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Reconfigurable Loop Antenna With Two Parasitic Grounded Strips for WWAN/LTE Unbroken-Metal-Rimmed Smartphones

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ABSTRACT A reconfigurable loop antenna with two parasitic grounded strips for modern smartphone devices is presented in this paper. The most essential merit of this proposed reconfigurable antenna is that it can keep the intactness of the outer metal rim. In addition, it can generate multiantenna modes. The outer metal rim generates three loop modes and the inner parasite grounded strips can provide two monopole modes. By merging these two types of antenna modes, it can offer two wide bandwidths to cover GSM850/900, DCS/PCS/UMTS2100, and LTE2300/2500 operations with a compact antenna size of 945 mm^2. The detailed operating principles and design considerations of this proposed reconfigurable antenna are described. In order to validate this proposed antenna, it was fabricated and tested. The measured antenna efficiencies and gains are satisfied with the requirements for the modern communication devices.

INDEX TERMS Reconfigurable antenna, unbroken metal rim, WWAN/LTE, smartphone.

I. INTRODUCTION

In recent years, customers pay more attention to smartphone devices, especially metal-rimmed smartphones [1]. Actually, the metal rim not only can make the smartphone more comfortable and better looking, but also can increase its robustness. However, the performances of the inner antenna designs, like the inverted-F antennas or monopole antennas, will be seriously weakened if without any effective modification on the outer metal rim. To solve this problem, several promising metal-rimmed antenna designs are proposed in [2]–[9]. One method in [2] is to introduce several gaps and grounded patches into the outer metal rim. This modification can reduce the bad influence on the performances of the inner antennas. The other alternative method is to take full advantage of the entire or partial metal rim functioning as radiation elements, which can reduce the antenna size and the difficulty of antenna design [3]–[9]. The antenna performances reported in [3]–[6] are very outstanding, while at least one gap is introduced into the outer metal rim which is usually intolerable and unacceptable for a proportion of consumers. Generally, compared with inverted-F antennas and monopole antenna, loop antennas and slot antennas are easier to be integrated into the outer metal rim without breaking its intactness [7]–[9]. It should also be noted that, the proposed compact antenna in [9] employs the hybrid mode of loop mode and monopole slot mode can achieve an eight-band operations, which effectively overcomes the negative influence of the metal rim.

Owing to the rapid development of communication, the bandwidth for modern mobile devices should cover the LTE/WWAN operations. Numerous techniques have been proposed to make distinct bandwidths. The common methods include but not limited to matching networks, [10]–[12], reconfigurable technique [13]–[15] and coupling feeding [16]–[18]. In addition, parasitic elements, like grounded strips [19]–[21], is also a competitive alternative, which can increase the antenna bandwidth with a compact configuration.

In this paper, a reconfigurable loop antenna with two parasitic inverted-L grounded strips is introduced. It contains two types of antenna modes, namely, loop modes and monopole modes. By merging these hybrid antenna modes with the aid of reconfigurable technique, it is capable of covering the WWAN/LTE operating bands. Herein, the most merit of

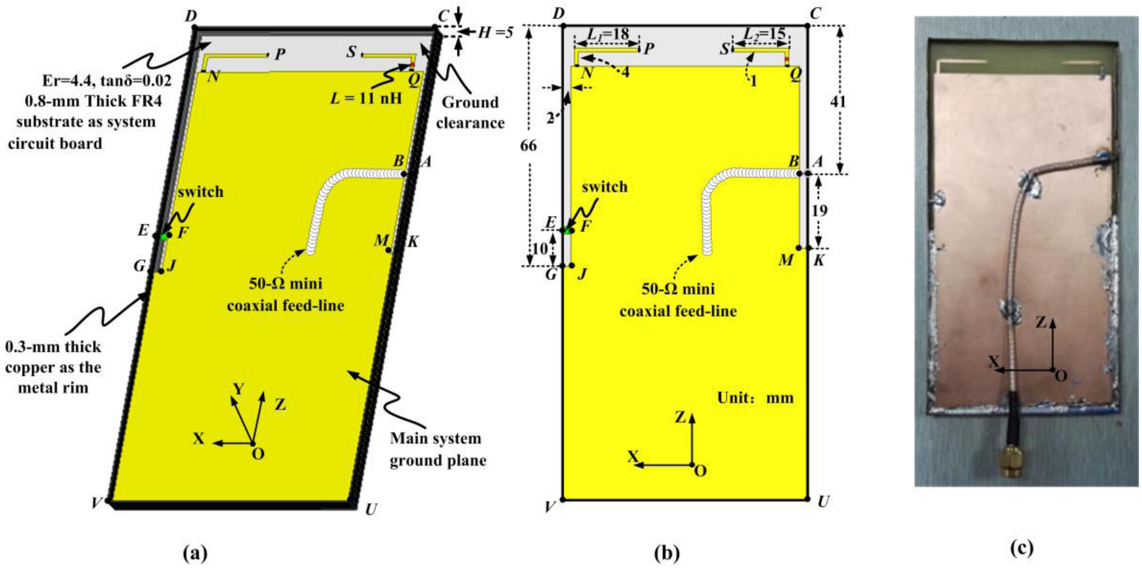

FIGURE 1. Proposed reconfigurable antenna with unbroken metal rim: (a) geometry; (b) detail dimensions; (c) photos of the manufactured reconfigurable antenna (Unit: mm).

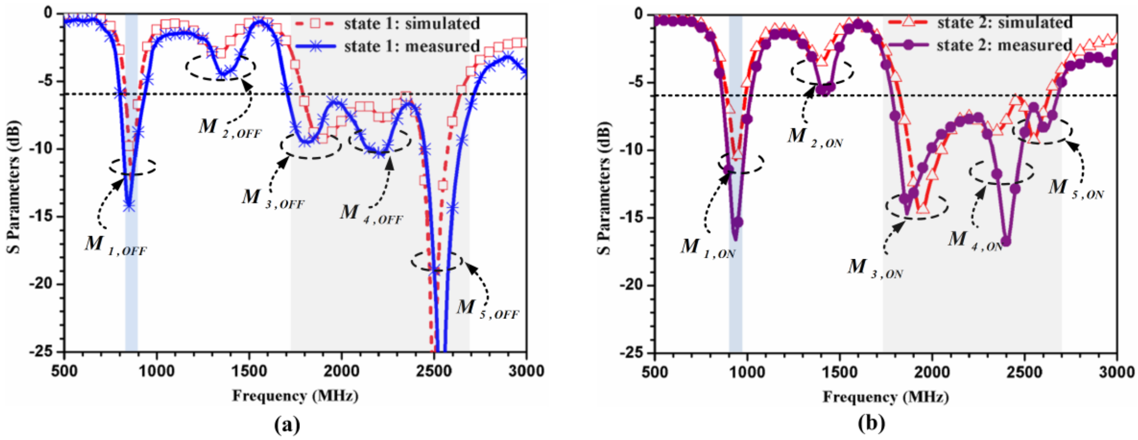

FIGURE 2. Simulated and measured *S* parameters for (a) state 1 (OFF state); (b) state 2 (ON state).

this work is that it not only can keep the intactness of the outer metal rim but also can cover hepta-band with a compact antenna size.

II. ANTENNA CONFIGURATION

Fig. 1 shows the detailed configuration of this reconfigurable unbroken-metal-rimmed antenna. As shown in Fig. 1(a), the proposed antenna is mounted on a FR4 substrate ($\varepsilon_r = 4.4$ and $\tan\delta = 0.024$). Its size is of $130\times67\times0.8\text{mm}^3$. Moreover, the FR4 substrate is surrounded by a metal rim. Its thickness and height are 0.3 mm and 5 mm, respectively. Two parasitic inverted-L grounded strips are printed in the U-shaped ground clearance whose total size is of 945 mm^2. An ON/OFF switch is located between the inner ground plane and the outer metal rim through a narrow strip $\overline{EF}$. The outer conductor of a 50-Ω coaxial cable is welded to the system ground through shorting point (point B). Its inner conductor is fixed to the metal rim via the feeding point (point A), which can excite this proposed antenna.

This studied reconfigurable antenna is composed of two inverted-L strips, an ON/OFF switch and the upper part of the metal rim, illustrated in Fig. 1(b). A U-shaped closed-loop antenna is comprised by the top metal rim and the inner ground plane, which can provide three loop modes (0.5-, 1.0- and 1.5λ) [22], [23]. The ON/OFF switch can control the length of the U-shaped closed-loop antenna, which can provide two working states. By combining these two working states, the desired lower-band can be achieved. In addition, the ground strip $\overline{NP}$ can generate a fundamental mode around 2.45 GHz, corresponding to the $\lambda/4$ mode. The other ground strip $\overline{QS}$ can contribute a fundamental mode at about 1.75 GHz, which can decrease the required resonant length with the aid of a series chip inductor of 11nH. Hence, the desired upper-band can be obtained

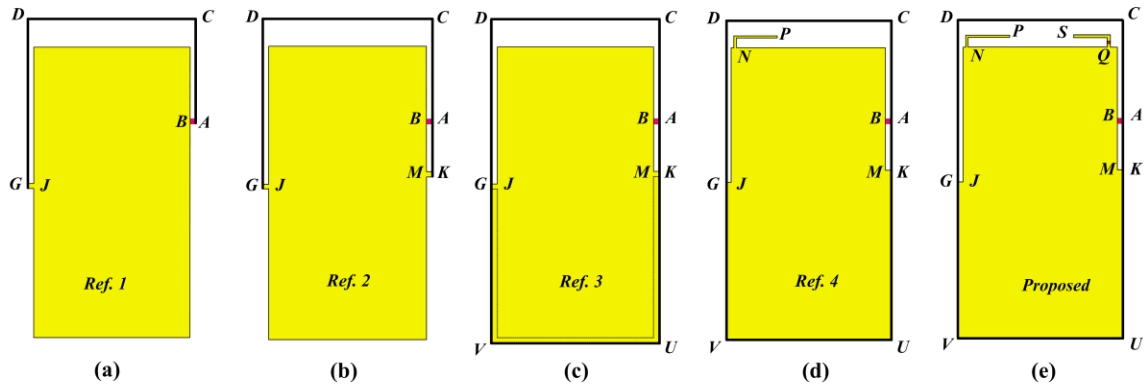

FIGURE 3. Geometric evolution of the proposed antenna.

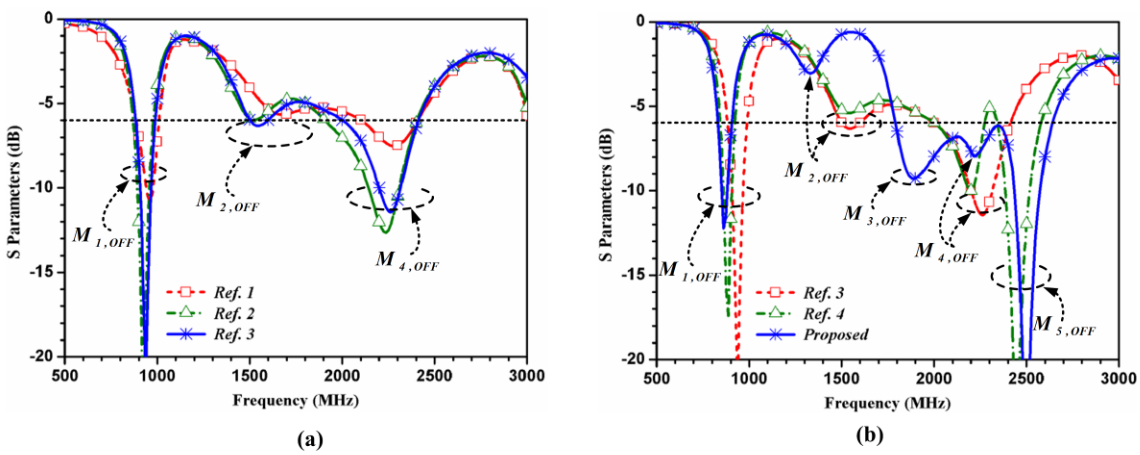

FIGURE 4. Simulated *S* parameters of (a) *Ref_1*, *Ref_2* and *Ref_3*; (b) *Ref_3*, *Ref_4* and proposed antenna.

by merging two high-order loop modes and two monopole modes.

In order to validate this proposed antenna design, the proposed reconfigurable antenna was fabricated and tested. To simplify the manufacturing process and focus on the operating principle of this proposed antenna, the switch diode is simulated and measured as an open gap for its OFF state (state 1) and as a metal strip for its ON state (state 2) [24],[25].

The simulated *S* parameters of the studied antenna and its corresponding measured *S* parameters are plotted in Fig. 2. Seen from Fig. 2, When the switch is working at OFF state, marked as state 1, the gained bandwidth is able to cover the lower-band of GSM850 and the entire upper-band of DCS/PCS/UMTS2100/LTE2300/2500 operations. When the switch is working at ON state, marked as state2, the achieved bandwidth can provide wide coverage for GSM900 and the desired upper-band of DCS/PCS/UMTS2100/LTE2300/2500 operations. Hence, this studied reconfigurable antenna can cover 824–960 MHz and 1710–2690 MHz by merging its two working states (state 1 and state 2).

In addition, when the switch is OFF, the corresponding five resonant modes of the studied reconfigurable antenna is marked as $M_{1,OFF}$, $M_{2,OFF}$,$M_{3,OFF}$, $M_{4,OFF}$ and $M_{5,OFF}$ in sequence from the lower frequency to upper frequency. Similarly, the corresponding resonant modes are written as $M_{1,ON}$, $M_{2,ON}$, $M_{3,ON}$, $M_{4,ON}$ and $M_{5,ON}$ for ON state.

III. WORKING PRINCIPLES

In order to analyze its corresponding antenna modes, several *Ref.* antennas are introduced. In addition, its working mechanism remains unchanged while changing the working states of the studied antenna (state 1 and state 2). Hence, the introduced analysis in the following section is based on the condition that the studied antenna operates at state 1 (OFF state) for the sake of brevity.

The design evolution of the proposed antenna is illustrated in Fig. 3 and the corresponding simulated *S* parameters are plotted in Fig. 4. A simple U-shaped closed-loop antenna formed by the upper part of the metal rim and the inner ground plane is labeled as *Ref. 1* illustrated in Fig. 3(a). The U-shaped loop antenna can generate one fundamental loop mode ($M_{1,\ OFF}$) and two high-order loop modes ($M_{2,OFF}$ and $M_{4,OFF}$) shown in Fig. 4(a). Compared with *Ref. 1*, another shorting ground strip $\overline{MK}$ is added in the place of 19 mm away from the feeding point shown in Fig. 3(b). In order to provide good robustness for the smartphone, the partial

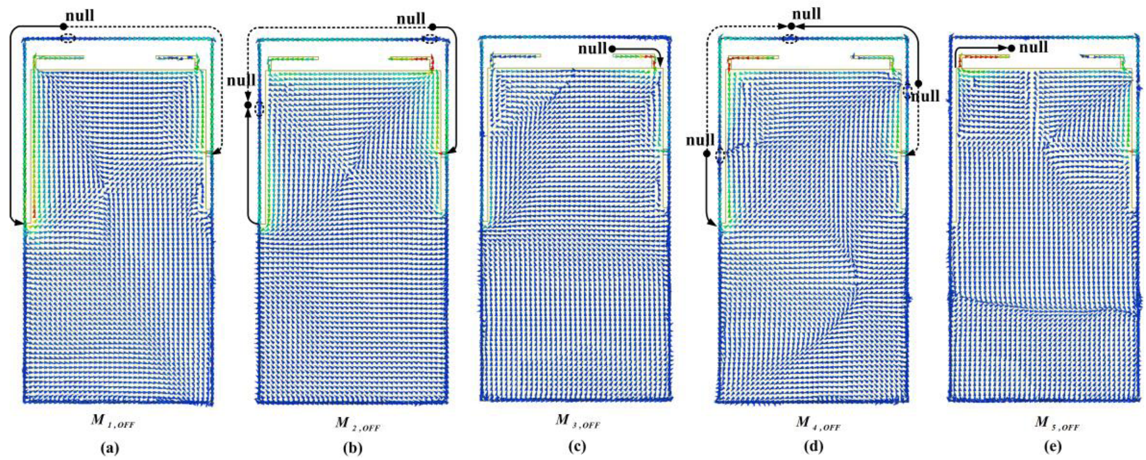

FIGURE 5. Simulated surface current distributions in the proposed antenna at the corresponding resonant frequencies of (a) 860 MHz; (b) 1270 MHz; (c) 1750 MHz; (d) 2200 MHz; (e) 2450 MHz.

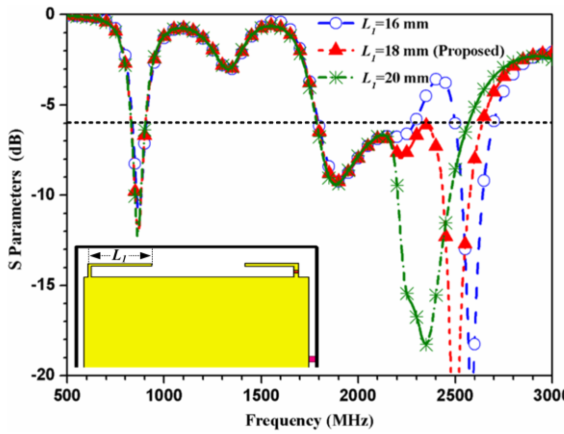

FIGURE 6. Simulated *S* parameters for the proposed antenna as a function of the length L_1 (other dimensions are the same as given in Fig. 1).

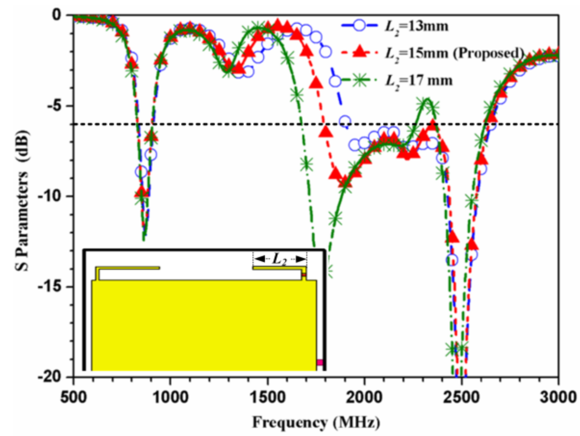

FIGURE 7. Simulated S parameters for the proposed antenna as a function of the length L2 (other dimensions are the same as given in Fig. 1).

metal rim $\overline{GVUK}$ is fixed to the inner ground plane by filling the gap between the partial metal rim $\overline{GVUK}$ and the system ground with a U-shaped metal strip shown in Fig. 3(c). Seen from Fig. 4(a), obviously, the processing in *Ref. 2* and *Ref. 3* has tiny effect on $M_{1,OFF}$, $M_{2,OFF}$ and$M_{4,OFF}$. In addition, it also does not excite new resonant modes. This indicates that this three modes are the fundamental mode and high-order modes of the U-shaped loop antenna, respectively. To broaden the bandwidth the proposed antenna, a grounded L-shaped strip $\overline{NP}$ is introduced into *Ref. 3* which forms *Ref. 4* shown Fig. 3(d). At last, a new monopole mode ($M_{5,OFF}$) appears at approximately 2.45 GHz. The proposed antenna is achieved by adding the other grounded strip $\overline{QS}$ loaded with an inductor of 15nH. Seen from Fig. 5, another monopole mode ($M_{3,OFF}$) of approximately 1.75 GHz is generated in the upper-band.

To more thoroughly comprehend the excited resonant modes of the proposed antenna, the surface vector current distributions of the corresponding five modes are simulated and plotted in Fig. 6. These five antenna modes correspond to 860 MHz, 1270 MHz, 1750 MHz, 2200 MHz and 2450 MHz, respectively. As shown in Fig. 5(a), a current null is found along the U-shaped loop antenna $\overline{ACDG}$ at 860 MHz. This indicates that the mode $M_{1,OFF}$ is its fundamental loop mode. Similarly, the other two high-order loop modes of $M_{2,OFF}$ and $M_{4,OFF}$ can be comprehended clearly after analyzing the corresponding current distributions illustrated in Fig. 5(b) and (d). By observing Fig. 5(c), the current is mostly concentrated in the inverted-L grounded strip $\overline{QS}$ at 1750 MHz whose current distribution has a maximum strength at the shorting point Q and decreases to be generally null at the end of the shorted strip (point S), which means that the grounded strip $\overline{QS}$ operates at its 0.25λ monopole mode. From the above analysis of current distributions, the antenna modes and the resonant mechanisms at different frequencies are straightforward.

IV. PARAMETER STUDY AND MEASURED RESULTS

In order to gain the optimal antenna design, several key parameters are studied. The effects of the lengths of the two

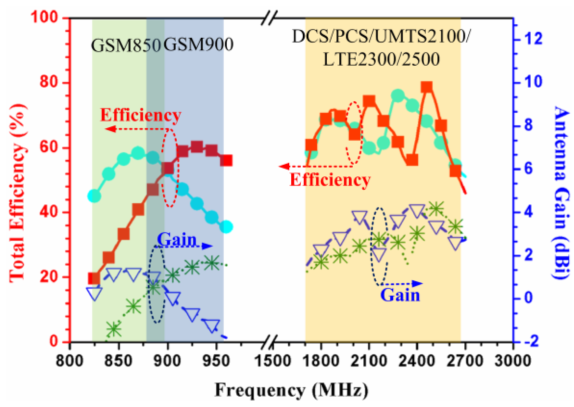

FIGURE 8. Measured total radiated efficiency (mismatching loss included) and antenna gain of proposed antenna across the two operating bands of interest.

parasitic grounded strips are analyzed illustrated in Fig. 6 and Fig. 7, respectively. The effect on the antenna S parameters while changing the length (L_1) of the horizontal part of the grounded strip $\overline{NP}$. The physical length of $M_{5,OFF}$ will increase asL_1 increasing. Hence, the corresponding resonant frequency of $M_{5,OFF}$ is shifted to lower frequency. For $L_1. = 16$ mm, the antenna bandwidth is not good to over the desired upper-band. However, the obtained bandwidth for the upper-band would become narrow as the length L_1 increased to 20 mm. Hence, in this study, it is a good choose that the length (L_1) of the horizontal part of the grounded strip $\overline{NP}$ equals to 18 mm.

When varying the length (L_2) of the horizontal part of the grounded strip $\overline{QS}$, the influence on the antenna performances of is shown in Fig. 7. Obviously, the resonant frequency of the $M_{3,OFF}$ moves to lower frequency when L_2 varied from 13 mm to 17 mm, which indicating that the resonant mode is contributed by the inverted-L parasitic grounded strip $\overline{QS}$. Additionally, a smaller L_2 (13 mm) will narrowed the obtained upper-band, while a larger L_2 (17 mm) will generate impedance mismatch between $M_{4,OFF}$ and $M_{5,OFF}$. Therefore, the length L_2 value is optimized to 15 mm.

The measured results of the studied antenna, including the total efficiencies and antenna gains, are exhibited in Fig. 8. For frequencies over the lower-band (824–960 MHz), the measured antenna gains and total efficiencies are approximately 0.3∼1.7 dBi, 45∼60%, respectively. As for the desired upper operating band (1710–2690 MHz), the range of the measured antenna gains is about 1.2 to 4.2 dBi. The measured total efficiencies are better than 47% over the interested upper-band. In summary, the measured results are generally acceptable for practical smartphone systems.

V. CONCLUSION

A reconfigurable loop antenna with two parasitic inverted-L grounded strips has been analyzed in this paper. This proposed antenna takes full advantage of the outer metal rim as an effective radiation element without introducing any slot/gap into the outer metal rim. By combining the loop modes and monopole modes and utilizing the reconfigurable technology, it can present two wide bandwidths for covering 824∼960 MHz and 1710∼2690 MHz, respectively. Furthermore, the measured good efficiency is larger than 45% and peak gains vary from 0.3 to 4.2 dBi across the desired operating bands. Obviously, it can meet the requirements for smartphone systems. Therefore, the proposed reconfigurable antenna with unbroken metal rim is a good candidate for modern smartphone applications.

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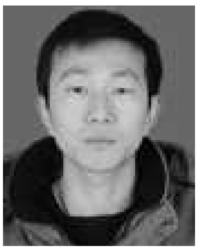

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