Low-Cost Miniaturized NFC Antenna Design for Mobile Phone

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Abstract ─ A low-cost and miniaturized NFC antenna design for mobile phone is proposed. Among all the phone antennas, NFC antenna is the biggest one, thus leading to higher manufacturing costs and adverse conditions for device integration. It is well known that four radiation sides are used in the traditional NFC antennas However, this letter presents a novel single side radiation slender NFC antenna structure, which well solves the adjacent sides reverse current interference through magnetic substrate selectivity laying in the traditional slender NFC antenna. This proposed structure can not only save magnetic substrate materials, but also significantly increase the radiation capacity through asymmetric structure design, and ultimately lead to a 38% increase in the communication performance. Simulation and experiment results verify that this simple design can significantly reduce the cost, suggesting a good prospect in practical use.

Index Terms ─ Magnetic substrate, miniaturization, NFC antenna.

I. INTRODUCTION

NFC system operating at 13.56 MHz allows devices to communicate in a short distance (around 30 mm) through inductive coupling [1]. Owing to a high security level, NFC technology has been used in many fields, such as payment field, public transport field, access control field, etc [2-5]. Consequently, NFC functional modules have been integrated into mobile phones [6,7]. Among all the phone antennas, NFC antenna is the biggest one (usually 35mm × 35mm) [8], which need to be assembled with magnetic substrate to decrease metal environmental disturbance. This makes the cost of NFC antenna 3 to 5 times more expensive than that of other phone antennas. Furthermore, with the continuous improvement of the systems integration of mobile phones, such a large NFC antenna structure is not suitable for device integration. Based on above reasons, NFC antennas with miniaturization and low cost have been the focus of research in this field [9,10]. Slender type NFC antenna structure help reduce antenna dimension. Nevertheless, reverse carry currents of the adjacent sides will decrease space magnetic field, leading to poor antenna radiation performance. Hence, the magnetic field interference of the adjacent sides must be solved. Early researchers point out that wrap one side of slender NFC antenna with magnetic material can effectively decrease the magnetic field interference of adjacent sides, thus achieving good radiation performance [11]. Moreover, Murata company patent indicates that magnetic substrate through slender type NFC antennas would make antenna adjacent sides lie on different sides of magnetic substrate, which results in signal isolation on two adjacent sides. This method well solved NFC antenna miniaturization and radiation problem as well [12].

Previous researches proved that the designs of slender NFC antenna structure and magnetic substrate were beneficial to antenna miniaturization. In this case however, only single side of slender NFC antenna is utilized for radiation, resulting in a well radiation performance. Herein, this paper proposes a novel slender NFC antenna, in which antenna structure and magnetic substrate are combinational designed. The key to realize the miniaturization of slender NFC antennas lies in magnetic field radiation. In order to achieve the purpose of single side radiation, what made it different is that magnetic substrate only lay behind the one side of slender NFC antenna for radiation, and the opposite side lay on the metal environment. It is well known that NFC antennas usually affix to metal environment (in the main-board/battery of mobile phone in actual applications). The side on the magnetic substrate could emit magnetic field to the space. However, eddy current will offset most magnetic field of the side on the metal environment. In this way, it effectively decreases the interference of two adjacent sides, and thus forms well radiation field.

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In order to further improve the antenna radiation performance, the effect of line width and magnetic substrate area and permeability on the radiation characteristics of antennas are studied. The results indicate that the asymmetric antenna structure can obviously improve radiation performance of the antenna.

II. ANTENNA DESIGN

A. Radiation line width optimization

Different from the traditional NFC antenna, only single side is used for radiation of the slender NFC antenna. Therefore, the distribution width of the antenna magnetic field is related to the total linewidth of the radiation side, as shown in Fig. 1 (b). According to the NFC Forum standard [13], the measurement diameter of the 000 plane is 10 mm, as shown in Fig. 1 (a). Hence, the total linewidth of radiation side should be closed to 10 mm, which lie in the range of the magnetic field distribution. NFC antenna is formed by several turns of planar spiral line, if radiation side total linewidth and turn number are fixed, then how to set each turn width will become an important factor that influence the antenna space magnetic field distribution.

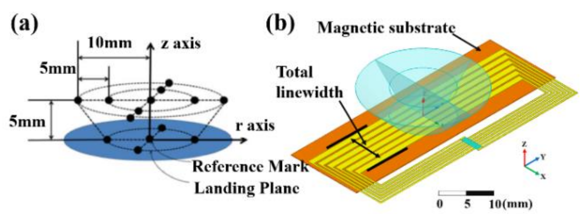

Fig. 1. NFC Forum standard testing zone: (a) test area and (b) slender NFC antenna structure with single side radiation.

The magnetic induction intensity of the long straight-line current in space can be expressed as equation (1) [14]. The magnetic field generated by the radiation side of slender NFC antenna is theoretically equivalent to the superposition of magnetic fields in space by multiple long straight-line currents. The different line width of antenna can be considered as different evenness currents in different lines. Assuming there are two parallel current lines, the distance between each line is L originally, and then each line splits into multiple lines. This model can be expressed as the magnetic field distribution variation with the current density or line width. The expression of spatial magnetic field can be written in equation (2), where L represents line distance, and N represents split number. Figure 2 shows the curve of the magnetic field intensity versus line split number at the height of symmetry center 30mm, where L is set to 10mm, and total current I is set to 1 A. It can be found that, the more uniform the current is distributed, the wider the magnetic field is distributed. Hence, as for the slender type NFC antenna, wide wire width is better for radiation performance under the same total linewidth and turn number:

$$\vec{B}=\vec{e_\phi}\frac{\mu_0 I}{2\pi r}=\frac{y\mu_0 I}{2\pi\left(x^2+y^2\right)}\cdot\vec{e_x}+\frac{x\mu_0 I}{2\pi\left(x^2+y^2\right)}\cdot\vec{e_y}, \tag{1}$$

$$\vec{B}=\sum_{n=-N}^{2N}\left(y\mu_0 I\Big/4\pi N\left(\left(x-\frac{L}{2N}\cdot n\right)^2+y^2\right)\cdot\vec{e_x}+\left(x-\frac{L}{2N}\cdot n\right)\mu_0 I\Big/4\pi N\left(\left(x-\frac{L}{2N}\cdot n\right)^2+y^2\right)\cdot\vec{e_y}\right). \tag{2}$$

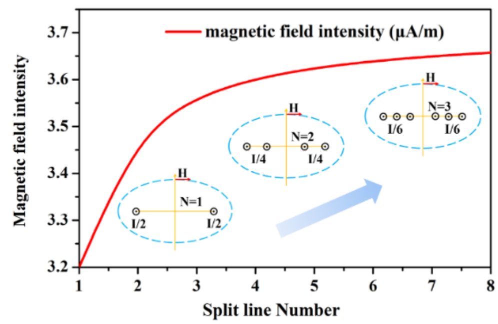

Fig. 2. The curve of the magnetic field intensity versus line split number.

B. Magnetic substrate area optimization

Another key factor that affects the performance of NFC antennas is the magnetic substrate. NFC antenna is always integrated on battery or mainboard of the smartphone, so the magnetic substrate is assembled to shield the impact of metal environment in the phone. Generally, NFC antenna is the same size as the designed magnetic substrate, which is placed between the antenna and metal environment. If magnetic substrate area is larger than that of NFC antenna, whose performance gets better. However, the traditional NFC antenna is large enough to have good performance, leading to less attention to magnetic substrate structure. As for the slender NFC antenna, magnetic substrate width is wider than the total linewidth, which results in obvious improvement in radiation performance. Hence, it is needed to balance the size and performance of the magnetic substrate.

In order to set the width of magnetic substrate we have a hypothesis that a long straight-line current flow above the magnetic substrate, whose permeability is high enough. In this case, both of substrate thickness and metal environment have no influence on the magnetic field of antenna (actually, the permeability of the ferrite magnetic substrate is very high indeed). Applying mirror principle, the single current generates double the magnetic field intensity in the semi-infinite space [15]. Equation (3) can be formed from the integration of Equation (1), the distribution of magnetic flux around the line current can be obtained according to Equation (3), where a represents line current radius, b represents magnetic substrate width. Figure 3 is the curve of magnetic flux versus magnetic substrate width, where a is 0.1mm, and total current I is 1 A. It is can be found that, the growth rate of magnetic flux e decreases with the substrate width, which results in a decrease in the space magnetic field. As shown in Fig. 3, the 80% area integral is set to be the dividing point, and then a suitable width can be found as a reasonable distance of the magnetic substrate to exceed the radiation side of the antenna:

$$\Phi = \int_a^b \overrightarrow{e_y} \frac{\mu_0 I}{2\pi x} dx = \frac{\mu_0 I}{\pi} \ln \frac{b}{a} \cdot \tag{3}$$

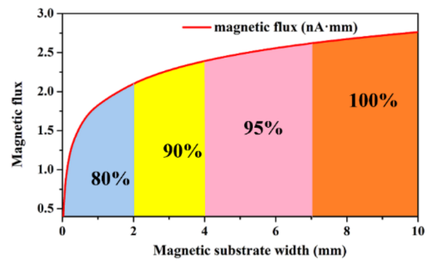

Fig. 3. The curve of magnetic flux versus magnetic substrate width.

C. Magnetic substrate permeability optimization

The magnetic permeability of the antenna substrate also has a great influence on the radiation performance of the NFC antenna. When the NFC antenna structure is fixed, the radiation performance can be reflected from the side of the antenna inductance. In this paper, the magnetic substrate thickness is 0.15mm for the designed NFC antenna. Figure 4 shows the simulation curve of NFC antenna inductance versus magnetic substrate permeability. It can be seen that the change rate of antenna inductance is less than 10% when the permeability exceeds 100. Which is due to the saturated magnetic field passing through the magnetic substrate. This result further conforms Hurley's computational theory [15]. Therefore, the permeability of the magnetic substrates is set to 150, which is also a common parameter of magnetic substrates in the current engineering applications.

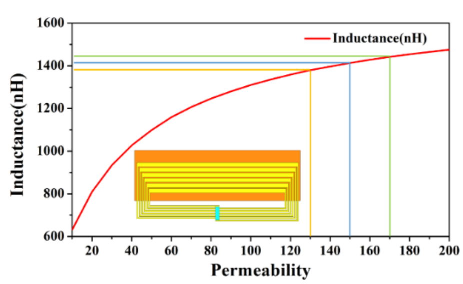

Fig. 4. The curve of NFC antenna inductance versus magnetic substrate permeability.

D. Antenna structure

In order to verify the design ideas above-mentioned, three types NFC antenna are built to illustrate the structural and radiation characteristics. As shown in Fig. 5, they are named, normal slender NFC antenna, single radiation (symmetry) slender NFC antenna and single radiation (asymmetric) slender NFC antenna, respectively. The orange square represents magnetic substrate with thickness of 0.015mm, permeability of 150 at 13.56MHz, and magnetic loss tangent of 0.02 at 13.56MHz. For normal slender NFC antenna, the overall dimension is 40mm×14mm×0.035mm, and there are 4 turns with width of 0.5mm and line spacing of 0.3mm. For single radiation (symmetry) slender NFC antenna, the dimension is 40mm×14mm×0.035mm, and there are 6 turns, with width of 0.5mm and line spacing of 0.3mm. It should be noted that the magnetic substrate lays under one side. As for single radiation (asymmetry) slender NFC antenna, it has a unique structure with outside dimension of 40mm×14mm×0.035mm. The top wires are design as radiation part with a width of 1mm for each turn, wider than that of the traditional antenna. The width of the magnetic substrate is larger than total-linewidth (2mm) in each side. The line width of leftover sides is 0.3mm and turn spacing is 0.3mm, thinner than those of the traditional antenna, and the leftover sides lay on the metal surface. Antenna inductance means the ability to generate magnetic field, so all these antennas approach the approximative inductance value (around 1400nH).

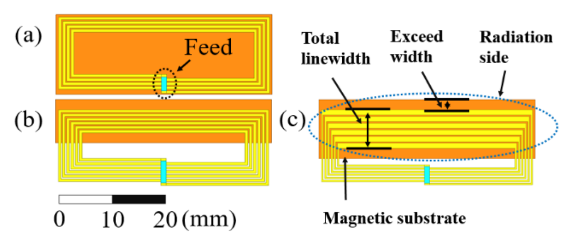

Fig. 5. Structure schematic diagrams for three types of NFC antenna: (a) normal slender NFC antenna, (b) single radiation (symmetry) slender NFC antenna, and (c) single radiation (asymmetric) slender NFC antenna.

Three types of NFC antennas are placed on the metal surface, which simulates the metal environment of mobile phones. Each antenna is excited by the same current source. Figure 6 illustrates the magnetic field distribution on XZ plane, which is the symmetry plane of these NFC antennas. Owing to the different radiation mechanism, normal slender NFC antenna forms a symmetrical field distribution, and single radiation slender NFC antenna forms an asymmetric field distribution. Adjacent sides of slender NFC antenna carry invert current, which generates invert space magnetic field and counteracts each other. In order to acquire better radiation performance, one of the adjacent sides must have no emission to the space. Although only one side of symmetry antenna emit space magnetic field, a better space field distribution performance is acquired than that of normal one. In order to further improve the radiation capacity of single radiation slender NFC antenna, the wider line and magnetic substrate is adopted for radiation wires, then forms a single radiation (asymmetry) slender NFC antenna structure. Simulation results prove that the space magnetic field strength of single radiation (asymmetry) slender NFC antenna has been further improved.

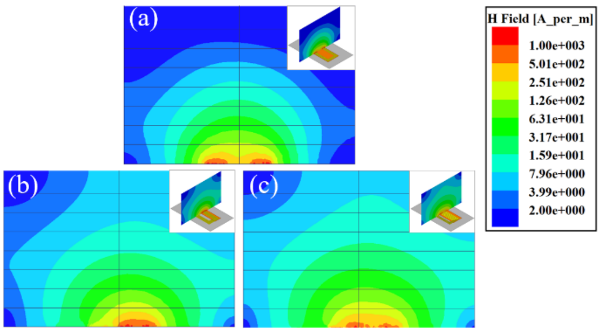

Fig. 6. Magnetic field distribution of three types of NFC antennas: (a) normal slender NFC antenna, (b) single radiation (symmetry) slender NFC antenna, and (c) single radiation (asymmetric) slender NFC antenna.

Vector magnetic field distribution on XZ plane of three types of NFC antenna are shown in Fig. 7. Vector magnetic field around radiation wires appears in form of irregular circles, but only Z-axis component of vector magnetic field can be received by opposed receive antenna. Therefore, when the position where Z-axis component of vector magnetic field tends to zero is identified as the dividing point, the maximum radiation direction of the antenna can be clearly determined. Take the height of 15mm as reference, and the direction angle θ of the NFC antenna can be calculated easily, as shown in Fig. 7. Direction angle θ of single radiation NFC antenna is around 82°, but the normal slender type NFC antenna is only 58°. This means that the reverse currents of adjacent sides of normal slender NFC antenna not only make magnetic field counteract each other, but also make radiation direction to the side position, which is more detrimental to antenna communication. For the single side radiation NFC antennas, the definition of radiation direction helps to point the maximum communication direction.

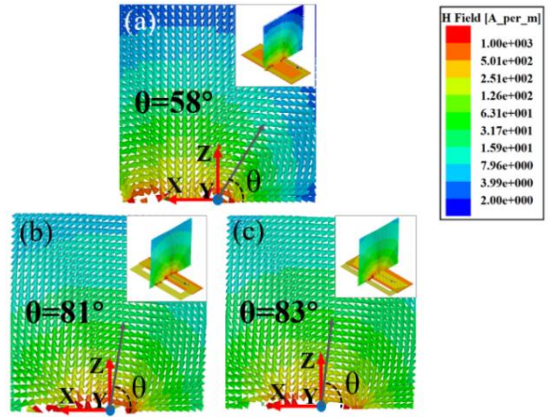

Fig. 7. Vector magnetic field distribution of three types of NFC antenna: (a) normal slender NFC antenna, (b) single radiation (symmetry) slender NFC antenna, and (c) single radiation (asymmetric) slender NFC antenna.

Then, along the direction of maximum radiation, simulation the Z direction magnetic flux (Φ) of the receiving plane in different height. In addition, the dimension of receiving plane is 40mm×30mm, similar with that of traffic card, which convenient to compare with actual card reading measurement later. As shown in Fig. 8, through simulation Φ data, antenna field emission & communication capabilities can be evaluated. The simulation result illustrates that single radiation (asymmetric) slender NFC antenna achieves better emission performance. As shown in Fig. 8, Φ strength of 0.008 Wb (empirical parameter) is acted as reference, and then the communication distance for three types of NFC antenna are 18mm, 21.5mm, 25mm respectively. The result shows that the proposed NFC antenna has a marked improvement in communication distance compared with normal slender NFC antenna.

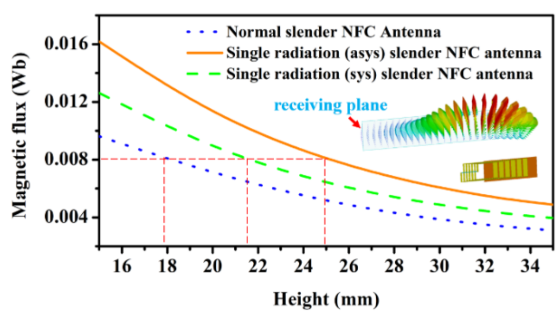

Fig. 8. Simulated magnetic flux (Φ) of the reference receiving plane in different heights.

Figure 9 shows the simulated magnetic field distribution of two typical slender NFC antennas, which are mentioned in the introduction and the proposed NFC structure in this paper. The three types of NFC antennas are basically the same size and have the same inductance. From the magnetic field distribution, it can be seen that under the same inductance value, the radiation intensity of wrap type NFC antenna is slightly lower than that of the other two antennas, because part of the magnetic field is bound to the inside of the magnetic substrate and can not radiate into space, as shown in Fig. 9 (a). Murata company patent slender NFC antenna exhibits good magnetic field radiation ability, and the space radiation field is almost the same as the proposed NFC antenna in this paper. However, its magnetic substrate area is 30% larger than than that of the proposed NFC antenna structurer, as shown in Fig. 9 (b).

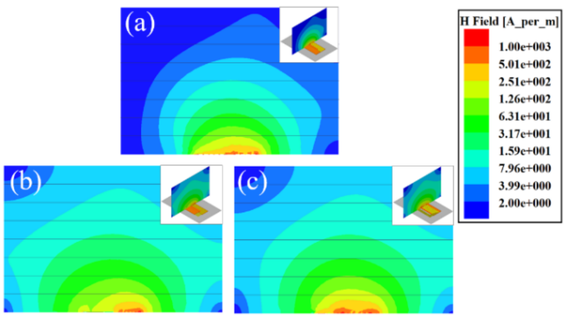

Fig. 9. Magnetic field distribution of two typical slender NFC antenna structures and the proposed NFC structure in this paper: (a) wrap type slender NFC antenna, (b) Murata company patent slender NFC antenna, and (c) single radiation (asymmetric) slender NFC antenna.

Above simulation results prove that, by combining NFC antenna structure and magnetic substrate distribution design, single radiation (asymmetric) slender NFC antenna exhibits a good radiation performance. The following experiments will verify the actual communication performance of this proposed NFC antenna.

III. MEASURED RESULTS

In order to verify the simulation results, three types of NFC antenna are fabricated on PCB board, as shown in Fig. 10. These NFC antennas are equipped with magnetic substrate and laid on the metal surface. The port characteristic of these three types NFC antenna are shown in Table 1. These NFC antennas get approximative volume of inductance, which are similar with simulation results. Owing to more wire turns and metal environment, single radiation slender NFC antennas have higher resistance compared with normal NFC antenna (resistance usually below 5Ω@13.56MHz), leading to lower antenna Q factor and disadvantage to communication. According to the classical π-type matching network of NFC system [16], these three types of NFC antennas are matched to 50Ω, and prepare to the radiation signal strength measurement.

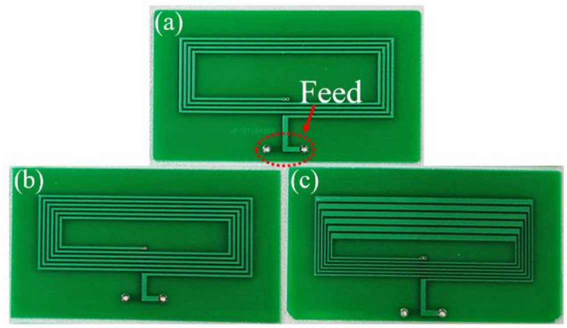

Fig. 10. Three types of fabricated NFC antennas: (a) normal slender NFC antenna, (b) single radiation (symmetry) slender NFC antenna, and (c) single radiation (asymmetric) slender NFC antenna.

Table 1: Port characteristic of three types NFC antennas

NFC Antenna Type	Resistance Ω@13.56MHz	Inductance μH@13.56MHz
Normal slender NFC antenna	3.2	1.51
Single radiation (symmetry) slender NFC antenna	9.5	1.45
Single radiation (asymmetric) slender NFC antenna	9.3	1.4

NFC antennas and receiving sensor are connected to signal generator and oscilloscope, respectively. AC voltage of the signal generator is set to 5V. 4 turns spiral wires are used to forms receive sensor, whose dimension is the same as the traffic card, as shown in Fig. 11. Based on the Faraday law, sensor voltage could change the magnetic flux volume, and then the sensor measurement data and simulation data can be unified. The measurement and simulation results are shown in Fig. 12. Comparison results indicate that measurement results are generally consistent with simulation ones. Because of higher inductance of the fabricated normal slender NFC antenna, measured magnetic flux data of normal slender NFC antenna is higher than the corresponding simulation result. However, the measurement result shows that a lower Q factor of single radiation (asymmetric) slender NFC antenna does not significantly affect the antenna's radiation capability, and the proposed NFC antenna structure exhibits a good magnetic field radiation performance.

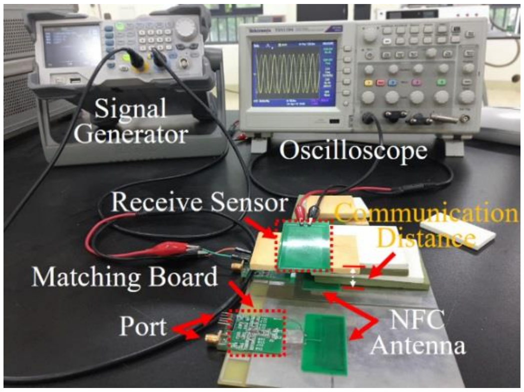

Fig. 11. Aerial view of magnetic flux (Φ) measurement.

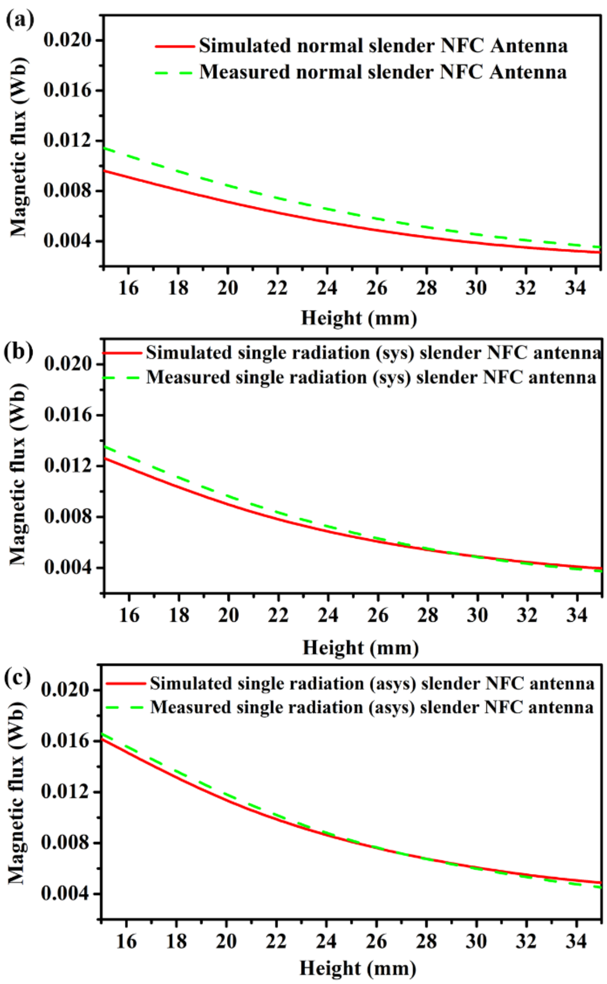

Fig. 12. Measured magnetic flux (Φ) of the reference receiving plane in different heights: (a) normal slender NFC antenna, (b) single radiation (symmetry) slender NFC antenna, and (c) single radiation (asymmetric) slender NFC antenna.

In order to verify the actual communication performance, these antennas are connected to the real smart phone circuit, as shown in Fig. 13. This experimental smart phone is equipped with NXP Company PN548 NFC controller chip, which is widely used in smart phone. All these NFC antennas are connected to the smart phone successively to measure the communication distance with Tag-4 standard NFC card. The measurement results are listed in Table 2. Communication distance of single radiation (asymmetric) slender NFC antenna reaches 25mm, which is a large communication distance for Tag-4 standard NFC card. The measurement results are consistent with the simulation results.

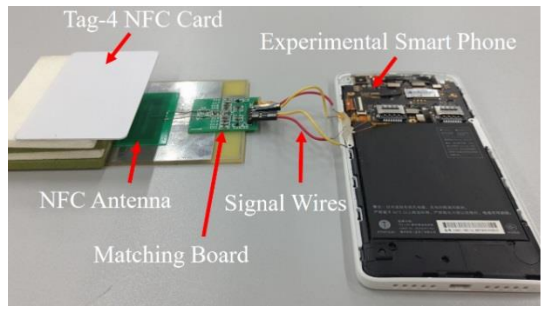

Fig. 13. Aerial view of actual communication distance measurement with Tag-4 NFC card.

Table 2: Communication distance of three type NFC antenna with TAG-4 NFC card

NFC Antenna Type	Communication Distance (mm)
Normal slender NFC antenna	18
Single radiation (symmetry) slender NFC antenna	22
Single radiation (asymmetric) slender NFC antenna	25

IV.CONCLUSION

NFC antenna is applied to the space magnetic field radiation, and a novel slender structure is proposed in this paper. By analyzing the mechanism of NFC antenna radiation, wider lines with magnetic substrate are utilized in the proposed NFC antenna for radiation, and thinner line with metal surface is useful for miniaturization. These two characteristics ultimately lead to the formation of asymmetric slender NFC antenna structure. The mutual interference of adjacent sides of slender NFC antenna has been reduced, resulting in the significant increase of the radiation capacity for NFC antenna. These design methods greatly reduce the NFC antenna size and magnetic substrate consumption, thereby reducing the cost of production. The proposed NFC antenna obtains a good performance of communication distance, simulation and experiment results verify that this proposed design is simple, effective and cost effective, suggesting a good prospect in practical use.

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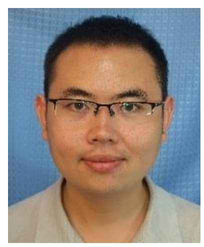

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