Japanese Patterns as NFC Antennas for Interactive Urushi-ware

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ABSTRACT

Urushi (Japanese lacquer) is a natural resin paint with electrical insulating capability. We focused on Japanese patterns on an urushi-ware that is a product coated urushi. To make urushi-wares interactive without losing elegance and beauty, we transformed Japanese patterns into near-field communication (NFC) antenna patterns. We developed three types of prototype antennas and confirmed their functionality. In addition, we developed an IC key tag and an interactive lunch box as example applications of interactive urushi-wares.

CCS CONCEPTS

• **Hardware** → *Communication hardware, interfaces and storage*; Wireless devices;

KEYWORDS

fabrication; urushi circuit; screen printing; traditional Japanese craft; visual design; gold foil; silver paste

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Figure 1: Urushi-ware prototypes with NFC tags whose antennas form Japanese patterns: left) a key chain and right) an ornament. Our method enables designers to embed an NFC tag into an urushi-ware and even decorate it with the tag's antenna in a visually harmonized way with urushi.

1 INTRODUCTION

Urushi (Japanese lacquer) is a type of natural resin paint. It has been used to coat wooden crafts such as furniture and dishes mainly to protect them from degradation, taking advantages of its good properties such as durability, waterproofness, and anti-microbialness. A craft coated with urushi is called an urushi-ware. Moreover, a traditional Japanese urushi-ware is often decorated with patterns made of gold or silver, which are electrically conducting materials; their designs are based on patterns in the natural world such as plants and clouds (hereafter, Japanese patterns). To craft a traditional Japanese urushi-ware, these patterns are printed using screen printing or drawn by sprinkling gold powder. An urushi-ware is a work of art because it has a beautiful gloss and an elegant pattern on the surface. If we could add functionality to urushi-wares by using these patterns, it would be possible to give interactivity to urushi-wares without losing elegance and beauty provided by their glossy and decorative surfaces.

A number of previous studies used a conductive pattern drawn on the surface of urushi-ware as a touch interface. Suzuki et al. [23] built a musical instrument coated with urushi, whose surface has touch-sensitive electrodes made of gold. Moreover, since it is possible to make multilayered circuits using urushi (multilayered urushi circuit) [7] by taking advantage of urushi’s electrical insulating capability, a multitouch surface using a multilayered urushi circuit was developed [9]. While these studies presented methods that can be used to achieve interactive urushi-wares, these methods require external devices directly connected to the urushi-wares, such as power supplies and microcomputers, to make the touch interfaces functional. As a result, it is difficult to give interactivity to a thin object without increasing its thickness.

In this study, we focus on the functionality of a near-field communication (NFC) tag to give interactivity to traditional crafts. While an NFC tag is attached to an object to identify the object, it is known that the capability of such identification also realizes interaction [16]. In addition, we focus on the fact that NFC tags work without directly-connected external devices, where they can be attached to the surface of a thin urushi-ware without increasing its thickness. However, attaching an NFC tag to the surface of an object tends to diminish the appearance of the object. In particular, urushi-wares are valuable for their glossy and decorative surfaces. Therefore, giving interactivity to an urushi-ware without losing the value is an issue. Moreover, forming an NFC tag requires two-layered wiring since an NFC chip has two connectors that are connected to a loop antenna with multiple turns.

In this paper, we present a method to enable designers to embed an NFC tag into an urushi-ware and even to decorate it with the tag’s antenna in a visually harmonized way with urushi (Figure 1). This method utilizes a multilayered urushi circuit [7] to form an NFC tag that requires two-layered wiring. Specifically, the primary contributions of our study are as follows:

- We developed a method of using a Japanese pattern as an antenna for an NFC tag and demonstrate the antenna’s effectiveness.
- We demonstrate how the above method can be used to create interactive urushi-wares with an NFC tag by using a multilayered urushi circuit.

2 RELATED WORK

We compare our study with relevant previous studies, which can be categorized into those that used gold foil or silver paste for fabricating/prototyping circuits and those that applied radio-frequency identification (RFID) for interaction.

Fabricating/Prototyping Circuits using Gold Foil or Silver Paste

Previous studies have used gold foil or silver paste for fabricating/prototyping circuits.

DuoSkin [10] uses gold foil to fabricate interactive tattoos that have touch-sensitive user interfaces (e.g., buttons and sliders) and NFC tag antennas. Srimongkon et al. [20] presented a method of adhering gold foil into a circuit shape onto a paper substrate using the black toner of a commercial laser printer as an adhesive. In our study, we fabricated an NFC antenna on the basis of the method of Srimongkon et al.

Screen printing is a printing method used as a traditional craft technique. It transfers ink onto a target surface through a pattern cut into a piece of cloth stretched across a frame, and has also been used to fabricate circuits using conductive ink. For example, Kuznetsov et al. [12] used screen printing to embed circuits in a range of substrates making them interactive. In addition, PrintScreen [17] is a method of producing a flexible display using screen printing. Furthermore, Ikegawa et al. [9] manufactured a touch sensor using screen printing and a multilayered urushi circuit. In our study, as with these studies, we embedded a circuit in objects by screen printing to make the objects interactive.

Studies on methods to form an NFC antenna using screen printing have also been conducted. For example, Li et al. [14] presented a method to screen print silver nanoparticle ink to create an antenna for an NFC reader. Liu et al. [15] investigated how to make an effective NFC antenna using screen printing with silver paste by studying the effect of scraper speeds and curing conditions on an antenna’s properties and recognizable distance. In our study, screen printing is used for printing circuits, including NFC antennas, with decorative patterns on urushi-wares.

Moreover, methods to create antennas by inkjet printing with silver nanoparticle ink were studied. Kawahara et al. [11] invented a technology for prototyping circuits including RFID antennas using silver nanoparticle ink and an inkjet printer. Pachler et al. [18] prototyped an NFC antenna on a ferrite substrate using inkjet printing with silver nanoparticle ink. As an inkjet printer cannot be used for thick urushi-wares, in our study, we use gold foil to form patterns on urushi-wares instead of silver nanoparticle ink.

In addition, there are studies on prototyping circuits including antennas using conductive threads. Zhiglova et al. [24] embedded circuits in a carpet using conductive threads to create an interactive carpet. Del-Rio-Ruiz et al. [5] prototyped an NFC antenna using conductive threads for a flexible and robust wearable NFC tag. Grabham et al. [6] used screen printing and conductive threads to embed an

NFC tag in cloth. In our study, we use conductive paste instead of conductive thread to make a more presentable decorative pattern.

NFC, RFID for Interactions

There are three types of RFID technologies based on the range of frequencies they use to communicate data: low frequency (LF) RFID, high frequency (HF) RFID, and ultra-high frequency (UHF) RFID. LF RFID uses 30 kHz to 300 kHz radio waves. HF RFID uses 3 MHz to 30 MHz radio waves and a loop antenna; NFC is based on this technology, which uses 13.56 MHz radio waves. UHF RFID, which simply called RFID, uses 300 MHz to 3 GHz radio waves and a dipole antenna. Among the three technologies, we describe studies on NFC and RFID (i.e., UHF RFID), since they show their potential for sensing various types of information in addition to identification.

RFID antennas can be used as sensors by measuring changes in their characteristics. Bhattacharyya et al. [3] used an RFID tag as a sensor to measure the liquid level in a beverage glass by measuring characteristic changes in the antenna due to the level of liquid. In addition, Bhattacharyya et al. [4] used an RFID tag as a temperature sensor by measuring the amount of antenna deformation caused by temperature change. Previous studies enabled gesture input by measuring the radio wave intensity of RFID. PaperID [13] applies machine learning to the radio wave intensity of RFID and recognizes gesture input in the air. In addition, both Paper ID and RIO [19] show that an RFID tag can be used as a touch sensor. Moreover, an RFID tag can be used as a switch by separating its antenna and IC chip. For example, RFIBricks [8] used RFID tags as switches to determine the construct of stacked blocks. Since an NFC tag could be used as a sensor/switch in a manner similar to an RFID tag, in our study, we embed an NFC tag in an urushi-ware; therefore, it would be able to design an urushi-ware with such interactivities as the above studies achieved, since an NFC tag could be used as sensors/switches in a manner similar to an RFID tag.

RFID tags with decorative antennas have been developed. Tribe et al. [22] prototyped RFID tags that are used as tattoos, each of which has a slot line antenna designed on the basis of a logo. Abdelnour et al. [1] prototyped RFID tags that have slot line antenna designs based on artistic figures and symbols as with the study of Tribe et al. Similar to [22], NFC tags were also used as tattoos. DuoSkin [10] uses gold foil to create one of their interactive NFC tattoos. A standard shaped antenna is used for a DuoSkin NFC antenna. The purpose of our study is to develop a method to form an NFC antenna that has a decorative pattern onto an urushi-ware.

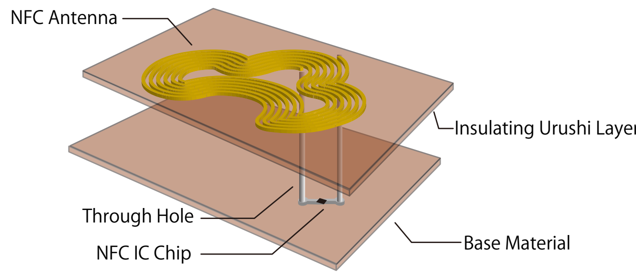

Figure 2: Construction of an NFC tag by using a multilayered urushi circuit.

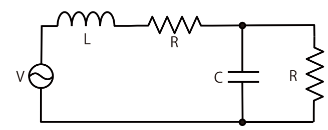

Figure 3: Equivalent circuit of an NFC tag.

3 METHOD OF TRANSFORMING JAPANESE PATTERN INTO AN NFC ANTENNA PATTERN

In this section, we briefly explain the structure and mechanism of an NFC tag. We also show our method of transforming a Japanese pattern into an antenna pattern to embed an NFC tag onto an urushi-ware.

Structure and Mechanism of an NFC Tag

An NFC tag consists of a spiral loop antenna, an insulating layer, and a chip. When making an NFC tag using urushi, the insulating layer is replaced with an insulating urushi layer, as shown in Figure 2. The spiral loop antenna operates as a coil. When an NFC reader sends 13.56 MHz radio waves to this antenna, an electromotive force is generated by electromagnetic induction. If this electromotive force exceeds the operating power of the chip, the NFC tag works.

An NFC tag is represented by the equivalent circuit shown in Figure 3. L is the inductance determined by the number of turns and area of the coil. C is the capacitance generated between the wires of the antenna. R are the resistances of the antenna and the chip. V is the voltage generated by electromagnetic induction. From the equivalent circuit, the resonant frequency f can be expressed by the following equation:

$$f = \frac{1}{2\pi\sqrt{LC}}. \quad (1)$$

In accordance with the equation, f can be adjusted by L and C. To maximize the power obtained from the antenna, we specifically adjust L to bring the resonant frequency of the

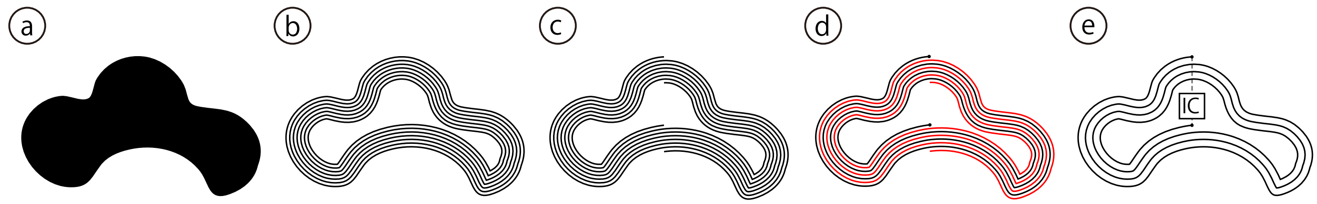

Figure 4: Procedure of transforming a Japanese pattern into a loop antenna: a) outline the pattern, b) draw lines inside at a regular interval of T, c) cut this pattern at the center and shift the right side vertically, d) remove the unnecessary part (the red part), and e) attach the NFC chip.

antenna closer to 13.56 MHz. L can be expressed by the following equation:

$$L = AN^2S, \qquad (2)$$

where A is a constant, N is the number of turns, and S is the surface area of the antenna. In accordance with this equation, we can adjust L by changing the antenna size and the number of turns.

Transforming a Japanese Pattern into an Antenna Pattern

We show the method of transforming a Japanese pattern into an antenna pattern with the following procedure (Figure 4). First, the designer outlines the pattern to be used as the antenna. Then, she/he draws lines inside of the outline at a regular interval of T. Next, she/he cuts this pattern at the center and shifts the right side vertically. After that, she/he removes the unnecessary part and attaches the NFC chip. The interval of the lines becomes $T/2$ at this time.

4 TEST IMPLEMENTATION

In this section, we describe the NFC tag prototypes with antennas using gold foil, silver paste, and a multilayered urushi circuit. First, we prototyped tags with gold-foil antennas to test whether the above procedure could create a functional antenna. Since creating a gold-foil antenna takes only 10 minutes, we could quickly make and test many annotations by trial and error. Next, we prototyped NFC tags with silver-paste antennas. Creating a silver-paste antenna takes 90 minutes. Finally, we prototyped a tag with a multilayered urushi circuit to test whether a tag can be embedded in an urushi-ware. Creating this type of tag requires a minimum of four days.

Gold Foil Prototype

We formed three NFC tags on paper, each of which has a square-, cloud-, and Kiri- (an emblem of paulownia used by the Government of Japan on official documents) shaped antenna as shown in Figure 5.

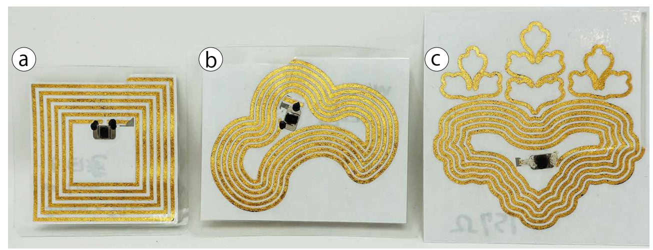

Figure 5: NFC tags formed on paper with gold-foil antennas: a) a square-, b) cloud-, and c) Kiri-shaped antenna.

To form each of these tags, we used Adobe Illustrator to transform each previously-designed shape into an antenna pattern by following the above procedure manually with the interval T set to 1 mm. Moreover, we added a straight line (Figure 6a) to one end of the pattern (i.e., one end of the antenna) to connect the antenna to an NFC chip via the back of the paper.

Next, we used the method described by Srimongkon et al. [20] to print gold-foil antennas on the paper, as shown in Figure 6. We first printed each antenna pattern in black using a laser printer on copy paper (Figure 6a). Then, we placed gold foil (24k gold, 109 mm square, 0.1 μm thick, IMAIKINPAKU, Tachikiri) on the printed pattern and heated it for two minutes using a ski iron (Vitora, CVRDIE) at 180°C to stick the gold foil to the pattern (Figures 6b and 6c). Next, we scraped the gold foil on the copy paper with a sponge to remove the excess gold foil (i.e., gold foil in the spaces of the pattern) from the paper (Figure 6d). After this, we connected both ends of the antenna to an NFC chip (Rodanliu, NTAG215), by first folding one end of the antenna back (Figure 6e), making a through-hole, and connecting both ends of the antenna to the chip using a conductive adhesive (Figure 6f).

Exploring Parameters of Antenna

Before forming an NFC tag on paper, the parameters of the antenna (i.e. the size and number of turns) must be determined so that its resonance frequency becomes close to

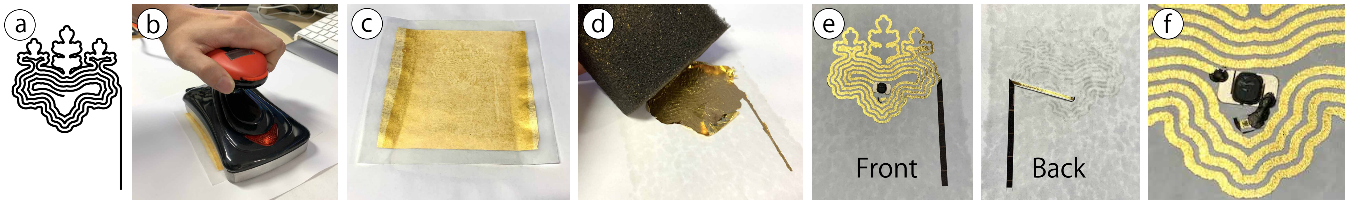

Figure 6: Process to make a gold-foil antenna on paper: a) print an antenna pattern on paper, b) stick gold foil to the printed pattern using an iron, c) remove the iron after two minutes, d) remove the excess gold foil, e) fold one end of the antenna back, f) connect both ends of the antenna to the chip using a conductive adhesive.

13.56 MHz. Here, we adjusted only the antenna size because it was easier to change the size than to change the number of turns.

To determine the antenna size that would achieve a resonance frequency of 13.56 MHz, we repeatedly changed the antenna size, formed only gold-foil antennas on the paper, and measured the resonance frequency, until the antenna resonance frequency approached 13.56 MHz. We used the method described in AN2972 Application note [21] to measure the antenna resonance frequency. To do this, we used two loop antennas (ISO 10373-7) as shown in Figure 7. One was connected to a function generator (SIGLENT, SDG 2042X), and the other was connected to an oscilloscope (IWATSU, DS-5120B). Between the two loop antennas, we placed an antenna to be tested. The function generator outputs 5.0 V_{PP} signals from 5.0 MHz to 20.0 MHz in 5.0 MHz steps. We recorded the voltage observed with the oscilloscope. The final sizes of each antenna were 5.0 cm × 5.0 cm for the square, 3.5 cm × 7.0 cm for the cloud, and 3.8 cm × 7.0 cm for the Kiri.

The characteristics of the antennas after adjustment are shown in Figure 8. As this figure shows, the antennas peak around 13 MHz. Furthermore, we confirmed that writing and reading to these tags were possible using an LG Nexus 5 smartphone and NFC Tools.

Silver Paste Prototypes

We prototyped NFC tags with silver-paste antennas (Figure 9) to test whether such antennas would work. In this test, we used the same antenna patterns used for the gold-foil antennas, whose sizes were the ones we found using gold foil (i.e., 5.0 cm × 5.0 cm for a square, 3.5 cm × 7.0 cm for a cloud, and 3.8 cm × 7.0 cm for a Kiri). The silver-paste antennas were screen printed by the following procedure. First, we drew a hole in an antenna pattern on the screen for a through-hole. Next, we poured silver paste onto the screen. After that, we screen printed the antenna pattern using a wooden spatula. Since the silver paste is ultraviolet (UV) curable, we irradiated the silver paste with UV light for approximately one hour. Finally, we connected an NFC

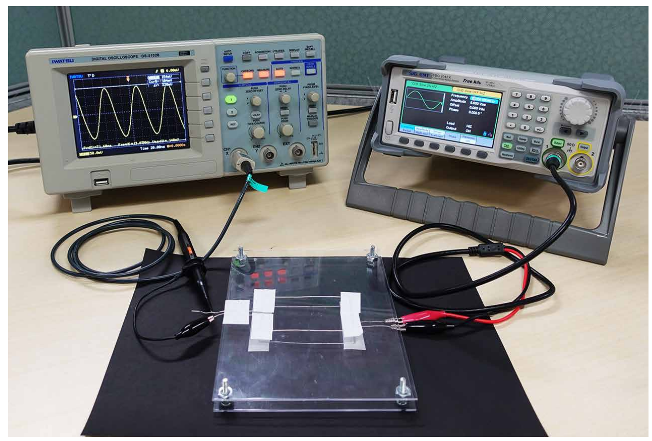

Figure 7: Setup for measuring antenna resonance frequency: left) an oscilloscope, center) two loop antennas attached to acrylic boards, and right) a function generator.

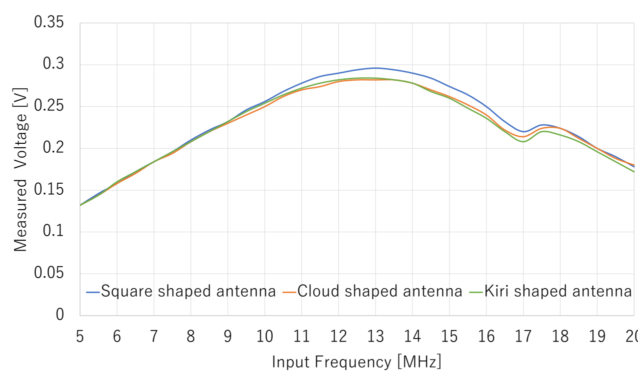

Figure 8: Resonance frequency of gold-foil antennas.

chip to the printed antenna using a conductive adhesive and masking tape.

We measured the characteristics of these antennas. The results are shown in Figure 10. As this figure shows, all antennas resonated at around 13.5 MHz. Furthermore, as with the gold-foil antennas, we confirmed that writing and reading to these tags was also possible using an LG Nexus 5 smartphone and NFC Tools.

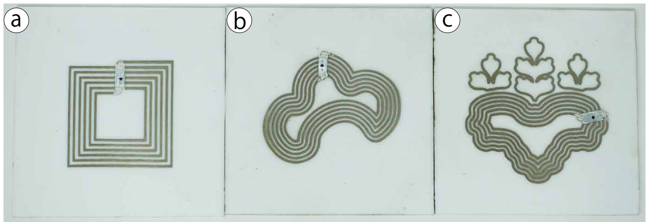

Figure 9: NFC tags with silver-paste antennas: a) a square-, b) cloud- and, c) and Kiri-shaped antenna.

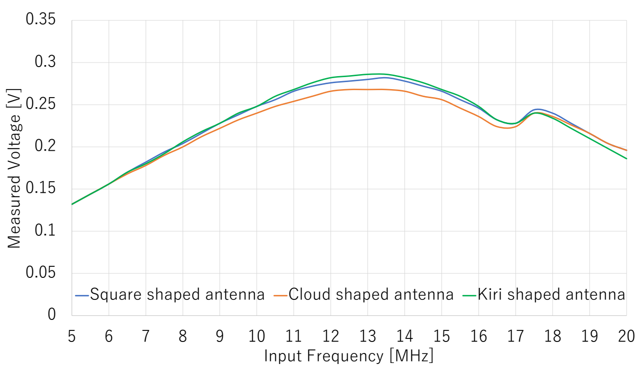

Figure 10: Resonance frequency of silver-paste antennas.

Multilayered Urushi Circuit

We investigated whether the antennas could be embedded into urushi-wares. To determine this, we made an NFC tag with a square-shaped antenna (5.0 cm × 5.0 cm) in a multilayered urushi circuit using the following procedure (Figure 11). We first coated a PVC plate with urushi (Figure 11a). Then, we dried the urushi in a wooden box for a day (Figure 11, which is the approximate time needed to cure it. Next, we made a screen for pattern printing (Figure 11c), and screen printed a pattern on the plate (Figure 11d). After that, we irradiated the silver paste with a UV light while changing the point of irradiation for approximately an hour to cure the silver paste (Figure 11e). Then, we coated the antenna with urushi for insulation and dried it for another day (Figure 11f). Next, we connected the NFC chip with the antenna via the through-holes using a conductive adhesive (Figure 11g) and coated the NFC tag once again with urushi for embedding and dried it for another day. After that, we attached a cloth to the tag using adhesive mixed with urushi and starch paste, which takes a day to cure. Finally, we pulled off the tag with the cloth from the PVC plate (Figure 11h).

To embed tags in an urushi-ware, the above procedure must be conducted in reverse. First, the designer attaches the chip to a base plate. Then, she/he coats the plate with urushi, leaving both ends of the chip for insulation. Next, she/he screen prints a pattern onto the plate. Finally, she/he connects the chip to the antenna using a conductive adhesive. In the screen printing process, it is difficult to print the antenna at the position where both ends of the antenna overlap the ends of the chip. To make the process easier, we made the tag by following this reversed procedure.

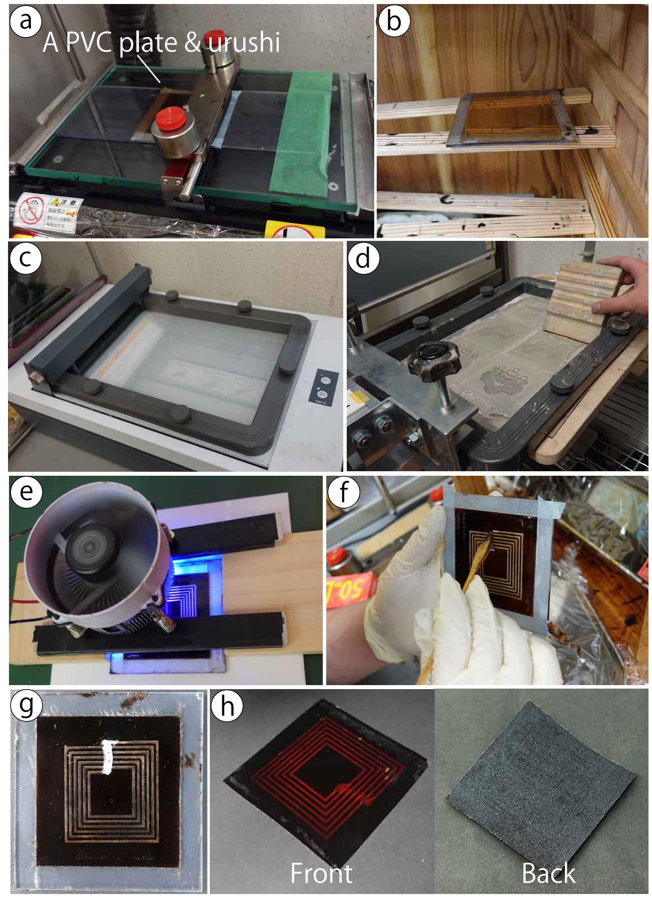

Figure 11: Procedure to make an NFC tag with a multilayered urushi circuit: a) coat a PVC plate with urushi, b) dry urushi for a day, c) make a screen for printing the pattern, d) screen print the pattern on the plate, e) irradiate silver paste with UV light to cure it, f) coat the antenna with urushi and dry it for a day, g) connect an NFC chip to the antenna, and h) pull off the NFC tag from the PVC plate.

The characteristic of the antenna is shown in Figure 12. The resonant frequency of this antenna is higher than that of the silver-paste antenna of the same shape, which peaks around 14.5 MHz. The reason for this shift would be that the capacitance has changed due to the urushi. However, despite this frequency shift, we confirmed that writing and reading to this tag were possible using an LG Nexus 5 smartphone and NFC Tools.

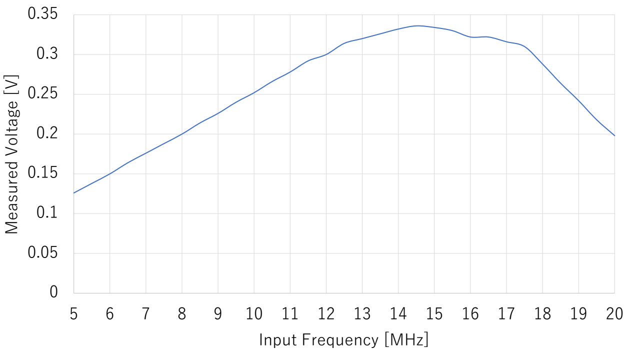

Figure 12: Resonance frequency of square-shaped antenna with a multilayered urushi circuit.

5 EXAMPLE APPLICATIONS

We present two example applications for our NFC tags.

IC Key Tags

NFC tags are often embedded in employee cards for personal identification. Also, urushi-wares are traditional crafts that are often sold as souvenirs, most commonly as key holders. Inspired by these facts, we combined the features of an NFC tag with those of an urushi-ware to form a key-type IC tag (Figure 13a). A user can enjoy the functionality of an IC tag with the added value of traditional crafts.

Interactive Lunch Box

Traditional Japanese lunch boxes are urushi-wares. They are still used in sushi delivery and to serve quality meals at hotels or restaurants. Using a lunch box with an NFC tag, chefs can provide information about the meals inside the box, such as names of the foods, how to eat them, their ingredients, nutrition, and allergens (Figure 13b). A user can see such information on their smartphone by holding it over the pattern of the lunch box. With this design, interactivity is added to the lunch box while maintaining the elegance and luxury of urushi.

6 DISCUSSION AND LIMITATIONS

Embedding Commercially Available NFC Tags. While it is physically possible to embed a commercially available NFC tag into an urushi-ware instead of prototyping one as we did in our study, it imposes a number of problems. First, the performance of an NFC tag degrades in close proximity to metal [2]. Second, an NFC tag does not work under the metal foil because the metal foil inhibits electromagnetic induction. These two characteristics prevent a designer to embed an NFC tag near Japanese patterns made of metal. On the other hand, if an NFC tag is embedded in a part far from such decoration, the tag will work; however, the tag will be invisible to the user, which prevents a user from knowing with what part of the urushi-ware to interact. Our method can solve the above problems by transforming a Japanese pattern into an antenna pattern that enable a designer to design a Japanese pattern that can serve as a point of interaction.

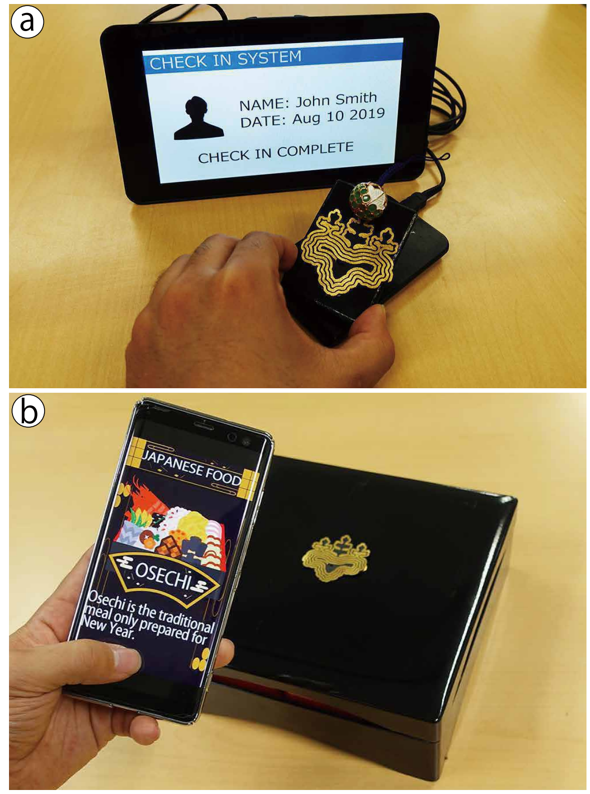

Figure 13: Example applications: a) an IC key tag and check-in application and b) an interactive lunch box that has the information about the meals inside it.

Antenna Size. The performance of a screen printer is an important factor in designing an antenna pattern in our method. Generally, the size and number of turns of the antenna are parameters of the inductance L of the antenna. Increasing the number of turns is necessary to reduce the size of the antenna while maintaining L (i.e., maintaining the resonance frequency). Currently, our screen printer cannot print patterns with a line width less than 1 mm and line spacing less than 1 mm. This limits the antenna size. For example, in a square antenna with a side length of l mm, the maximum number of turns of the antenna is $l/4$.

Antenna Shape. Our pattern design procedure only uses the outline of the original pattern. This means that it is impossible to use complicated patterns such as filled, nested, or dots patterns.

Antenna Characteristics. The fabricated antenna has a low Q factor. As a result, the power obtained by electromagnetic induction is smaller, and thus the communication distance is shorter than commercially available tags. The Q factor is calculated as follows:

$$Q = \frac{\omega L}{R}, \tag{3}$$

where ω is the angular frequency used for NFC. In accordance with this equation, the high resistance R and the low inductance L of the antenna are the causes of the low Q factor. When comparing the characteristics measurement results for the gold-foil (Figure 8) and silver-paste (Figure 10) prototypes, the voltage measured in the gold-foil prototypes is larger. This is because the resistance of the gold foil is lower than that of the silver paste. Therefore, to improve the performance of the antenna, we plan to investigate the following approaches: 1) using conductive materials with resistances lower than that of the silver paste we used and 2) using a screen printer that can print an antenna pattern with a larger number of turns to obtain a larger inductance.

Antenna Materials. While the gold-foil antennas show better performances than the silver-paste ones as shown in Figures 8 and 10, we used silver paste for the multilayered urushi circuit simply because we do not have the required technique to stick gold foil directly onto urushi and urushi-wares. Therefore, a collaboration with experts of gold, including artisans of urushi-wares, will be the next step to embed NFC tags with gold antenna onto urushi-wares.

Besides their performance in the antennas, there is a difference in production time between gold foil and silver paste. The silver-paste antenna takes longer to create than the gold-foil antenna. The difference in the production time is the difference in the curing time of the adhesive. By using a strong UV light or a silver paste that cures quickly, the production time of the silver-paste antenna can be shortened.

Example Applications. The example applications described above inherit the advantages of traditional urushi-wares in that they have the elegance and luxury of urushi. However, they also inherit some disadvantages of traditional urushi-wares. First, our method is not suitable for mass production because artisans must make IC key tags and lunch boxes manually. Second, urushi and gold foil are expensive. Finally, since urushi-wares can be deteriorated with UV rays, they cannot be placed under the sun for a long time.

7 FUTURE WORK

Aside from the future work described in the above section, our immediate future work is to automate the antenna transforming procedure by implementing it into an application.

Second, we will also try to use an NFC antenna as a feed. In general, an NFC tag is used not only for communication but also as a feeding device. If this is possible, LEDs and electroluminescence can be embedded in urushi-wares and used for presenting information.

Another future work is to use gold powder to make an antenna. In the traditional technique to decorate an urushi-ware, called makie, an artisan decorates an urushi-ware by sprinkling gold powder on its surface. The range of expression is expanded by using this technique, so that a designer can use patterns such as gradation and matte when creating antennas. Therefore, we will make an antenna by using makie and measure its characteristics.

8 CONCLUSION

We presented a procedure for making an antenna in the shape of a Japanese pattern that functions as an NFC tag. Three types of antennas prototyped in accordance with this procedure confirmed that the procedure works. We also confirmed that NFC tags can be made with a multilayered urushi circuit. The above findings show the possibility of making traditional Japanese crafts interactive without affecting elegance and beauty.

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