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Design of a Simple Structured NFC Loop Antenna for Mobile Phones Applications

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Abstract—A novel structure of a near-field communication (NFC) loop antenna for mobile phones with a metal back case is proposed. The proposed structure of the metal back case itself can operate as an NFC loop antenna through the design of a simple single turn loop antenna on the top portion of the metal back case, so that the simple structure of the proposed NFC loop antenna can reduce the overall thickness of the NFC antenna for slim mobile phones. Since a sintered ferrite sheet with generally higher relative permeability ($\mu_r \approx 200$) must be used to reduce the performance deterioration of the conventional NFC loop antennas due to the eddy current in the battery pack of a mobile handset, the cost of these conventional NFC antennas is high, and they are considerably fragile. In this paper, the proposed NFC antenna is designed without the ferrite sheet and in the optimal location to ensure minimum interference from the adjacent metallic components.

1. INTRODUCTION

A near-field communication (NFC) service has attracted attention for mobile phone applications. An NFC system at 13.56 MHz is a short-range communication technology that allows devices to communicate through inductive coupling [1–7]. The demand for a mobile NFC service has been increasing with popularization of mobile smartphones. Since most NFC antennas for mobile phone applications are embedded into metallic components such as the printed circuit board (PCB) ground or the battery pack of mobile phones, NFC technology involves several challenges such as reducing the thickness of the NFC antenna, the high manufacturing costs, and the performance degradation of the reading and tagging range. To avoid performance degradation of an NFC antenna due to an eddy current on the metallic components near an NFC antenna, a sintered ferrite sheet with high relative permeability ($\mu_r \approx 200$) is generally inserted between the NFC antenna and the shielding metal case of the mobile phone battery. This sintered ferrite sheet incurs a higher manufacturing cost, increases the thickness of the NFC antenna, and is very fragile.

We had already proposed a novel structure of an NFC loop antenna by changing the sequence of the loop winding and applying a modified inner loop structure, in order to achieve a stable operating volume and larger reading range for mobile phone applications [8]. We had also proposed a new structure of a compact NFC loop antenna by adding a parasitic loop to the outer side of a conventional loop antenna in order to improve its performance [9]. In [8, 9], NFC loop antennas were proposed for mobile phones, which do not have the metal back case, and were designed by employing a ferrite-polymer composite that is more durable, has lower relative permeability ($\mu_r \approx 55$), and has lower cost than the sintered ferrite sheet ($\mu_r \approx 200$). The demand for the refined design and hardness of a slim device has been increasing recently in mobile smartphone applications, so that commercial mobile smartphones with a metal back case [10–16] have recently been released. For mobile NFC systems, this metal back case can

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result in the performance degradation of the conventional NFC loop antenna. The ferrite sheet is still used to avoid performance degradation of the NFC antenna caused by the eddy current in the metal back case. The manufacturing cost therefore remains high, and the thickness of the NFC antenna is increased.

In this paper, a novel structure of an NFC antenna, without the ferrite sheet, is proposed for mobile smartphones with a metal back case. Unlike the flexible PCB (FPCB) type of the conventional NFC loop antenna, the proposed NFC antenna can reduce the thickness of the NFC antenna, the high manufacturing costs, and the performance degradation of the reading and tagging range due to the incorporated metallic objects such as the printed circuit board (PCB) ground, the battery pack of mobile phones, or the LCD ground. It is generally difficult to fully utilize the metal back case in a mobile phone since the non-metallic areas within the top and the bottom-portion of a mobile phone are necessary to achieve optimal performance of the multiple-input multiple-output (MIMO) antenna elements (primary and secondary MIMO antenna). In this paper, the proposed structure of the non-metallic area on the top portion of the metal back case, which is usually necessary for the secondary MIMO antenna in order to radiate efficiently, is thus designed as a novel structure of the simple NFC loop antenna. The proposed NFC antenna is located immediately above the secondary MIMO antenna which is mounted on the non-metallic area within the top portion of a mobile phone, so that it can operate without the ferrite sheet. Although the proposed NFC antenna is closely mounted near the secondary MIMO antenna, the secondary MIMO antenna can still cover the existing LTE 3, 5, 6, and 9 Rx bands ($869 \sim 894$ MHz, $1840 \sim 1870$ MHz, and VSWR < 3) without performance degradation. The proposed NFC antenna has a simple structure of a single turn loop antenna, which is designed to achieve an optimal value of quality factor (measured Q-factor = 39.4). The measured results of the proposed antenna meet the criteria values of an NFC system. In the detection range test for the reader/writer mode (R/W mode), the detection range responding to a reference tag (Mifare 1 k) is about 43 mm. In the load modulation test for the card emulation mode (Card mode), all of the measured load modulation levels within the specific operating volume meet the criteria values of an NFC system.

2. ANTENNA STRUCTURE AND DESIGN CONCEPT

Figure 1(a) shows an overall view of the metal back case of a commercial mobile phone and the proposed NFC antenna loop structure. The proposed NFC antenna is designed to sit on the top portion of the metal back case and printed on an FR-4 substrate ($\varepsilon_r = 4.4$, thickness = 0.6 mm). The metal back case can operate on its own as an NFC loop antenna by placing the simple single turn loop on the top-portion of the metal back case. The proposed NFC antenna is designed so that the antenna is placed immediately above the secondary MIMO antenna by generating the single turn loop as the non-metallic area on the top portion of the metal back case. The ferrite sheet used to reduce the eddy current is unnecessary because it is located on the non-metallic portion of a mobile phone. Figures 1(b) and 1(c) show the dimensions of the metal back case and the proposed NFC loop antenna, respectively. The total dimension of the back case is $66 \times 136 \times 0.6\,\text{mm}^3$. The dimension of the metal back case including the single turn loop, which is printed on the FR-4 substrate, is $66 \times 120\,\text{mm}^2$.

In an NFC antenna design, although a higher quality factor is required for a longer detection range, an excessively high quality factor (Q) is the cause of the bit-rate error of the NFC system, so that Q-factor of less than 40 is demanded in the NFC system [17]. Figure 2 shows the simulated inductance, resistance, and Q-factor of the proposed NFC antenna at 13.56 MHz with varying loop size. It is observed that although the simulated inductance and resistance of the proposed antenna, which has a simple structure of a single turn loop antenna mounted on somewhat away from the battery pack to avoid the eddy current, are much lower than those of a conventional $4 \sim 5$ turn NFC loop antenna, the proposed antenna with the optimal loop size of $46 \times 8\,\text{mm}^2$ gives optimal Q-factor of 39.58 as shown in Figure 2(b). Figure 3 shows the matching circuit between the NFC chip and the NFC antenna, and the simulated current distribution of the proposed NFC loop antenna at 13.56 MHz. By inserting the component values of $C_{1a} = 11.2\,\text{nF}$, $C_{1b} = 11.2\,\text{nF}$, and $C_2 = 4.5\,\text{nF}$, the proposed NFC antenna resonates at 13.56 MHz with a compact single loop size, and impedance matching is achieved. The current distribution of the single turn loop on the top-portion of the metal back case shows that the proposed single turn loop can operate as the single turn loop antenna for an NFC system.

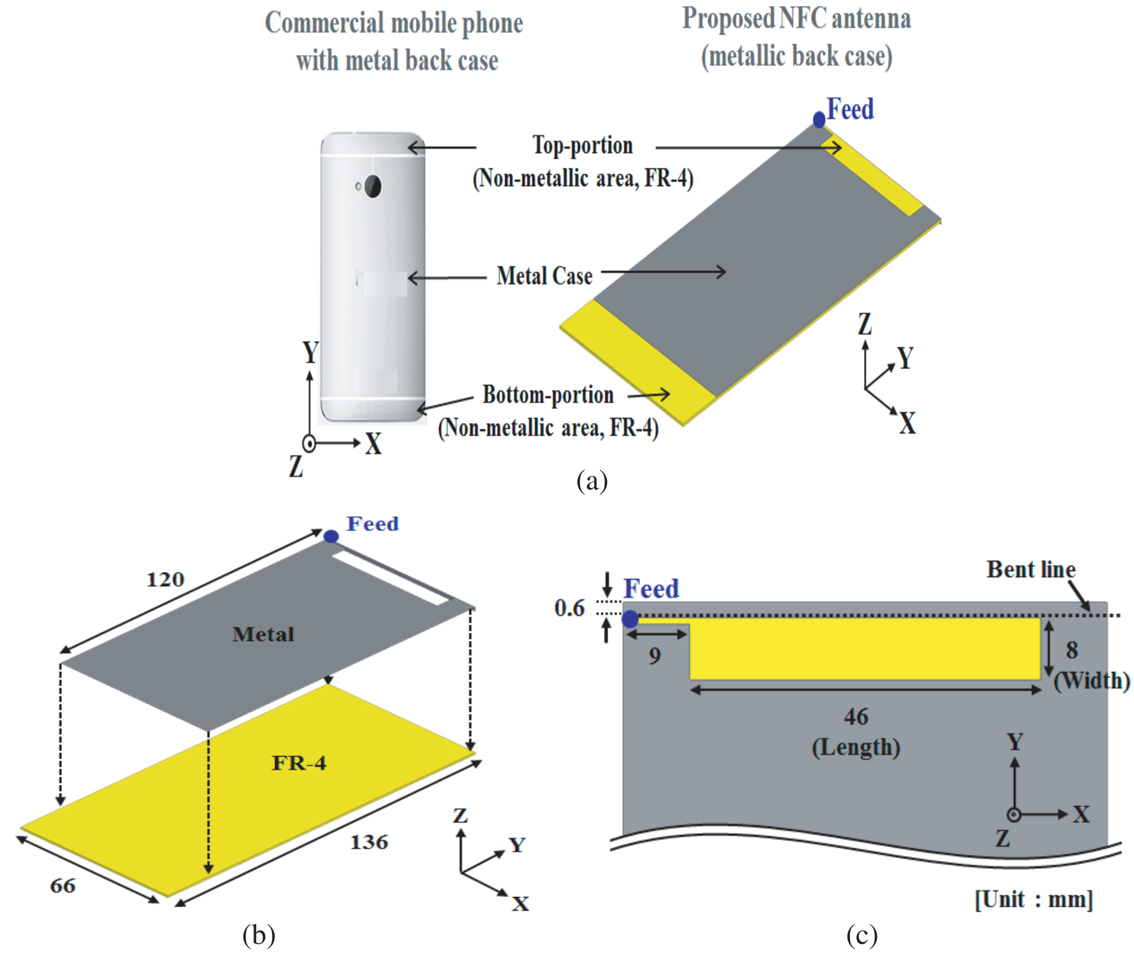

Figure 1. Geometry of the proposed NFC antenna: (a) Overall view, (b) dimension of the back case, and (c) dimension of the proposed single turn loop antenna on the top portion of the metal back case.

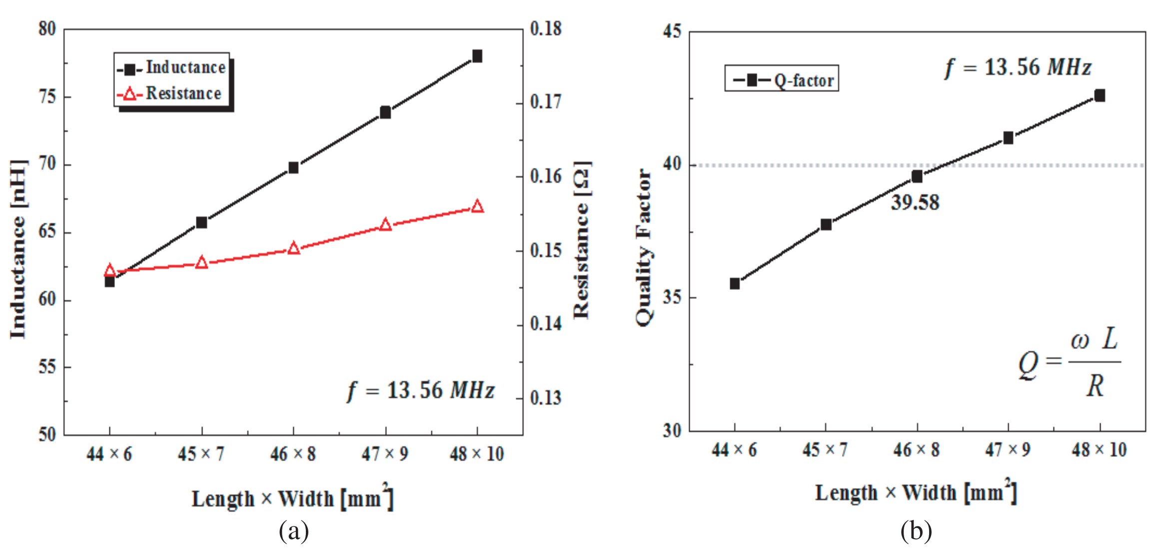

Figure 2. Simulated results of the proposed antenna with varying loop size at 13.56 MHz: (a) Inductance and resistance and (b) Q-factor.

Since this current distribution is concentrated on the top potion of a mobile phone, the performance degradation of the NFC antenna due to interference by the user's hand is also avoidable. Figure 4 shows the simulated H-field (near-field) intensity at the center of the proposed NFC antenna mounted on the top-portion of the metal back case and the center of the conventional 4-turn NFC loop antenna (Dimension $= 37\,\text{mm} \times 52\,\text{mm}$, Line width $= 1.0\,\text{mm}$, Line gap $= 0.3\,\text{mm}$) mounted on the battery pack of a mobile phone. While the conventional NFC antenna has a ferrite sheet, the proposed NFC

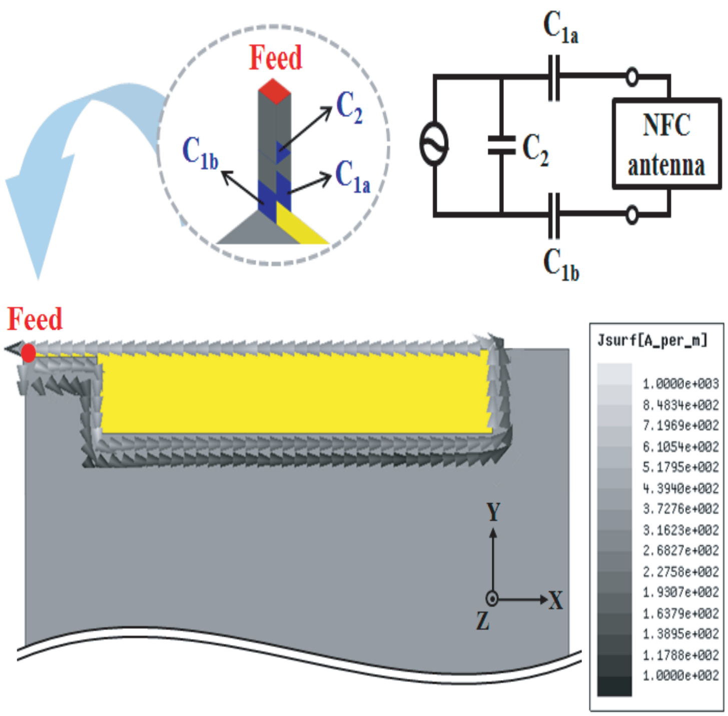

Figure 3. Matching circuit between the NFC chip and the NFC antenna, and current distribution of the proposed NFC antenna at 13.56 MHz.

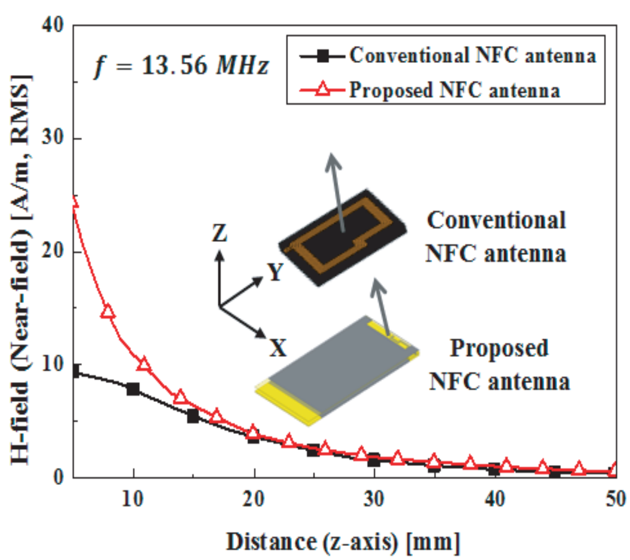

Figure 4. Simulated H-field (near-field) intensity with a normal direction (z-axis) at the center of the proposed NFC antenna and the conventional 4-turn NFC loop antenna at 13.56 MHz.

antenna is designed without a ferrite sheet. It is observed that the proposed antenna provides the H-field intensity higher than or similar to that of the conventional 4-turn loop antenna. The proposed NFC antenna is simulated by the HFSS 15.0 (ANSYS).

Since the proposed NFC antenna is located immediately above the secondary MIMO antenna which is mounted on the non-metallic area within the top portion of a mobile phone, the secondary MIMO antenna is designed to check the coupling effect between the NFC and secondary MIMO antennas. Figure 5 shows the geometry of the proposed secondary MIMO antenna, which has a structure of a planar inverted-F antenna (PIFA) fabricated on a FR-4 substrate ($\varepsilon_r = 4.4$). The overall dimension is $66 \times 12 \times 3\,\mathrm{mm}^3$. The size of the ground plane is $108 \times 66 \times 1\,\mathrm{mm}^3$. The gap between the metal back case and the secondary MIMO antenna is 1 mm. The electrical length of the radiating element is approximately a quarter-wavelength at the center frequency (880 MHz) of LTE 5, 6 Rx bands (869 $\sim$ 894 MHz). An additional branch line is designed to cover the LTE 3, 9 Rx bands (1840 $\sim$ 1880 MHz). Figure 6(a) shows the simulated and measured reflection coefficients (dB magnitude of S_{11}) of the proposed secondary MIMO antenna with the metal back case including the proposed NFC

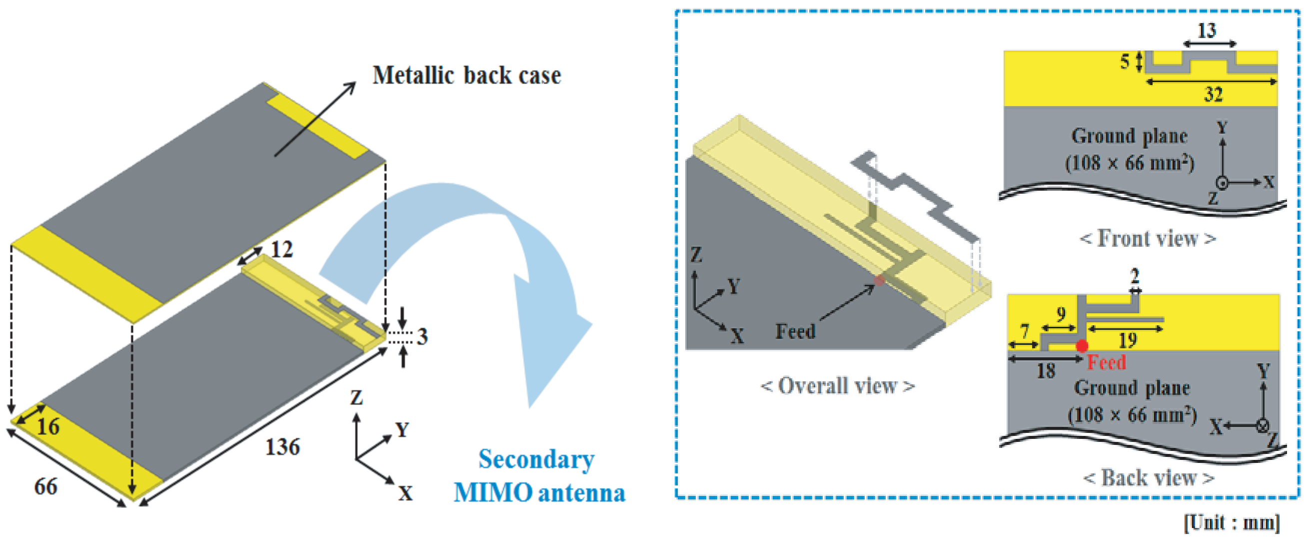

Figure 5. Geometry of the secondary MIMO antenna including the metal back case.

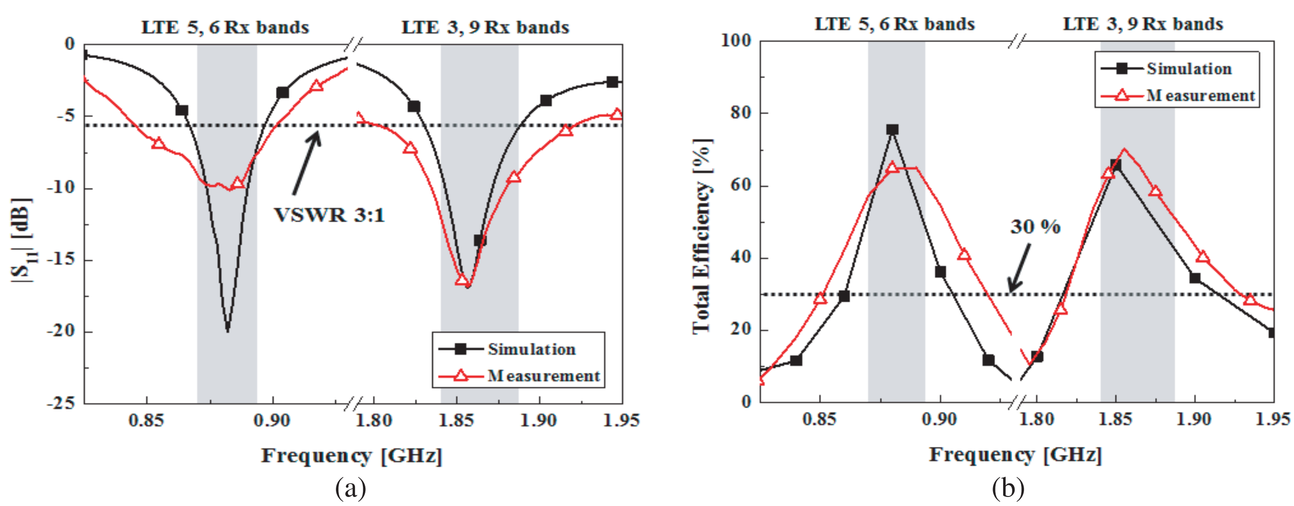

Figure 6. Simulated and measured results of the secondary MIMO antenna with the metal back case: (a) S_{11} and (b) total efficiency.

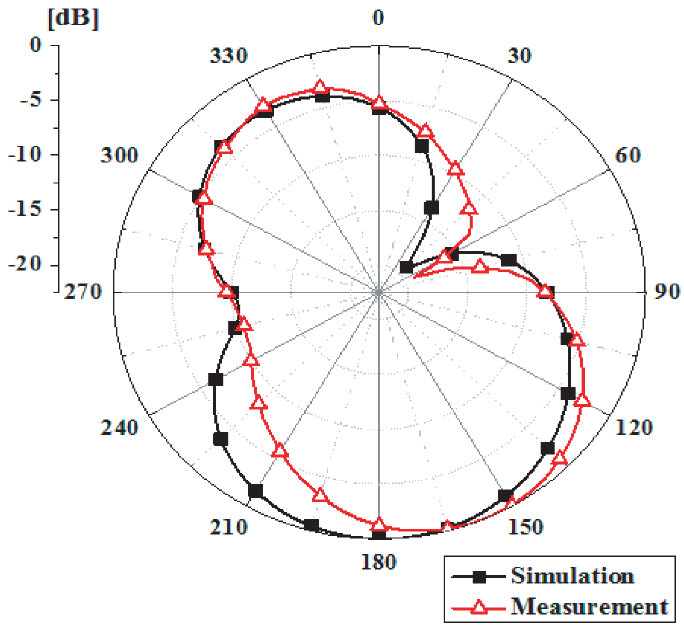

Figure 7. Normalized simulated and measured radiation patterns of the proposed secondary MIMO antenna at 880 MHz (XY-plane).

loop antenna. The proposed antenna (VSWR < 3) covers the LTE 5, 6 Rx bands ($869 \sim 894$ MHz) and LTE 3, 9 Rx bands ($1840 \sim 1880$ MHz). It has a total efficiency of more than 30 % for all operating frequency bands as shown in Figure 6(b). The normalized radiation pattern of the secondary MIMO antenna is simulated and measured at 880 MHz as shown in Figure 7. By arranging the location of the feed point and the radiating element on the right edge of the top portion of the non-metallic area as shown in Figure 5, the diagonally tilted radiation pattern can be obtained at low bands (LTE 5, 6 Rx), so that the polarization diversity is available to achieve high isolation between MIMO antenna elements. From these results as shown in Figures 5, 6, and 7, when the proposed NFC antenna and the proposed secondary MIMO antenna are in close proximity, both antennas operate well without performance degradation. The secondary MIMO antenna is simulated by the HFSS 15.0 (ANSYS) and measured by the network analyzer (E5071B) and the anechoic chamber.

3. MEASURED RESULT

Since the proposed NFC loop antenna is located immediately above the secondary MIMO antenna which is mounted on the non-metallic area within the top portion of a mobile phone, the secondary MIMO antenna is designed, as shown in Figure 5 in Section 2, to check the coupling effect between the NFC and secondary MIMO antennas. Figures 6 and 7 indicated that the proposed NFC antenna has little influence on the secondary MIMO antenna.

To verify the performance of the proposed NFC loop antenna and to check the effect of the secondary MIMO antenna on the proposed NFC loop antenna, the prototype of the proposed NFC loop antenna is now mounted immediately above the secondary MIMO antenna of a commercial mobile phone (SHW-M440S), where an NFC chip (PN544, NXP Semiconductor corp.) is embedded [17], as shown in Figure 8. The proposed NFC antenna is excited through the feed line to the matching circuit of a mobile phone. Table 1 shows the measured inductance and resistance by using the network analyzer (E5071B), and Q-factor of the proposed NFC antenna mounted on a commercial mobile phone (SHW-M440S).Since the simulated results ($L \approx 70$ nH, $R \approx 0.15\,\Omega$), as shown in Figure 2, come from the proposed NFC antenna with considering only the PCB ground and the secondary MIMO antenna and without considering a commercial mobile phone, it can be seen that the measured inductance ($L_a = 290$ nH) and resistance ($R_a = 0.627\,\Omega$) are different from those of simulated results. It is important to notice that although the simulated and measured inductance and resistance do not agree well, Q-factors (Simulated $Q = 39.58$, Measured $Q = 39.4$) agree well, and they are less than 40 that demanded in the NFC system. With these measured values, the matching circuit between the NFC chip and the antenna is designed. Subsequently, the card mode and the R/W mode tests are conducted. The card mode test is performed using the Euro-pat, Master-card and Visa (EMV) test which measures a load modulation level (V_{pp}) within a specific operating volume (r, ϕ, z) as shown in Figure 9 [18]. The R/W mode test is accomplished by measuring the detection range regarding to the reference tag(Mifare 1 k). Table 2 shows some of the measured load modulation levels (cardmode test) and the measured detection ranges (R/W mode test). In the card mode, the measured values of load modulation within all the specific operating volumes (r, ϕ, z) meet the criteria values of an NFC system when the reader supplies the power of 600 mW. Whena mobile phone is in the R/W mode, the detection range of the proposed antenna is 43 mm. It can be seen that although the proposed NFC loop antenna is closely mounted near the secondary MIMO antenna, it meets the criteria values of an NFC system without performance degradation.

Table 1. Measured inductance, resistance, and quality factor of the proposed NFC antenna mounted on a commercial mobile phone (SHW-M440S) at 13.56 MHz.

	Inductance, L_a [nH]	Resistance, R_a [Ω]	Quality factor (Q)
Proposed NFC antenna	290	0.627	39.4

Figure 8. Prototype antenna with a mobile phone.

Table 2. Measured results in the card mode and the R/W mode tests.

r, ϕ	Card mode test							R/W mode test
	Load modulation level [mV$_{\text{pp}}$]							Detection range [mm]
	$r = 0$ (cm)		$r = 1.5$ (cm)					
z	Min. Spec.	ϕ 0°	Min. Spec.	ϕ 0°	90°	180°	270°	
0 (cm)	**8.8**	38.1	**4.9**	24.9	33.7	28	28.8	
1 (cm)	**7.2**	16.6	**4.1**	12	14.3	13.2	12.7	43
2 (cm)	**5.6**	7.9	**3.3**	5.7	6.3	6.4	5.9	

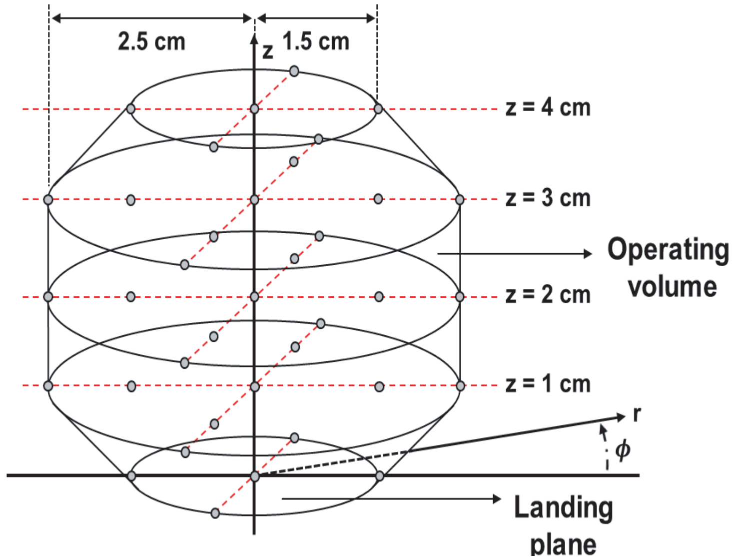

Figure 9. Operating volume for the EMV test.

4. CONCLUSION

A simple novel structure of a compact NFC loop antenna is proposed for mobile phones with a metal back case. The proposed structure of the non-metallic area on the top portion of the metal back case, which is usually necessary for enhanced radiation efficiency of the secondary MIMO antenna, is designed as a novel structure of the proposed NFC loop antenna. Since the proposed NFC antenna is located immediately above the secondary MIMO antenna which is mounted on the non-metallic area within the top portion of a mobile phone, it can be designed without the ferrite sheet, to reduce the thickness of the NFC antenna, high manufacturing costs, and performance degradation due to the adjacent metallic objects. It is also confirmed that although the proposed NFC antenna and the secondary MIMO antenna are in close proximity, both antennas operate well without performance degradation.

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