Embroidered Inductive Strain Sensor for Wearable Applications

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***Abstract*—This paper presents a textile-based, embroidered inductive strain sensor that can be fabricated with standard embroidery processes and aesthetically integrated with apparel and garments fabrics. The sensor consists of two embroidered coupling coils (called coupling planar coils, or CPC) connected in series, and stacked on top of each other. The mutual inductance of this coupling coils pair is determined by the relative positions and displacement between them. This structure can be used as a restorable and repeatable strain sensor for human movements and activities, such as the measurement of respiratory rate. This structure can also form a passive sensor by using the coils as antennas to connect with RFID/NFC chips, such that the sensing information can be extracted wirelessly as phase and amplitude variations by RFID/NFC readers. Experiments demonstrate that a wearable belt embedded with this proposed sensor can be worn on human body to monitor breathing activities reliably under normal wearing conditions. The sensor structure can be fabricated by commercial embroidery machines using off-the-shelf conductive yarns and all the materials are commercially available in large quantity; therefore, it also has good potentials to be commercialized as a low-cost health monitoring system in mass production.**

***Index Terms*—l embroidery, passive sensor, wireless, IoT**

I. Introduction

Over the past few decades, the improvement of quality of life has led to the growing demands for wearable devices for healthcare. However, due to the form-factor limitations [1] [2], conventional devices based on solid-state materials could not integrate seamlessly with apparel fabrics. Therefore, embroidered devices that can be fabricated with conventional embroidery processes will have great potentials in satisfying the requirements of wearable applications. Researchers had already used conductive yarns to build textile-based antennas for UHF RFID tags [3], as well as inductive coils for NFC and energy harvesting [4]. With soft, flexible and breathable structures and materials, embroidered devices have obvious advantages in building wearable health monitoring apparatus:

1) Embroidered sensors provide a non-intrusive method to monitor human movements and vital signs, without interfering normal daily activities.
2) Embroidered devices can be integrated with traditional embroidery processes and have the potential to be cost-effective in mass-production.

Previous studies on smart textiles have been focused on fabricating embroidery-friendly sensors using nano-materials (such as nanowires, silicon nanoribbons) [5] or graphene [6]. The sensors based on those methods have excellent electrical and mechanical properties but their fabrication processes are complex and expensive. Recently, some electronic portable devices are successfully used on real-time human health monitoring field. For example, a new wearable device is designed for human joints training monitoring [7]. A system comprised of four non-contact sensors is presented for long-term monitoring of respiration and pulse [8]. Chu et al. introduced a wearable sensor capable of simultaneously measuring both respiration rate and volume [9]. However, these sensing devices are mainly resistor-based sensors, which require battery to operate. Their application is limited by the size or life of the battery. So, a durable and comfortable sensor that can work passively will be of great value.

In this paper, we introduce an embroidered inductive strain sensor fabricated with off-the-shelf conductive yarns that can be seamlessly woven on a shirt or sweater. The sensor consists of two embroidered and mutually coupled planar coils (CPC) connected in series and stacks on top of each other, of which the mutual inductance is affected by the relative positions between the two coils. Furthermore, when the CPC sensor is served as the antenna for RFID/NFC (ISO14443, ISO15693) transponders, then admittance of the antenna will vary with the displacement, and the sensing information can be extracted wirelessly by the RFID/NFC reader from the variation of the phase and amplitude of the receiving signals.

Several inductive-based displacement sensors had also been proposed and widely used in industrial sensing and automation. However, most of the inductive sensors are PCB-based and lack of flexibility, and their applications are limited. For example, PCB-based rigid sensors are used as mechanical movement detectors in humanoid robotics [10]. A mutual inductive-based sensor is reported in [11], it uses two separated planar spiral coils printed on board and stacked on top of each other separately, one of two coils is stationary, the other is movable (and short circuited). When a displacement occurs between the two coils, the input inductance of the sensor is changed correspondingly. Researchers in [12] proposed an enhanced inductive displacement sensor by applying an additional stationary coil, which increases the sensing range and sensing linearity. However, these sensors all need power supply during sensing and acquisition. Our proposed embroidered

CPC-based sensors have the following advantages:

- The two coils are connected in series, the mutual inductance is doubled compared to separated coils, this structure enhances the sensitivity significantly. The experiments results show that the sensitivity of inductance is better than any other inductive-based sensors with comparable size. (Inductance vary between 3.47 uH to 4.63 uH within 30 mm displacement.)
- When connected to NFC/RFID chips as antennas, the sensor can harvest energy to provide self-sustained power source, which can work perpetually without the need of replacing batteries.
- The fabrication of CPC sensors uses standard embroidered process, which has low manufacturing cost and can be aesthetically integrated to apparels.

The paper is organized as follows. Section 2 introduces the basic mechanism of strain sensor based on CPC structure. Then, the design and fabrication of the proposed strain sensor is described in Section 3. Section 4 discussed experimental results and theoretical analysis, followed by the conclusion.

II. Strain Sensor Using Coupling Planar Coils Structure

A. Mutual Inductance of Series-Connected Inductors

It is well known that the equivalent inductance of two series-connected coupling inductors can be calculated as:

$$L = L_1 + L_2 \pm 2M \tag{1}$$

$$M \propto \frac{d\Phi}{dt} \tag{2}$$

Where L_1 and L_1 are the individual coil self-inductance of the CPC respectively, and Φ is the magnetic flux between the two inductors, which is determined by the geometries as well as the relative positions of the two inductors. We can utilize this property to construct a sensor which is sensitive to the mutual inductance change. From the formulas above, it is evident that the changes of the total equivalent inductance double the variations of the mutual inductance, which means any factors that cause the variations of the mutual inductance can actually be amplified.

B. Coupling Planar Coils (CPC) Pairs

The proposed sensor uses two coupling planar coils (CPC) to construct a sensor with varying inductance, as shown in Fig. 1. When a lateral displacement occurs between coil 1 and coil 2, the mutual inductance between them is altered correspondently. In fact, the mutual inductance M is related closely with the overlapping area of the two coils.

The two coils can be embroidered onto fabric substrates and then stacked on top of each other, with a non-conductive layer inserted in-between them as the insulator. When a force is applied on the two layers in opposite directions, the coils are displaced from each other. The total inductance of this structure will change accordingly, as calculated from Eq. (1).

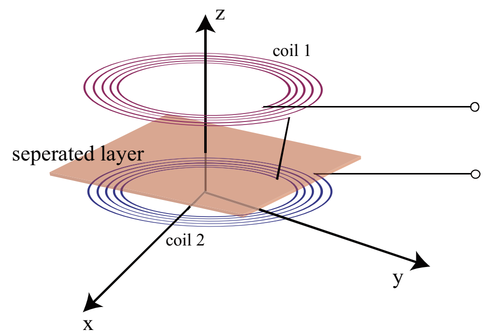

Fig. 1. Embroidered spiral CPC inductor prototypes.

C. Sensor's Repeatability and Restorability

To achieve repeatable sensing and measurement, the sensor structure needs to be restorable when the external force is released. The restorable structure is illustrated in Fig. 2. The two layers that the coils are embroidered on are separated by a layer made of stretchable fabric, and one edge of the top layer is stitched to the stretchable fabric, while the bottom layer is stitched to the stretchable layer with another edge, as shown in the sawtooth line in Fig. 2(a). When a strain is applied, as Fig. 2(b) illustrated, the stretchable layer will be elongated and cause displacement between the two coils. The structure will restore to the original position after the strain is released.

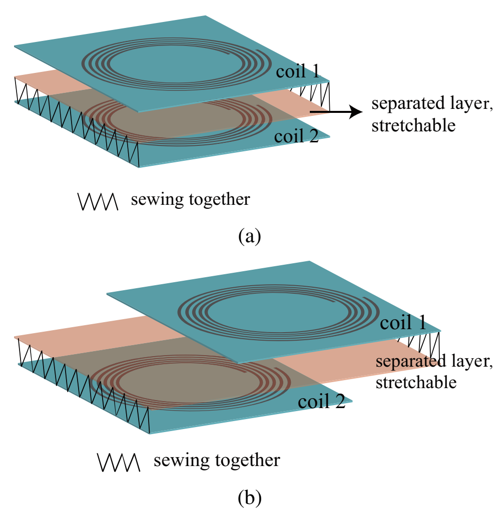

Fig. 2. The restorable structure of CPC.

III. Design and Fabrication

A. Design Consideration

Fabric-based coils have traditionally been regarded as non-practical because of their inherently low Q-factors and the inaccuracy of geometries [13]. To solve these issues, the embroidered CPC design has taken into account several factors: first, the spacing between adjacent turns cannot be too close because embroidered geometries do not have high resolution; second, the spacing and the number of turns N cannot be too large either, otherwise the whole coil area will be too big and not practical. The detailed fabrication process will be discussed in later chapters.

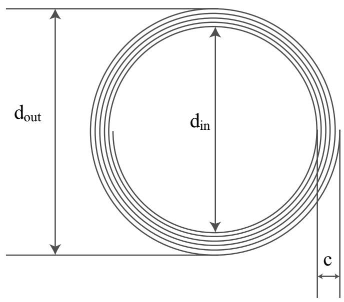

Fig. 3. Circular spiral coil shape.

The embroidered structure is illustrated in Fig. 3. Circular coil geometry is selected because of its higher inductance and lower self-resonant frequency, as compared to square spiral coil inductors. The inductance of the spiral inductor is determined by several geometric parameters and can be estimated using Eq. (3) [14].

$$L_{spiral} = 31.33u_0N^2\frac{a^2}{8a+11c} = 31.33u_0N^2\frac{a}{8+22\rho} \quad (3)$$

Where u_0 is the magnetic permeability of free space ($u_0 = 4\pi \times 10^{-7}Hm^{-1}$), N is the number of turns in the coil, a is the average radius of the coil, where $a = \frac{d_{in}+d_{out}}{4}$, c is the distance between inner turn and outer turn, and ρ is defined as $\frac{d_{out}-d_{in}}{d_{in}+d_{out}}$.

We can use above equation to estimate the geometry parameters of the designed coils derived from known inductance.

B. Prototype Fabrication

A circular spiral CPC design has been embroidered and constructed into strain sensor prototype, as shown in Fig. 4. The inductors have five turns in each spiral coil, where the inner diameter (d_{in}) is 15 mm and the outer diameter (d_{out}) is 25 mm, respectively.

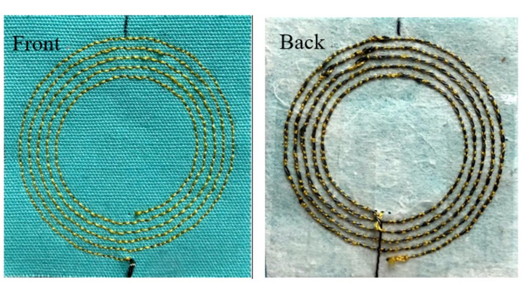

Fig. 4. Fabricated coil geometries of circular spiral coil.

The conductive yarn used for the coil embroidery is a plied bundle of stainless-steel filaments, with a diameter of 0.48 mm, and resistivity of about 9.3 ohm/m.

Embroidery process was performed on a Brother commercial embroidery machine PR670E with a stitch speed of 400 rpm, the minimum stitch length of the machine was 1 mm.

A cotton fabric with a thickness of 0.33 mm is used as the non-conductive substrate for two series-connected coils to form a CPC-based inductive strain sensor. An elastic fabric, with a thickness of 0.5 mm is selected as the stretchable insulating layer between the two coils.

IV. Experiment Results and Discussion

A. Inductance Sensitivity

The CPC-based inductive strain sensor prototype is illustrated in Fig. 5. In order to measure the inductance, the sensor was connected to the Keysight Vector Network Analyzer E5071 through an adapter. The network analyzer is calibrated to the terminals of the adapter to eliminate parasitic elements from the fixture. The measurement frequency is set from 1 MHz to 50 MHz with 201 points.

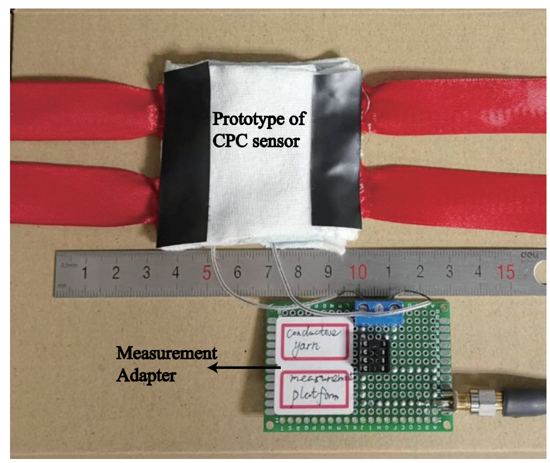

Fig. 5. CPC sensor prototype and measurement adapter.

In order to test the sensitivity to the displacement, one side of the structure is fixed while the other end is stretched laterally (x direction), as shown in Fig. 6. The displacement is changed from 0 to 30 mm, where 0 means resting position without strain, with 1 mm for each stretching step along the x-axis. The total equivalent inductance at the frequency of 13.56 MHz is measured at each stretching step, as shown in Fig. 7, as the displacement increases from 0 to 30 mm, the equivalent inductance changes from 3.47 uH to 4.63 uH. The results demonstrate that the relationship between inductance variation and displacement is quite significant. The CPC structure can be used as an ideal displacement or strain sensor.

B. Human Respiration Rate Measurement with Carrier Wave Modulation

The proposed strain sensor can work passively when being coupled in a magnetic alternate field as transformer coil. The sensing information can be extracted from the reflected wave modulated by the variations of the inductance.

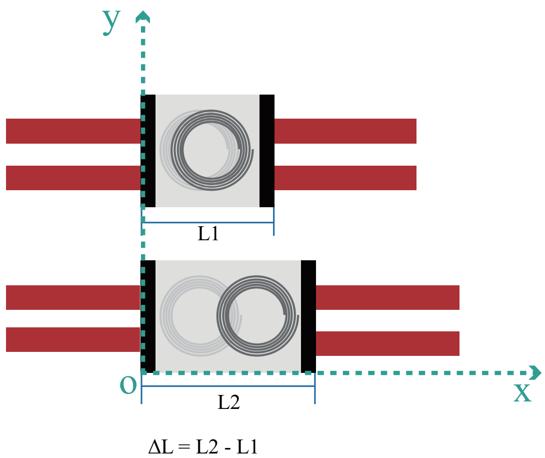

Fig. 6. Setup of the strain sensor.

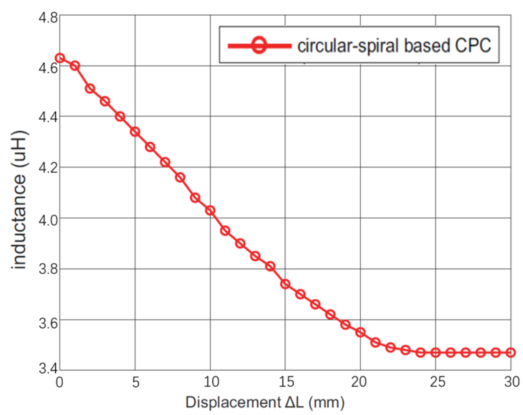

Fig. 7. Inductance measurements of CPC inductor under different displacement.

The sensing scheme is demonstrated in Fig. 8, where the sinusoidal carrier wave of 13.56 MHz is generated from a signal generator (Keysight 33611A). The carrier wave has a peak-to-peak amplitude of 1V and is connected directly to an NFC reader antenna.

To measure the respiration rate on the human body, the sensor prototype is placed around the wearer's chest area on top of a cotton T-shirt with a thickness of about 0.5 mm, as shown in Fig. 9. One NFC reader antenna is placed 10 cm away from the wearer and send carrier waves of 13.56 MHz to the sensor. And another NFC antenna, which is used to receive the signal from the tag, is placed right next to the reader antenna. The receiving antenna is connected to the Keysight oscilloscope DSOS804A to analyze the returned signal from the sensor.

A 30 pF capacitor is connected to the sensor and tune the LC resonant frequency to be the same as the carrier wave. The carrier wave from the transmitter is coupled in the sensor coils, the variations of the inductance modulates the carrier wave back to the receiving antenna and transformed into the amplitude (also phase) modulation of the coupling current inside the reader antenna, which is then measured and displayed in real-time through the oscilloscope, as shown in Fig. 10.

Experiments were conducted while the wearer of the sensor is at rest and breathe normally. Each measurement is conducted for a 20-second breathing cycle.

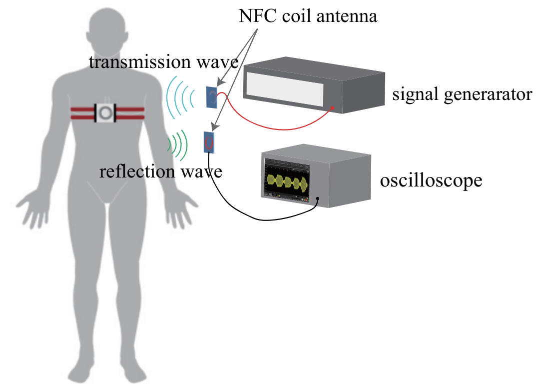

Fig. 8. The scheme diagram of the measurement.

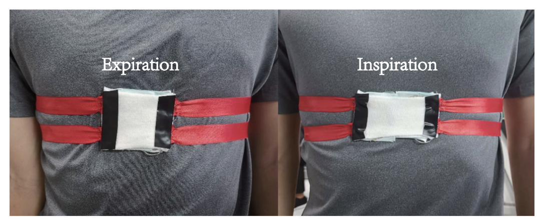

Fig. 9. CPC inductor on human body.

Fig. 10. Coupled voltage in the NFC receiving antenna, showing the modulated signals caused by the human respiration activities. (Left: normal breathing; Right: deep breathing.)

The waveform of the modulated coupling current (shown as the voltage induced inside the receiving reader antenna) captured from the oscilloscope is shown in Fig. 10, which demonstrates that the 13.56 MHz carrier wave is modulated by the variation of the inductance of the sensor. The results from both normal breathing and deep breathing of the wearer are measured, as illustrated on the left side (normal breathing) and right side (deep breathing) of Fig. 10 respectively.

In this experiment, the distance between the CPC sensor and reader antenna is 10 cm. The modulation depth of the sensing

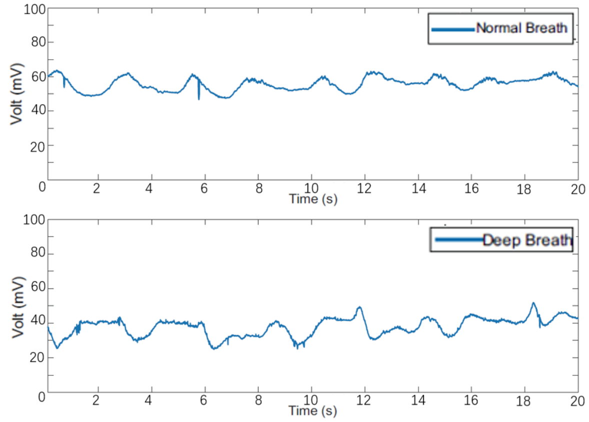

Fig. 11. The human respiratory signals extracted from the sensor.

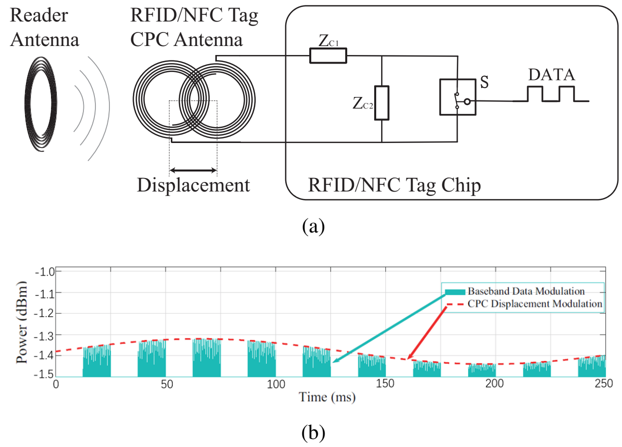

Fig. 12. (a) Working principle of the RFID/NFC based sensing, (b) displacement modulation and demodulation illustration.

signal in the receiving antenna varies from around 50 mV to 65 mV for normal breathing and from around 25 mV to 52 mV for deep breathing. The modulation depth will decrease when the coil antenna is placed further away from human, and will increase when the transmission power is increased.

To better measure the respiration rate, the modulated waveform is further filtered through a three-order Butters filter to remove the carrier wave, as shown in Fig. 11, The wearer's respiration rate can be calculated from the peak to peak period of each waveform.

C. RFID/NFC Based Sensing with Inductive Load Modulation

Although the sensing signal can be acquired by carrier modulation, as demonstrated above, it can only detect one sensor each time, when there are more sensors working at the same time, the reader cannot distinguish between them. To overcome these issues, the sensor can actually work as an RFID/NFC tag and modulate the transponder wave to the RFID/NFC reader antenna through mutual coupling. In this way, RFID/NFC reader not only can detect the modulated sensing signals, it can also distinguish the signals sent out from each individual sensors. Multiple sensors can work simultaneously under the same reader.

Fig. 12(a) demonstrates the working principle of the RFID/NFC based sensing. An RFID/NFC chip is mounted with the sensor. Based on the RFID/NFC protocol, the baseband data stream "DATA" controls the switch S to turn on/off, and consequently cause the chip's equivalent impedance to the antenna to switch between Z_{C1} and Z_{C1}+Z_{C2}. In this way, the phase/amplitude of the coupling EM wave from the tag to the reader is modulated by the data stream.

When the sensor is used as the RFID/NFC antenna, the impedance is also changed with the elongation/displacement of the sensor, in this way, the modulation of the CPC displacement is added on top of the modulation caused by the data stream. The combined modulated coupled EM wave can be illustrated in Fig. 12(b) .

To validate above discussion, an experiment is set up as Fig. 13. A large loop antenna (300*300 mm) is connected to a RFID reader (accordance with ISO/IEC 15693) to serve as interrogator antenna. The CPC coils are mounted with an NXP ICODE SLIX SL2S2002FUD chip to serve as a ISO15693 tag. The tag chip has a typical input impedance equivalent of a 23.5 pF capacitor. The tag is placed 165 mm above the reader's loop antenna.

To detect tag antenna's back-coupled EM signal, a sniffer antenna (size of 150*150 mm) is inserted between the reader antenna and the tag. The sniffer is connected to Keysight Signal Analyzer N9020B to analyze the modulated signal from the tag.

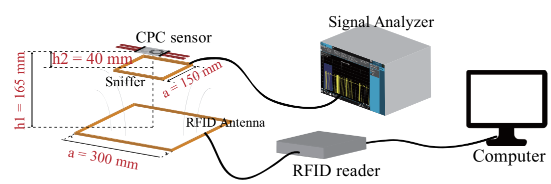

Fig. 13. An NFC (ISO 15693) based displacement sensor using CPC as the tag antenna.

Three scenarios of displacements are tested and measured, corresponding to the displacement of the two CPC coils to 1) fully overlap, 2) half overlap and 3) non-overlap, and imitate the two CPC coils to be stretched from original position to complete separation. Fig. 14 shows the screen captures of the coupled tag signals in time-domain after 2-BSK demodulation by the signal analyzer. The tag-reader coupled signals are marked in the figure. All three screen captures use the same x-y axis scale, so the signals magnitude can be compared in the figures.

From these screen captures, the displacement modulation from the CPC-coils can be clearly visible, i.e. the amplitude of the back-coupled signals changes significantly from full-overlapping to non-overlapping. This variation can be further quantified by measuring the peak-to-peak amplitude of the signals in each scenario, as illustrated in Fig. 15. The zoomed-in curves represent the coupled signals from the tags in three

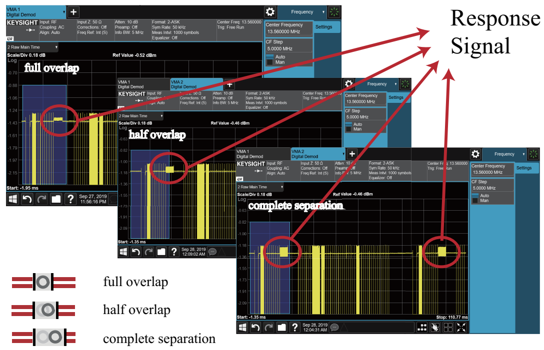

Fig. 14. Measurement results of three states of the sensor.

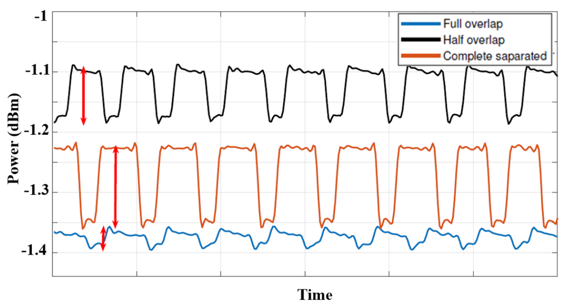

Fig. 15. RFID transponder signal in time domain. (Three states of the sensor.)

scenarios. The peak-to-peak amplitude of non-overlapping is 0.125 dBm, 0.09 dBm for half-overlapping and 0.03 dBm for full-overlapping.

Integrating impedance/antenna sensing with RFID/NFC systems has many advantages. 1) It can support multiple sensors simultaneously, as the RFID/NFC readers can distinguish the coupled/backscattered signals from each individual tag. 2) The sensing mechanism is passive, it does not need any batteries to operate the tags or transmit the signals, it can work perpetually. 3) The tag antennas can be embroidered with conductive yarns and seamlessly and aesthetically integrated with the fabrics of apparels, so the embroidered sensors are the perfect solutions for eTextiles and smart garments.

V. Conclusions

In this paper, we introduced an embroidered inductive strain sensor based on coupled planar coil (CPC) structure. The inductance of the structure is sensitive to the displacement between the two CPC coils and can be used as a strain sensor. When the sensor is used as an RFID/NFC tag antenna, the carrier wave from the RFID/NFC reader can be modulated by the variations of the inductance of the sensor, thus the sensing information can be extracted wirelessly. Experiments demonstrate that the sensor can be seamlessly integrated with apparels and used as a battery-less wearable respiratory rate monitoring device. Furthermore, the proposed sensor can be fabricated with normal embroidery processes using off-the-shelf materials for low-cost mass production.

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