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Coils and Antennas Fabricated with Sewing Litz Wire for Wireless Power Transfer

Hikari Ryu, Yuki Fukuda, Kento Oishi, Chiharu Igarashi, Shogo Kiryu

***Abstract*—**Recently, wireless power transfer has been developed in various fields. Magnetic coupling is popular for feeding power at a relatively short distance and at a lower frequency. Electro-magnetic wave coupling at a high frequency is used for long-distance power transfer. The wireless power transfer has attracted attention in e-textile fields. Rigid batteries are required for many body-worn electric systems at the present time. The technology enables such batteries to be removed from the systems. Coils with a high Q factor are required in the magnetic-coupling power transfer. Antennas with low return loss are needed for the electro-magnetic coupling. Litz wire is so flexible to fabricate coils and antennas sewn on fabric and has low resistivity. In this study, the electric characteristics of some coils and antennas fabricated with the Litz wire by using two sewing techniques are investigated. As examples, a coil and an antenna are described. Both were fabricated with 330/0.04 mm Litz wire. The coil was a planar coil with a square shape. The outer side was 150 mm, the number of turns was 15, and the pitch interval between each turn was 5 mm. The Litz wire of the coil was overstitched with a sewing machine. The coil was fabricated as a receiver coil for a magnetic coupled wireless power transfer. The Q factor was 200 at a frequency of 800 kHz. A wireless power system was constructed by using the coil. A power oscillator was used in the system. The resonant frequency of the circuit was set to 123 kHz, where the switching loss of power Field Effect Transistor (FET) was was small. The power efficiencies were 0.44-0.99, depending on the distance between the transmitter and receiver coils. As an example of an antenna with a sewing technique, a fractal pattern antenna was stitched on a 500 mm x 500 mm fabric by using a needle punch method. The pattern was the 2nd-oder Vicsec fractal. The return loss of the antenna was -28 dB at a frequency of 144 MHz.

***Keywords*—**E-textile, flexible coils, flexible antennas, Litz wire, wireless power transfer.

I. Introduction

In recent years, wearable devices such as portable electrocardiographs have been actively developed. The supply of electric power has become important for the miniaturization of such wearable devices. Wearable devices usually contain built-in rechargeable batteries. Since wireless power transfer is drawing attention when recharging batteries, researches have been conducted for this purpose [1]. The magnetic resonance type in the wireless power transmission methods has been studied extensively because of its high-power transmission efficiency [2]. This method is suitable for power transmission over relatively short distances and frequencies of several tens of kHz to tens of MHz. Electro-magnetic wave coupling at a higher frequency is used for long-distance power transfer. Since wearable devices are implanted the body, coils or antennas for wireless power transmission supply to them must also be attached to clothing. In order to attach to clothing, the coil or the antennas need to be flexible enough to deformation to some extent. In recent years, coils or antennas in which conductive wires are sewn or stitched into clothing using sewing techniques have been proposed and studied [1], [3]. These have better ventilation and flexibility than coils or antennas with flexible printed circuits. Therefore, coils or antennas fabricated with sewing techniques are suitable as a power transmission coil to supply power to wearable devices.

Fabrication of coils with vinyl covered copper wire [3], a thread coating conductive metal [1], Litz wire [3], [4] were proposed. Vinyl covered copper wire is harder and the loses is larger than Litz wire at a high frequency due to the skin effect. A thread coating conductive metal is more flexible but has high loss [1], [3]. Litz wires have moderate flexibility and lower skin effect.

In this paper, coils for magnetic resonance power transmission and antennas manufactured by sewing or stitching Litz wires into fabric were described.

II. Fabrication Method

A. Fabrication Method Using Running Stitches

Fig. 1 shows an example of a coil produced by the running stitch method commonly used in sewing. This is the most basic sewing method, in which the front and back of the cloth are sewn at certain intervals. Since the Litz wire is sewn directly onto the cloth instead of threads, a thick wire cannot be used. In addition, long wires cannot be used because the Litz wire must be pulled up after the needle is threaded through the cloth. Therefore, this method is difficult to manufacture coils with large size and number of turns. The Litz wire used in the fabrication has seven bundles of 0.07 mm sheathed copper wire. The Litz wire was stitched by using a No. 20 cross-stitch needle for embroidery to sew the Litz wire.

B. Fabrication Method Using a Sewing Machine

Fig. 2 shows an example of a coil fabricated using a sewing machine. Sewing machines sew fabric using upper and lower threads. The upper threads are subject to complex movements and will break if Litz wire is used for them. Therefore, Litz wire is used for the lower thread. However, since the lower thread is usually winded on a bobbin, it can only be stitched for the length that can be winded on the bobbin. In a domestic sewing machine, the bobbin has a diameter of about 20 mm, so it is difficult to manufacture coils of large size and number of turns.

Shogo Kiryu is with Tokyo City University, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan (corresponding author, phone: +81-3-5707-0104; e-mail: skiryu@ tcu.ac.jp).

Even industrial sewing machines have a bobbin diameter of 30 mm. It will be difficult for the sewing machines currently on the market to produce large-sized coils.

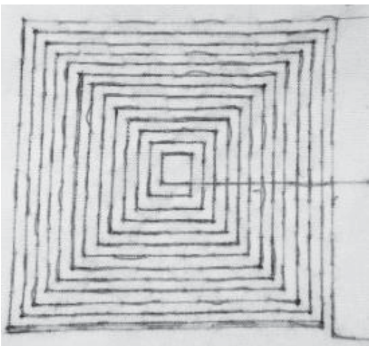

Fig. 1 A coil fabricated with hand sewing in tandem

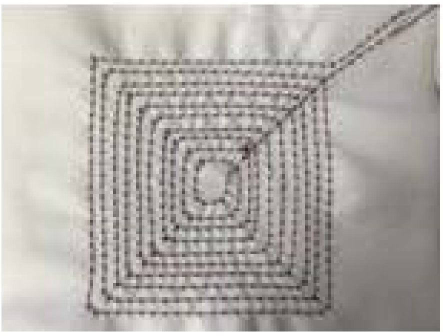

Fig. 2 A coil fabricated with a sewing machine

C. Fabrication Method to Sew Litz Wire Using Thread

One method of making relatively large or winding coils is to sew the Litz wire to the fabric with thread [3]. An example of a coil fabricated by this method is shown in Fig. 3. In Fig. 3 (a), the Litz lines were placed on the fabric in a circular pattern while several positions of the windings were sewn by hand with thread. Since they are sewn with thread while arranged in a circular pattern, their fabrication requires much time and skill. It is difficult to sew them by hand to increase the number of the positions to be sewn and make them stronger. Fig. 3 (b) shows a rectangular spiral coil made by sewing Litz wire onto fabric with a sewing machine. Because of sewing by a sewing machine, it is not as time-consuming as hand sewing. However, the shape is distorted, and it takes skill to produce coils of the intended size and shape.

D. Coil Fabrication Using the Needle-Punch Method

The needle-punch method is popular in handicraft. In this subsection, a coil fabrication using the method was described. Fig. 4 (a) shows the needle used in the method. When the needle is inserted into the cloth and then the needle is removed, a loop of thread is formed at the position through which the needle is inserted, as shown in Fig. 4 (b). When the Litz wire is passed through this loop and the thread is pulled, the loop shrinks and the Litz wire can be fixed to the fabric. An example of a coil fabricated by this method is shown in Fig. 5. The outer side of the coil measured 150 mm × 150 mm and the windings were 17 turns. The Litz wire used was a bundle of 300 strands of 0.04 mm. Compared to Fig. 3 (b), the shape is better.

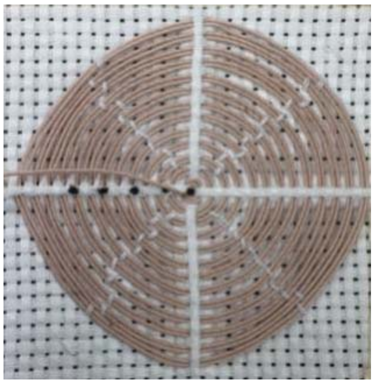

Fig. 3 (a) A coil fabricated with hand sewing Lits wire with thread

Fig. 3 (b) A coil sewn with thread using a sewing machine

Fig. 4 (a) A needle used in fabricated sewn coil

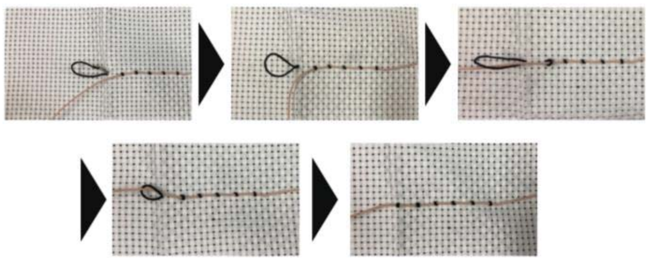

Fig. 4 (b) A procedure for sewing Litz wires with thread by using needle-punch method

III. Magnetic Resonance Power Transmission Using Sewn Coils

In this section, the results of power transmission experiments using a prototype power circuit for magnetic resonance power transmission in sewn coils are described.

Fig. 5 A receiver coil fabricated with needle-punch method for magnetic resonant wireless power transfer

A. Coil Used in the Experiment

The power receiving coil was shown in Fig. 5 and the power transmission coil was shown in Fig. 6. The power transmission coil was fabricated by fixing Litz wire with tape on a cardboard. Table I shows the dimensions of the coils.

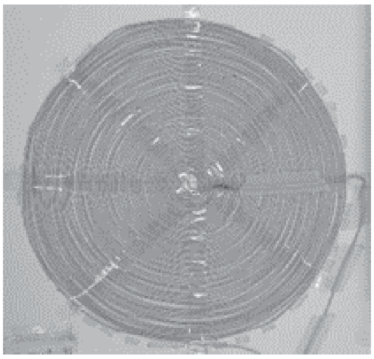

Fig. 6 A transmitter coil for experiment of wireless power transmission

Electrical properties were measured with an LCR meter. The used LCR meter was the model ZM2376 manufactured by NF Circuit Blok. The measurement frequency range was from 100 kHz to 1000 kHz.

Fig. 7 shows the measurement results of the self-inductance. The measured values were almost constant within the measurement range. Fig. 8 shows the measured values of the loss resistance. For the transmission coils, the loss resistance increases as the frequency. For the receiver coil, those were almost no change in the measured frequency range. The increase in the loss resistance would be due to the proximity effect caused by the use of thick Litz wires and the increase in equivalent loss due to stray capacitances between the windings.

TABLE I
PARAMETERS OF COILS SHOWN IN FIGS. 5 AND 6

	Transmission Coil	Receiving Coil
Outer Diameter [mm]	350 (Diameter)	150 (Sidereal length)
Pitch [mm]	3	4
Turns	53	17
Shape	Circle	Square
Types of LITZ wire	0.04 mm×660	0.04 mm×330

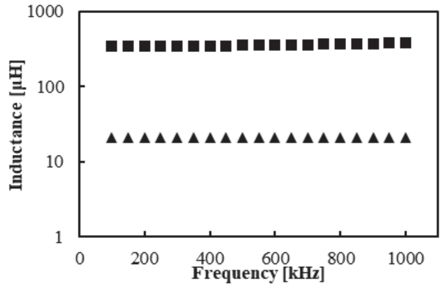

Fig. 7 Self inductances of fabricated coils. ■ indicates for transmitter coil, ▲ receiver

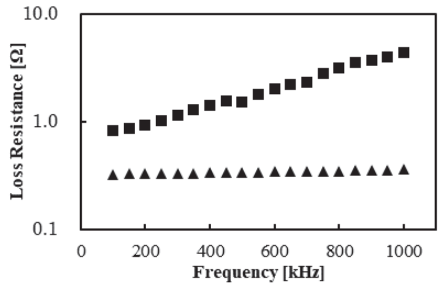

Fig. 8 Loss resistance of fabricated coils. ■indicates for transmitter coil, ▲ receiver

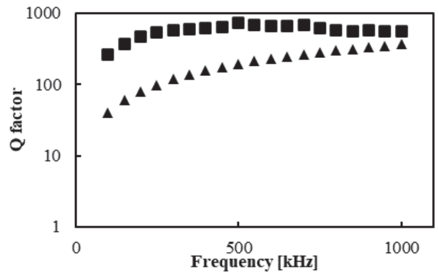

Fig. 9 Q factors of fabricated coils. ■ indicates for transmitter coil, ▲ receiver

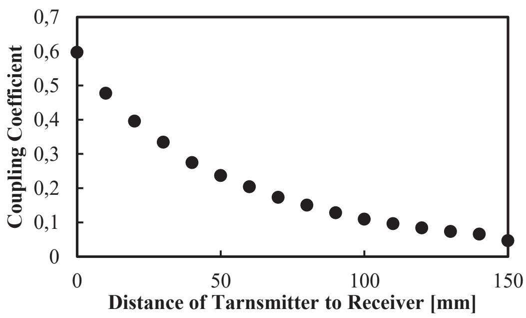

Fig. 10 Coupling coefficients of coils

In magnetic resonance power transmission, the Q factor of the circuit should be large to increase the transmission efficiency. The Q factor of the circuit cannot exceed the Q factor of the coil, so the Q factor of the coil should be as large as possible. Fig. 9 shows the measurement results of Q factor. The Q factor of the transmitter coil reaches a maximum around 500 kHz, while the Q factor of the receiver coil increases as the frequency in the measured frequency range. Transmission efficiencies also depend on by the coupling coefficient k between the transmitting and receiving coils. In the experiment, the transmitting and receiving coils were placed in parallel with the same central axis, and the coupling coefficient was measured at different distances between the coils. The open-short method was used to measure the coupling coefficients. Fig. 10 shows the measured coupling coefficients for different distances between the coils.

B. Power Transmission Experiments

In the magnetic resonance method, the power transmission efficiencies can be increased by increasing the product of the coupling coefficient k between the transmitting and receiving coils and the Q value of the circuit. When kQ is large, two resonance peaks can occur in the frequency characteristics of the circuit, and a change in kQ will vary the frequencies of the two resonance peaks [5]. To increase the load power, it is necessary to match the drive frequency to one of the two peaks. Therefore, in applications where the coupling coefficient varies, it is necessary to change the transmission frequency to follow the change. Recently, a wireless power transmission system using a power oscillator has been studied as a method to automatically adjustment of the frequency [6]. In the experiment, a power oscillator system for the magnetic resonance wireless power transmission was constructed using the coils shown in Figs. 5 and 6. The equivalent circuit is shown in Fig. 11.

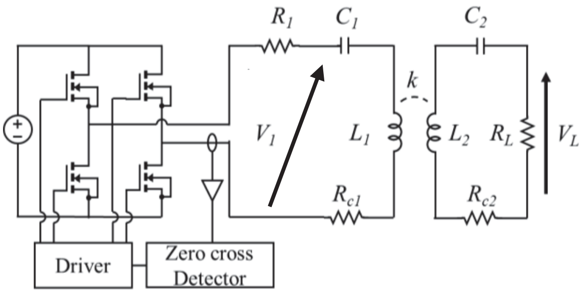

Fig. 11 A equivalent circuit of magnetic resonant wireless power transmission using a power oscillator.

The AC power transmission efficiencies were measured using the circuit shown in Fig. 11. The circuit parameters were shown in Table II.

TABLE II
PARAMETERS OF DEVICES SHOWN IN FIG. 11

Components	Part	Value
Supply voltage	V	2 [Vpp]
Current detecting resistance	R_1	1.0 [Ω]
Inductance of Transmitter Coil	L_1	343 [μH]
Loss resistance of L_1	R_{c1}	0.871 [Ω]
Resonant capacitor of L_1	C_1	4.7 [nF]
Inductance of Receiver Coil	L_2	20.8 [μH]
Loss resistance of L_2	R_{c2}	0.328 [Ω]
Resonant capacitor of L_2	C_2	80 [nF]
Load resistance	R_L	20 [Ω]

The AC power efficiencies were measured at different distances between the transmitting and receiving coils. In order to reduce the switching loss of the power oscillator, 123 kHz was chosen as the resonant frequency of the circuit. Resonance frequencies were measured separately using an external oscillator and current-sensing resistor for each of the transmitter and receiver circuits and found to deviate from the set frequencies. Therefore, we applied a voltage of 123 kHz with an external oscillator, and capacitors were selected so that the phase difference between the voltage and current became zero. The AC power efficiencies were calculated as follows. The voltage on the transmission side was indicated by V_I in Fig. 11. Since the transmission voltage is not a sinusoidal wave, it was measured with an oscilloscope. The oscilloscope was calibrated using a digital multimeter (Agilent 3458A) because the differences between the results in the experiment and the simulation were not ignored. The transmitted AC powers P_1 were calculated with multiplication of the voltage and current on the transmission side by taking the average. The received power P_L was calculated from the voltage V_L at both ends of the load resistance R_L using (1):

$$P_L = {V_L}^2 / R_L \tag{1}$$

The AC power efficiency was calculated from each power by $\eta = P_L / P_I$. A differential probe was used to measure each waveform. Fig. 12 shows the measurement results. The AC power efficiency was 0.44 ~ 0.99 within the measured distance range. The power efficiencies in a practical system should be taken into account of the power consumed by the powers of FETs, drivers, and comparators.

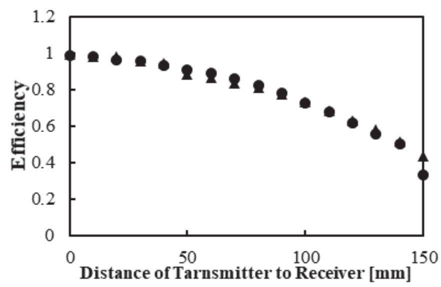

Fig. 12 AC power efficiencies of circuit shown in Fig. 11; experimental values were indicated by ● and Simulation values by ▲

IV. ELECTRICAL CHARACTERISTICS OF SEWN ANTENNAS

In this section, the electrical characteristics of antennas fabricated using sewing techniques and Litz wire are described. The fabricated antenna is targeted to have an impedance Z of 50 Ω and a phase θ of 0° at 144 MHz as the reflection loss is the lowest. Since the size of the antenna needs to be small enough to be sewn into clothing, the antenna should be fabricated using a shape called a fractal pattern, which is relatively small and can be sewn into fabric. Fig. 13 shows Vicsek fractal antennas changing the degrees from first to third order of fractals fabricated using the needle-punch method. The used Litz wires were 0.07 mm × 7 to fabricate the sewn antenna. The return loss was measured using a vector network analyzer in the range of 100 MHz to 200 MHz. The designed target frequency was 144 MHz which is permitted by regulation in Japan. Table III shows the frequency with the minimum return loss around 144 MHz, the impedance, the VSWR, and the size of the antenna fabricated. The second-order fractal antenna had the lowest return loss around -30 dB. The antennas will be intended to fabricate on a shirt. Table III shows the frequency, impedance, VSWR, and size of the antenna fabricated at a frequency when the return loss is minimum for each antenna. Table IV shows the results when wrapped around the human body. The frequency with the minimum return loss decreases and the impedance and the return losses of the second-order and third-order antennas were close to each other. Based on these results, third-order antennas will be suitable for practical use.

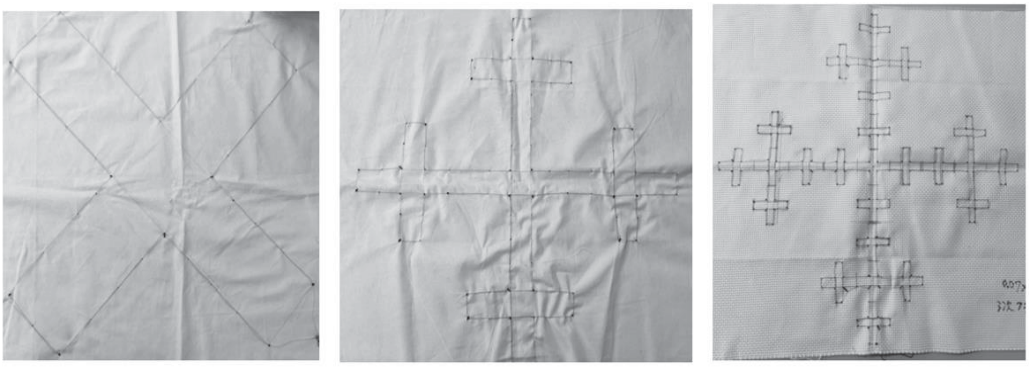

Fig. 13 Fabricated sewn antennas

TABLE III
COMPARISON RESULT FOR EACH FRACTAL ORDER

Fractal order	1	2	3
Frequency at minimum return loss [MHz]	138.9	128.5	128.1
Z at minimum return loss [Ω]	85.0 ＋i1.4	49.6 ＋i1.08	37.7 ＋i1.41
Minimum return loss [dB]	-11.7	-38.7	-13.1
VSWR at minimum return loss	1.701	1.023	1.569
Size [cm]	58×58	45×45	36×36

TABLE IV
COMPARISON FOR EACH FRACTAL ORDER WHEN WRAPPED AROUND THE HUMAN BODY

Fractal order	1	2	3
Frequency at minimum return loss [MHz]	129.9	118.1	114.5
Z at minimum return loss [Ω]	63.2 ＋i0.492	42.1 ＋i0.257	42.3 ＋0.730
Minimum return loss [dB]	-18.7	-21.3	-21.5
VSWR at minimum return loss	1.264	1.188	1.183
Size [cm]	58×58	45×45	36×36

V. DISCUSSION

A characteristic feature of sewn coils is deformable. This is both an advantage and a disadvantage. Advantages include ease of fitting the body when fabricated into shirts, and deformability, especially when fabricated into stretchable fabrics. A disadvantage is that deformation can change the electrical characteristics. The effect of coil deformation is related to various factors such as coil shape, fabric type, etc. This paper describes, as an example, the measurement results of changes in self-inductance and equivalent loss resistance of a coil fabricated by needle-punch on stretchable fabric. The coil used for the measurement is shown in Fig. 14, and a photograph of the coil when stretched is shown in Fig. 15. The coils are nearly circular in shape for ease of stretching. Circular coils are difficult to fabricate using the punch needle method, so they were fabricated in octagons. The outer diameter size of the coils was 15 cm. The number of turns was 15. The coil was measured for self-inductance and equivalent loss resistance using an LCR meter. The self-inductance and equivalent loss resistance were measured using an LCR meter when stretched and not. The measurement frequency range was 100 to 1000 kHz. The stretch distance was 3 cm ("stretch ratio" is 20 %) comparing Fig. 15 to Fig. 14. The maximum difference in self-inductance was 0.84% and the difference in equivalent loss resistance was 0.59%. In this measurement, the changes in self-inductance and equivalent loss resistance were small, even though the length of the coil was varied by 20%. The coupling coefficients will change with coil deformation. Since changes in the coupling coefficient are affected by geometrical arrangements between coils in addition to deformation, measurements and simulations of many patterns are required. Therefore, these effects will be investigated as a future research.

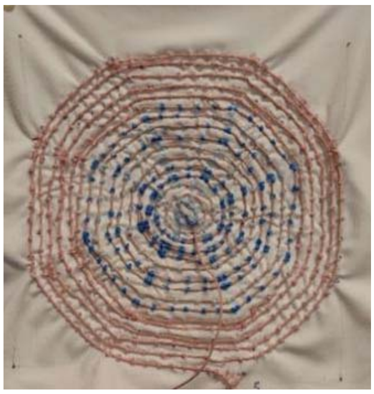

Fig. 14 A coil fabricated with needle-punch method

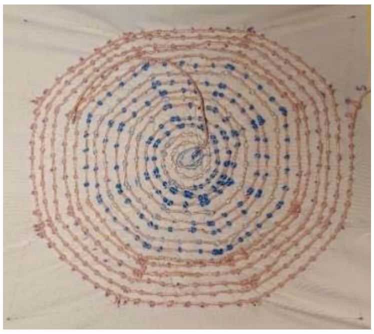

Fig. 15 The coil of Fig. 14 when extended laterally

VI. Conclusions

Coils for magnetic resonance power transmission fabricated by sewing or stitching Litz wires into fabric and wireless power transmission experiments using these coils were described. First, several different methods of sewing or stitching Litz wires into the fabric were described. Second, the results of a power transmission experiment using a prototype system that uses one of the fabricated coils were described. In the system, AC power efficiencies were 0.44-0.99. Antennas fabricated by sewing Lits wire was described. The return loss was -30 dB for an antenna with 2-order Vicsek fractal pattern.

Acknowledgment

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