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Wearable near-field communication bracelet based on highly conductive graphene-assembled films

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Abstract
Benefiting from the high conductivity and superb flexibility, graphene-based materials are promising to replace metal for near-field communication (NFC) applications. Herein, we report a flexible NFC tag antenna based on high-conductivity graphene-assembled films (HCGAFs) and investigate how the performance of the antenna is affected by antenna design and human body effect. The fabricated prototype via a one-step laser-direct mold engraving method shows a 10 dB bandwidth of 2.5 MHz centering at 13.70 MHz with a quality factor (Q) of 9.19. The maximum read range of the HCGAF NFC tag is measured to be around 7.5 cm, comparable to the commercially available metal NFC tags. Moreover, the flexible nature of HCGAFs guarantees excellent mechanical stability and deformation insensitivity, especially when compared to commercial metal-based counterparts. We further demonstrate the practical applications of the HCGAF tag as key card and electronic business card in the vicinity of human body.

KEYWORDS
graphene-assembled film (GAF), near-field communication (NFC), RFID, 5G, wearable device

1 | INTRODUCTION

The modern world is ever expanding and with it comes numerous new technologies that change the way people communicate. Among them, near-field communication (NFC), is a radio frequency identification (RFID)-based contactless communication technology which operates at a specific frequency of 13.56 MHz for close-range communications always within a few centimeters, thus, provides more security and privacy than RFID.[1,2] This close-range technology enables the passive devices, such as NFC tags, to harvest the power required for operation from the near-field of an active device known as the reader through magnetic induction coupling.[3-6] Thus, no power supply is needed in these tags, reducing the manufacture cost. Since its first introduction in early 2000s, NFC has been widely used in identification,[7] tracking,[8] access control and contactless payment systems,[9-11] demonstrating a key role in bringing the Internet of Things (IoTs) to reality with unimaged applications emerging every day.

Practical NFC antennas are usually manufactured based on traditional metals including copper (Cu), aluminum (Al) and silver (Ag) for use in mobile phones.[6,12-16] These materials, endowed with superb electrical conductivity and great mechanical properties, are well suited for conventional NFC antenna. However, with the increasing demand for electronic devices and the involved chemical etching steps, the production of metal waste and highly pollutant chemical reagents have becoming a severe problem which is neither environmentally friendly nor human-friendly. Moreover, the rapid development and rising interest in wearable devices require the NFC antenna to be lighter and more flexible. It is thus an urgent task to replace traditional metal materials with better-recyclable, lighter, more flexible and more durable materials.

Graphene, being one of the most extensively studied materials these days, offers a series of unique properties. It is the lightest and thinnest material ever known with good electrical conductivity and the ability to flex hundreds of thousands of times.[17-19] As a carbon-based material, graphene is also naturally more chemically inert comparing to metals which grants the graphene-based devices to operate properly under harsh conditions. All these properties make graphene well suited for the next generation NFC antennas. Recent works have been done involving the fabrication of graphene NFC antenna using screen printing technology but still required a silver coating and achieved an unsatisfactory conductivity of $\sim 3.7 * 10^4$ S/m which is two orders of magnitude lower than that of traditional metals.[13] The practical application of exfoliated multi-layer graphene in NFC antenna has also been demonstrated with a conductivity of $\sim 4 * 10^5$ S/m which is still incomparable with that of traditional metals.[20]

Motivated by the prospect that further improvements in the aspects of material and device design are still needed to meet the requirements of NFC applications, we set out to investigate the replacement of traditional metals by flexible high-conductivity graphene-assembled films (HCGAFs) in NFC tag antennas. Reported in our previous works, HCGAFs exhibited relatively low sheet resistance of 36 mΩ/sq. and excellent conductivity of $\sim 10^6$ S/m along with better mechanical stability and flexibility than traditional metal-based films.[21,22]

In this paper, we designed a flexible HCGAF NFC tag antenna with size of 80 mm × 50 mm according to the international standard communication protocol ISO/IEC 14443 on polyethylene terephthalate (PET) substrate, by using a simple one-step laser engraving method. The flexible NFC tag antennas which are designed to operate around 13.56 MHz showed a 10 dB bandwidth from 12.5 to 15 MHz. When bonded with two types of commercial NFC integrated circuits, NXP ICODE SL2S2602 and NXP Mifare MF1S50YYX_V1, both of the devices successfully demonstrated the exchange of data with commercial NFC readers and NFC-enabled smartphones with and without skin contact. Importantly, by applying the flexible HCGAFs and PET substrates, the fabricated NFC tag antennas can undergo bending deformations without the loss of proper functionalities.

1.1 | Preparation of HCGAF

The flexible HCGAFs are obtained by first dropping graphene oxide (GO) aqueous solution (15 mg/mL) on a PET film to form a uniform coating. The sample is then let dry at room temperature to acquire GO assembled-films before annealed at 1300 °C for 2 hours and then at 2850 °C for 1 hour under argon (Ar) gas environment.[21,23] The sample is finally rolling compressed under 200 MPa to obtain the high-quality HCGAFs with a final thickness of ∼25 μm as seen in the cross-sectional SEM image (Figure 1A). The sharp peak located at $2\theta = 26.5^\circ$ in the XRD spectrum (Figure 1B) indicates a regular packing of graphene layers with an interlayer spacing (d002) of ∼0.336 nm. Along with the diffraction peak (004), the high degree of graphitization of the flexible HCGAF is demonstrated.

1.2 | Antenna design

A simplified equivalent circuit of the microchip and matching antenna is shown in Figure 2A where the antenna is designed to conjugately match the microchip. According to the capacitance of the microchip, the required inductance of the antenna (L_{ant}) can be derived from the following equation[24]:

$$L_{ant} = \frac{1}{(2\pi f_r)^2 C_{chip}}, \tag{1}$$

where f_r is the circuit resonant frequency and C_{chip} is the capacitance of the microchip which in our case, is 23.5 pF for NXP ICODE SL2S2602 and 16.9 pF for NXP Mifare MF1S50YYX_V1 at 13.56 MHz. The following optimizations are based on capacitance of 16.9 pF unless otherwise noted. We show a typical design of NFC antenna with rectangular spiral coils in Figure 2B where the physical parameters including number of coils (N),

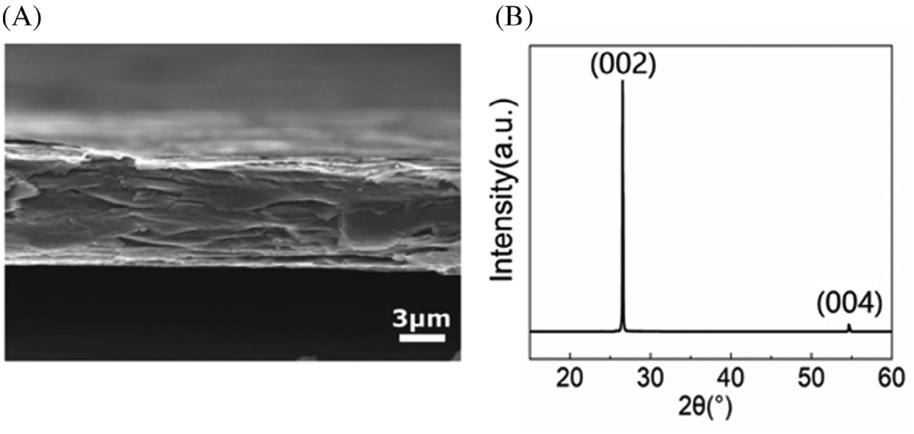

FIGURE 1 Material characterization of the HCGAF. A, Cross-sectional SEM image; B, XRD pattern

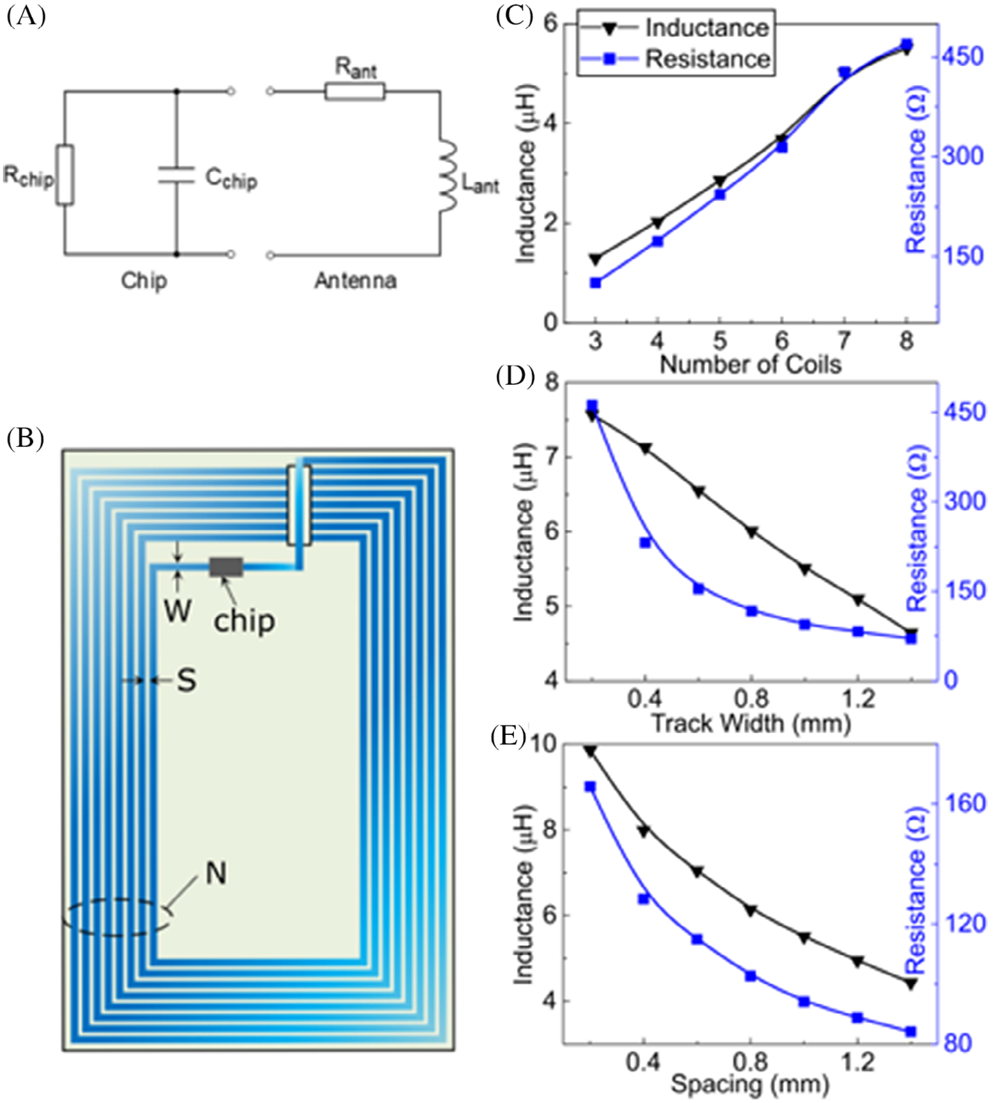

FIGURE 2 Design and optimization of the HCGAF NFC antenna. A, Equivalent circuit of a chip and its antenna. B, The geometry of the HCGAF NFC antenna with N = 8, W = 1.4 mm and S = 0.2 mm. C-E, Simulated inductance (black) and resistance (blue) at 13.56 MHz vs C, number of coils (N) (W = 1 mm, S = 1 mm); D, track width (W) (N = 8, S = 1 mm); E, space between adjacent coils (S) (N = 8, W = 1 mm)

track width (W), and spacing between adjacent coils (S) greatly affect the performance of the antenna. Simulations implemented by a finite element method (FEM) calculation tool have been carried out by sweeping the parameters to optimize the dimensions of the antenna for inductance matching. For a passive NFC tag, its performance depends also on the read range which is related to the quality factor Q as defined in the following equation:

$$Q = \frac{2\pi f_r L_{ant}}{R}, \tag{2}$$

where R is the resistance of the NFC tag antenna. By optimizing the Q-factor, we can simultaneously minimize the required interrogation field strength H_{min} since the Q-factor and H_{min} are negatively correlated. Figure 2C-E show the simulation results of inductance (black triangle) and resistance (blue square) of HCGAF NFC antennas with chosen geometries at the resonant frequency of 13.56 MHz. For a given size of the antenna, the performance is directly impacted by the number of coils (N) (Figure 2C), track width (W) (Figure 2D) and spacing between adjacent coils (S) (Figure 2E). Meanwhile, by carefully screening all the possible combinations we have while taking the fabrication limitations into account, the optimized NFC tag antenna is determined to be with N = 8, S = 0.2 mm and W = 1.4 mm.

2 | FABRICATION AND CHARACTERIZATION

The proposed prototype is fabricated with the flexible HCGAFs pressed on PET substrate to ensure device's flexibility. The high-precision manufacture of the antenna is achieved through a one-step laser-direct mold engraving technology which is compatible to industrial mass-production as shown in Figure 3A. The antenna is then connected by a jumper with the chip integrated to get the HCGAF NFC tag as we show in Figure 3B. The impedance of HCGAF NFC tag antenna is obtained with Keysight E4990A Impedance Analyzer. As depicted in Figure 3C, the prototype has an inductance of 6.8 μH at 13.56 MHz which is close enough to the required inductance calculated from Equation (1) to conjugately match the microchip with a capacitance of 16.9 pF. The resistance of the antenna at 13.56 MHz is measured to be 63.2 Ω yielding a Q-factor of 9.16 [Equation (2)]. The resonant frequency and bandwidth of the tag antenna are also verified by measuring the reflection coefficient (S_{11}) using the Tagformance Pro Measurement System which utilized the reference measurement data to eliminate the effect of the measurement antenna. As illustrated in Figure 3D, the self-resonant frequency of the HCGAF NFC antenna is measured to be 13.70 MHz with a S_{11} value of −34.4 dB and a quality Q-factor of 9.19. Though the measured resonant frequency is slightly off from 13.56 MHz, with the 10 dB bandwidth of 2.5 MHz from 12.5 to 15.0 MHz, which implies that above 90% power of the antenna is transmitted in this band, we can still achieve a reflection coefficient (S_{11}) of approximately −23.77 at 13.56 MHz. Minimum magnetic field strength (H_{min}) and read range data are also included as depicted in Figure 3E with a read range of ~7.5 cm at the resonant frequency which outperforms the reported non-metallic NFC tags.[25] The broad spectrum features also demonstrate good performances within wider operational frequency and better tolerance against deformation and human body effect compared to metal-based NFC tags.

In practical applications, the performances such as operating efficiency and reading distance of the NFC tag antennas should be stable enough under various bending conditions, making it important to determine how

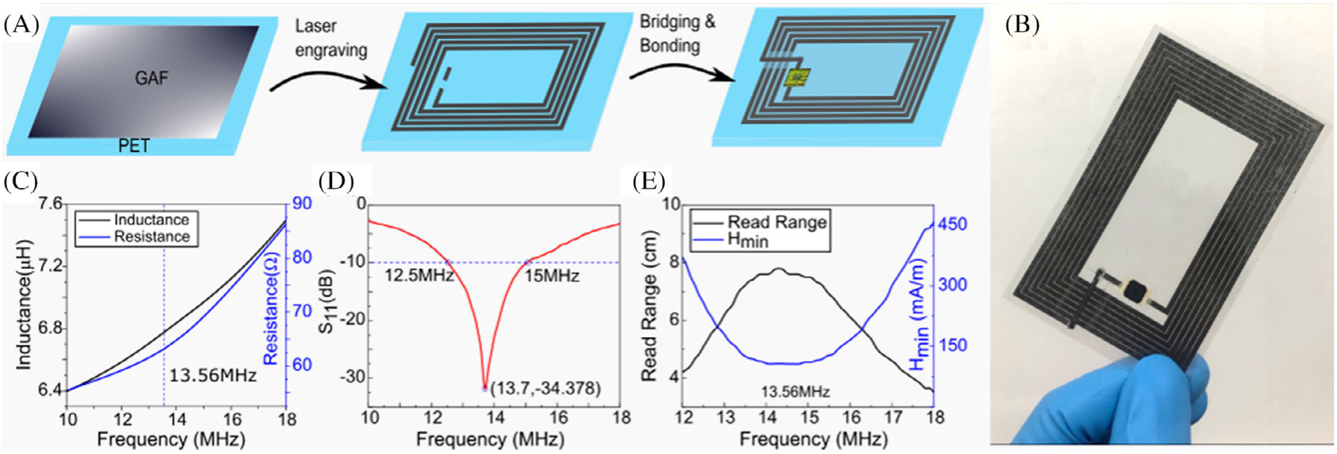

FIGURE 3 Fabrication and characterization of HCGAF NFC antenna. A, Fabrication Scheme. B, Digital photograph. C, Measured inductance (black) and resistance (blue). D, The measured S_{11}. E, The measured read range (black) and minimum magnetic field strength (blue)

bending deformations would affect the antenna performances. Here, we study the bending effect by conforming the antenna to PLA rings with different radii as illustrated in Figure 4B and measure the reflection coefficients accordingly. The radii are chosen so as that the bending angle θ as defined in Figure 4A increases with a step size of 30°. The resulting S_{11} curves are nearly indistinguishable under different bending conditions as depicted in Figure 4C which indicates that the performance of the antenna is robust against bending deformations. The minimum interrogation magnetic field strength required (H_{min}), however, increases with increasing degrees of bending as depicted in Figure 4D (blue square). As the bending angle increases, the effective radiation area of the antenna is reduced. Consequently, the read range decreases gradually (Figure 4D, black triangle) since there is less magnetic flux going through the antenna. Nonetheless, the NFC tag is still able to operate within ~3.4 cm even when the tag is bent with an angle of 270°. Aluminum-based NFC tag antenna with the same dimensions is also fabricated to further demonstrate the mechanical stability of HCGAF NFC tags. After folding in half for 50 times, obvious cracks are observed on the aluminum-based NFC tag that would prevent it from working properly (Figure 4E, left panel of inset), while the surface of the HCGAF NFC tag remains smooth and intact (Figure 4E, right panel of inset). The read range data in Figure 4E of HCGAF NFC tag shows a read range of 6.8 cm even after 500 times of repetitive folding further demonstrating its stable mechanical property.

As a wearable NFC antenna which often needs to operate in the close proximity of human body, the effect of human skin needs to be considered as well since human body will, to some extent, absorb radiated energy and thus decrease the antenna efficiency. To this aim, we test the on-body performance of the proposed antenna under two practical scenarios as an electronic key card (Figure 5A and Video S1) and as an electronic business card (Figure 5B and Video S2). The HCGAF NFC tag attached to the object's wrist shows great conformality of the antenna (Figure 5A). The successful exchange of data between the deformed NFC tag and commercial NFC reader demonstrates the deformation-insensitive characteristic of the HCGAF NFC antenna. S_{11} responses corresponding to the situations depicted in Figure 5A,B are shown in Figure 5C. When directly attached to the object's wrist and integrated with clothes, the resonant frequencies show a slight blue shift, but the −10 dB bandwidth still covers the operating frequency of 13.56 MHz. Therefore, the tag can work properly in the vicinity of human body. The inset of Figure 5C presents the read range data for wearable configurations at the operating frequency of 13.56 MHz. When attached to the object's wrist as shown in Figure 5A, the read range of the antenna drops to 3.4 cm. This can be attributed to the deformation of the tag when it conforms to the wrist which is consistent with the simulation results shown in

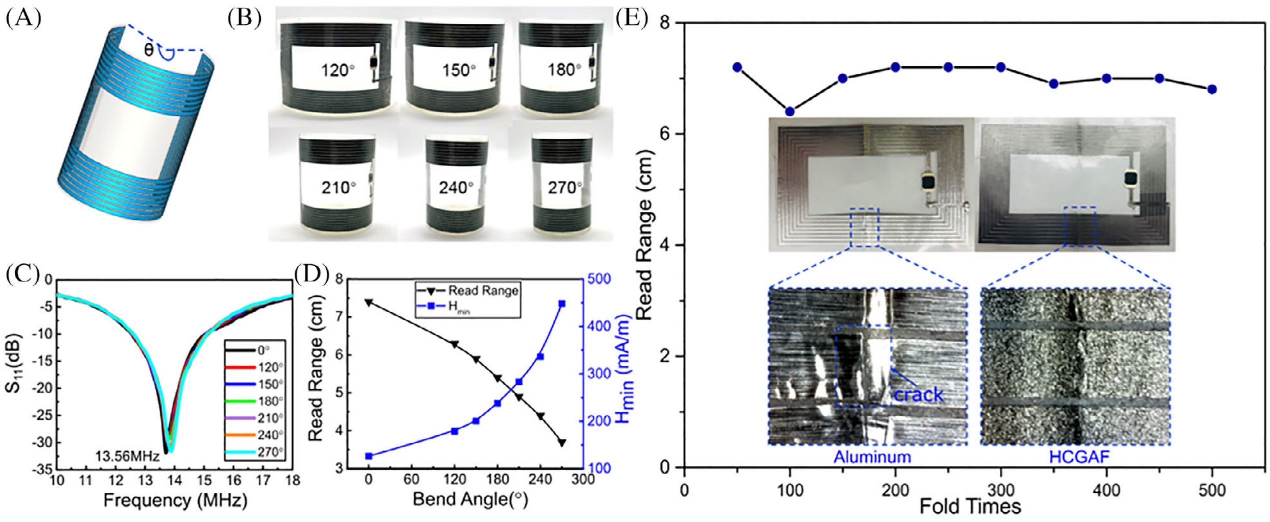

FIGURE 4 Bending test of HCGAF NFC tag. A, Schematic illustration of the antenna in bending state with bending angle θ. B, Photographs of the tag with different bending angles. C, Measured S_{11} of the antenna for various bending angles. D, The read range (black triangle) and minimum magnetic field strength (H_{min}) (blue square) of the tag for various bending angles at 13.56 MHz. E, Measured read range data of the tag with different fold times. Inset: Photographs showing aluminum (left panel) and HCGAF (right panel) NFC tags after the bending tests

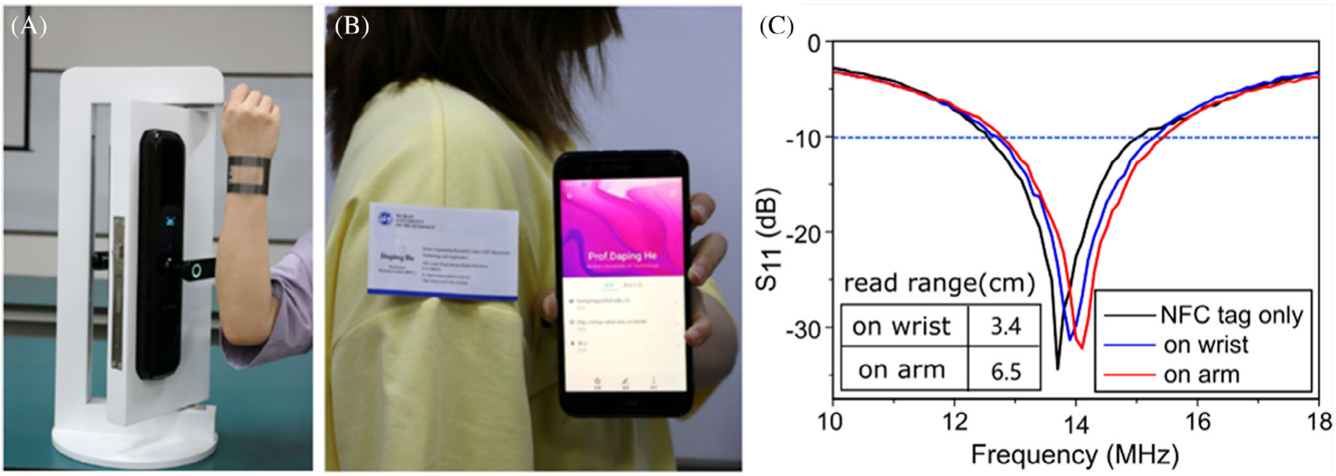

FIGURE 5 On-body demonstrations of the HCGAF NFC tag as an electronic key card A, and an electronic business card B. C, $|S_{11}|$ curves of the NFC tag only (black) and when it is attached to the wrist (blue) and arm (red). Inset: read range data for the corresponding wearable configurations at the operating frequency of 13.56 MHz

Figure 4D. Another possible reason is the human body loading effect as the tag is directly in contact with the object's skin. It however, still maintains a read range of ~3.4 cm to support proper functionalities as wearable devices. For the scenario shown in Figure 5B, the read range of the NFC tag is barely affected demonstrating its perfect compatibility with clothing.

3 | CONCLUSION

To summarize, HCGAF-based NFC tag antenna is proposed and investigated by optimizing figures of merit with targeted antenna size in this paper. The fabricated prototype shows 10 dB bandwidth of 2.5 MHz with the resonant frequency at 13.70 MHz and a quality factor of 9.19. Due to the wide bandwidth feature, the as-prepared antenna successfully demonstrates the exchange of data with commercial NFC readers when integrated with two types of commercial NFC microchips with different capacitances. We also confirm that the HCGAF-based NFC tag antenna is flexible and robust enough to sustain repetitive bending without noticeable performance deterioration. With the successful on-body demonstrations of the antenna as key card and electronic business card, the applications of the proposed HCGAF-based NFC tag antenna in wireless body-centric networks are to be expected.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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