. In other words, the good isolation between the two antennas is contributed from adopting a slot antenna structure and polarization diversity arrangement [4–6].

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Table 1: Measured antenna gains and total efficiency of #1.

| Frequency (MHz) | 825 MHz | 960 MHz | 2200 MHz | 2690 MHz |
|----------------|---------|---------|----------|----------|
| Maximum gain (dBi) | 1.49 | 2.5 | 2.55 | 3.1 |
| Efficiency (%) | 52 | 48 | 50 | 48 |

Table 2: Measured antenna gains and total efficiency of #2.

| Frequency (MHz) | 825 MHz | 960 MHz | 2200 MHz | 2690 MHz |
|----------------|---------|---------|----------|----------|
| Maximum gain (dBi) | 1.43 | 1.8 | 2.98 | 2.31 |
| Efficiency (%) | 49 | 44 | 55 | 54 |

Envelope Correlation Coefficient (ECC, $\rho_e$) is an important figure of merit for the comparison of MIMO capabilities of coupled antennas, which is obtained from the measured far-field patterns over a sphere by employing the ETS-Lindgren (AMS-8700) anechoic chamber. For a two-element MIMO antenna, ECC can be calculated as follows:

$$\rho_e = \frac{\left| \iint_{4\pi} \left[ \mathbf{E}_1(\theta, \phi) \cdot \mathbf{E}^*_2(\theta, \phi) \right] \, d\Omega \right|^2}{\left( \iint_{4\pi} |\mathbf{E}_1(\theta, \phi)|^2 \, d\Omega \right) \left( \iint_{4\pi} |\mathbf{E}^*_2(\theta, \phi)|^2 \, d\Omega \right)} \quad (1)$$

$E_i$ is the electric field radiated by antenna $i$ with another antenna terminated by a matched load. It is known that a lower envelope correlation leads to a larger channel capacity. As we can see from Figure 5, the ECC is lower than 0.02 on both lower and upper band of 4G LTE, which means a good MIMO performance. Tables 1 and 2 show the measured antenna gains and total efficiency within the operating bands of the proposed antennas #1 and #2. Stable radiation patterns are observed. The total efficiency was carried out by using pattern integration employing the ETS-Lindgren (AMS-8500) anechoic chamber. Acceptable radiation characteristics for the practical applications are obtained for the proposed antenna.

In Table 3, the proposed antenna is presented to compare with recently published works; although the application scenario is different, these antennas could meet the required performance. The proposed antenna indeed shows the simple structure because the matching components and tuning stub are not needed.

![Figure 5: Envelope correlation coefficient of the proposed antenna system.](image-url)
4. Conclusion

A novel multi- and wide-band antenna comprising non-uniform asymmetric U-shaped slot with stepped-fed structure for application in a 2 × 2 MIMO 4G LTE system has been proposed and implemented in the metal-housing mobile handset. Measurement results show that a wide bandwidth is obtained. The impedance matching of the proposed antenna is mainly achieved by adjusting the width of slots and stepped-fed structure. The performances of the proposed antenna, including S-parameters, radiation patterns, and envelope correlation coefficient (ECC) were examined, and the results show a 4G LTE MIMO antenna with high isolation is successfully achieved due to use polarization diversity and the slot structure. The contribution of the open stub in the lower-operating band to increase the bandwidth and the modified type III balun in the upper-operating band to improve the radiated efficiency is proved. In addition, the long slot of the #1 antenna is close to the middle of the metal back cover, which will cause significant visual interference, and a metal coated plastic film will be used to cover the existence of the slot. The design concepts presented in this paper can be extended to other metal environments of interest.

Data Availability

The .xls data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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