Carbon nonwoven RFID antennas for smart wearable applications

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***Abstract*— In this research, conductive carbon fiber cloth (CFC) is investigated as the conductive material for passive ultra-high frequency (UHF) radio frequency identification (RFID) tags. Laminated between compliant thermoplastic polyurethane (TPU) films, features, such as easy integration on textiles, flexibility, and watertightness can be promoted. Based on four different sample types, the optimum antenna structure with the highest read range is studied. The results show the conductive CFC can be laminated with TPU without damaging the microcircuit and read range of > 100 cm is achieved. The structure of material layering impacts the read ranges: adding additional TPU film inside the antenna can decrease read range loss. To demonstrate a possible application of the prepared RFID tag on clothing, the tag is laminated on a textile and covered with a decorative patch. The results and experiments show possibilities and development paths for cost-effective and washable RFID tags for smart textiles.**

Keywords—Carbon Fibers, Passive UHF RFID, Wearables, Lamination, Flexible.

I. INTRODUCTION

Wearable electronics have enabled the augmentation of our daily life items. In addition to the rigid smart wearables such as earphones and eyeglasses [1], [2], textile-based wearable electronics have been used for smart clothing and furniture [3], [4]. Smart clothing with embedded electronics has enabled new functions on our bodies, for example, shirts with stress measurement [5], diapers with temperature, wetting, and respiration sensors [6], and breathing frequency measuring face masks [7]. Most of the applications rely on wireless transmission, which requires antennas.

Antennas are used in smart clothing for communication [6], sensing [8], and tracking [9]. The antenna size, structure, and materials depend on the applications and manufacturing methods [6], [8], [10], [11], [12]. Bluetooth technology is used for data transfer in miniaturized Internet of Things (IoT) modules. For example, ~ 23 mm * 23 mm size rigid printed circuit board (PCB) Arduino Nicla Sense ME modules have 6,5 mm * 6,5 mm size ANNA-B112 Bluetooth modules with an internal antenna [13], [14]. The powerful and miniaturized IoT modules enable embedding smart functions in an environment [12], but still, their rigidness and need for a battery hinder their integration into smart clothing.

For sensing and tracking of smart clothing, battery-less passive ultra-high frequency (UHF) radio frequency identification (RFID) tags are used [8], [9], [10], [11]. RFID tags include an antenna and an integrated circuit (IC), with a simple structure that allows mass production and low price of tags [15]. Also, tags without IC are studied for even lower unit prices [16]. For example, with PCB manufacturing methods, cost-efficient flexible etched copper antennas are possible (unit price 1.6 cents) [15]. In smart clothing, more robust and textile-compatible antennas are needed, for which textile-based antennas are suggested.

Textile antennas are made with conductive fibers that are used in yarns and fabrics [17]. Knitted, woven, and nonwoven textile substrates are also coated with copper, silver, and nickel for conductivity [17], [18]. In RFID applications, yarns from silver-coated polyamide (PA) fibers are the most versatilely used, for example, in knitting [19], weaving [20], embroidering [8], and punch-needling [11]. Also, PA fabrics are coated with conductive metal layers [21]. In addition to metals, RFID antennas are made from more environmentally friendly and cost-efficient carbon-based materials. Carbon materials are especially applied for new types of RFID tags, where carbon ink is dispensed on the 3D-printed substrate [22], and carbon nanotubes (CNTs) are accumulated to antenna-shaped patterns [23].

In this study, inherent conductive carbon fiber cloth (CFC) is experimented as an RFID antenna material. The widely used nonwoven CFC material in the composite industry has already been applied for stretchable electronics, which together with thermoplastic polyurethane (TPU) matrix, enables deformable structures [24]. The textile-like CFC antenna layer, a commercial IC, and encapsulating TPU substrates are combined for RFID tags that are easily integrated into textiles.

II. METHODS

For an antenna design, the well-studied RFID antenna design is used (Fig. 1) [11], [22], [25]. Antennas are based on nonwoven cloth, which consists of ~ 2.54 mm long polyacrylonitrile (PAN) carbon fibers (800020i by APC Composites) (Fig. 2a) [26]. The thickness of carbon fiber cloth (CFC) is ~ 150 µm. CFC is encapsulated between two 100 µm thick thermoplastic polyurethane (TPU) films

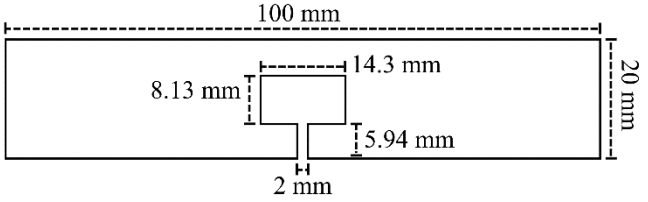

Fig. 1. Dimensions of RFID antenna.

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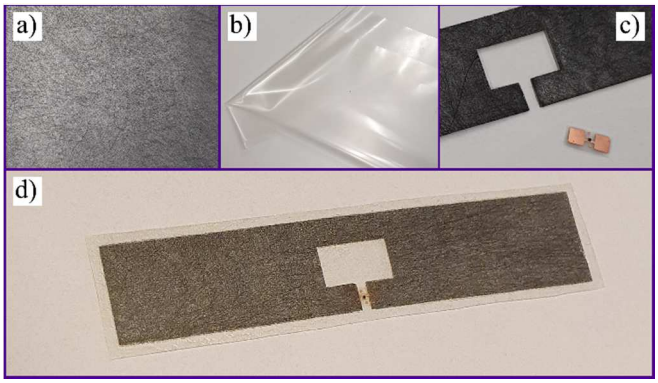

Fig. 2. Antenna materials and components: a) conductive CFC, b) deformable TPU film, c) a RFID chip and its placement area, and d) ready encapsulated antenna.

(Platilon U 4201 AU, by Covestro) (Fig. 2b). In the fabrication, first, CFC is laser-cut and laminated on the TPU film (Fig. 2). At the lamination of another TPU film, between the CFC and TPU film, IC UCODE G2iL (by NXP Semiconductors) is placed bottom side up on the CFC (Fig. 2c) [27]. The lamination is done by ironing with the highest temperature setting (> 200 °C). After lamination, an extra TPU film of a ready antenna is cut, leaving a ~ 2 mm laminated edge over the CFC for encapsulation of the conductive CFC (Fig. 2d).

In addition to the basic lamination of the antennas in sample series 1, the antenna structure and use of adhesives are further studied (Table 1). In series 2, RFID chips are adhered to CFC with conductive silver adhesive Shieldokit 3980 (by Holland Shielding Systems BV) before the lamination to decrease the contact resistance of CFC [28]. In series 3, the CFC layer consists of two CFCs (combined thickness ~ 300 µm) to decrease the resistance of the CFC layer [24], which can increase the range of the antenna [15]. In series 4, additional spacer TPU film is laminated between CFC layers to improve the bonding and compression of CFCs. Finally, to demonstrate the smart wearable applications, the series 4 antenna is laminated on textile.

Sample series have five parallel samples. Before the lamination, the resistance of the laser-cut CFC layer of antennas is measured with a Fluke 111 multimeter. The measurement is done by pressing probes on the contact areas of an RFID chip. After the lamination, the thickness of the samples is measured with a vernier caliber.

Despite previous experiments with CFC [24], the laminated tags are in the proof-of-concept stage. Therefore, a Thingmagic Mercury6 RFID reader system is used for functionality evaluation of the tags. The measurement system was connected with cables to both a circularly polarized reader antenna and a laptop. The study was carried out in European frequency standards (865.6 MHz -867.6 MHz), and the transmitted power was set to 28 dBm. All tags were measured first one by one taped on a foam trestle, and secondly, one by one taped on a human forearm (Fig. 3). In both measurements, the tags were exposed to electromagnetic radiation from the same direction.

TABLE I. RFID TAG SAMPLE SERIES

Sample series	Number of CFC layers	Fixture method of RFID chip	Spacer TPU film between CFC layers
1	1	Lamination	no
2	1	Conductive adhesive	no
3	2	Conductive adhesive	no
4	2	Conductive adhesive	yes

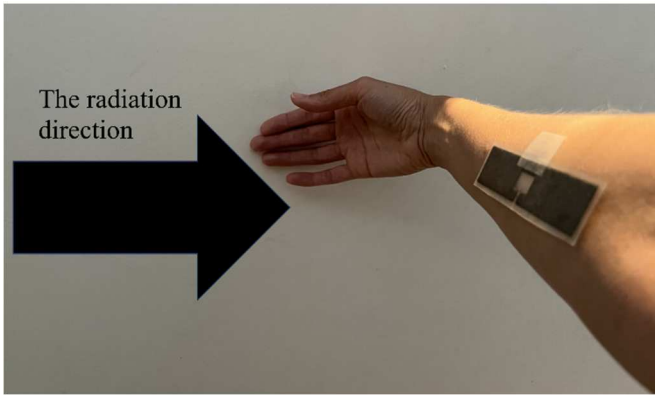

Fig. 3. The measurement position. The reader antenna was placed to the right side, thus the black arrow resembles the radiation direction. The tag was taped onto the forearm with office tape.

III. RESULTS AND ANALYSIS

Different structures and manufacturing methods of sample series affect the measured average resistance and read range in office settings (both on a plastic foam and the skin) of the samples (Table 2). Moreover, the average thickness of the sample series 1-4 is 0.30 mm, 0.31 mm, 0.39 mm, and 0.46 mm, correspondingly.

The sample series 1, 2, and 4 have a single CFC layer (Fig. 4), and the average resistance varies between ~ 61 Ω - 66 Ω, which is a mild variation when the random orientation of carbon fibers in the CFC is considered. With two layers of CFC, the resistance decreases ~ 43 %. During the manufacturing methods of the tags, notably, two samples of the samples series 3 and 4 are broken. This implies that the lamination process of antennas with thicker build-ups needs to be improved. For example, the design of sample series 1 is more planar than the design of sample series 4 (Fig. 4).

TABLE II. AVERAGE RESULTS OF THE SAMPLE SERIES

Sample series	Resistance (Ω)	Read range on foam (cm)	Read range on skin (cm)
1	61	79	54
2	61	81	56
3	35	105	71
4	66 and 64	99	77

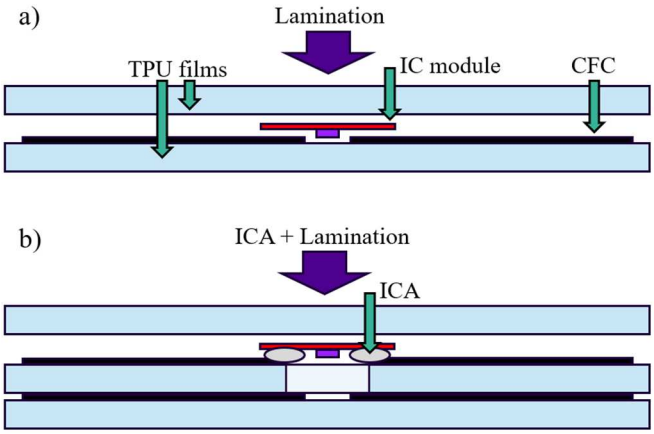

Fig. 4. Comparison of sample series 1 and 4: a) a planar design of sample series 1, and b) a multilayered design of sample series 4.

In Table 2, the different sample designs affect the average read range of the samples. As seen from samples series 1-2, the use of ICA can have non-existent or a minor effect on the read range on the trestle or skin. The results show that the ICA does not affect on the functionality of the antenna, i.e., but still, the ICA may have an effect on the mechanical stability of the structure. In the mass production of antennas, ICA increases costs, which makes it worthwhile to leave the adhesive out of the structure. In the future, the long-term stability of the antenna on clothing will be studied.

The sample series 3 has twice the amount of conductive material than the sample series 1-2, and by the lamination of CFC layers on top of each other, the overall conductivity is improved considerably. Compared to the sample series 1, the double CFC layer has ~ 40 % lower resistance and ~ 30 % higher read range on the trestle and skin. However, also the thickness of the antenna increases by 30 %, making it stiffer and increasing the angle of curvature. For higher conductivity and flexibility, a nonwoven cloth from silver-coated carbon fibers or PA fibers can be considered.

The sample series 4 has also twice the amount of CFC than the sample series 1-2, which is seen as higher read range results. Because the CFC layers are separated elsewhere than at the connection area of the RFID chip, the read range on foam is slightly smaller than with sample series 3. However, the extra TPU film between the CFCs isolates the antenna better from the skin, which improves the read range on the skin.

Compared to similar types of RFID antenna prototypes, the results around the 100 cm read range are promising. The antenna design with the same read range has been manufactured via 3D printing with a conductive filament [25]. The range can be increased by using a separate conductive material in the 3D printing. For instance, by applying a conductive ink on a 3D-printed TPU substrate, over 300 cm read range is achieved [22]. Additionally, solely by using textile methods, such as punch-needling, a read range between 60 cm – 130 cm is possible [11]. With the laminated CFC layer between TPU films, thinness (> 0.5 mm) and textile integrability can be promoted. Thus, finally, an application of fabricated antennas is demonstrated by laminating an antenna on a textile with a commercialized self-cuttable iron-on glitter sheet (Fig. 5).

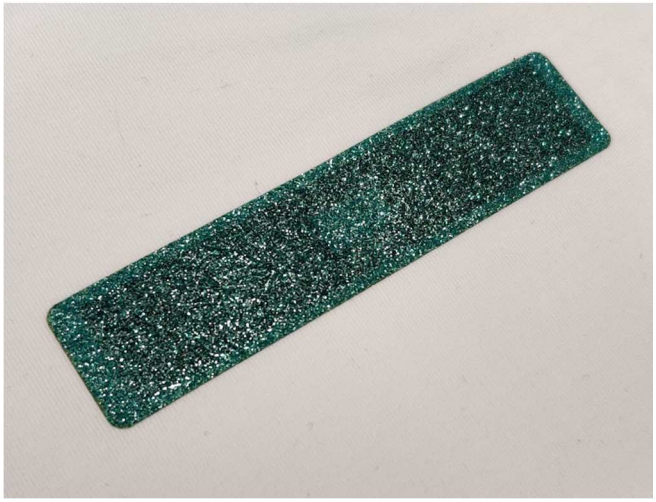

Fig. 5. Embedded flexible RFID antenna under a glitter patch on knitted fabric.

In Fig. 5, between the knitted fabric and the glitter patch, the laminated RFID antenna is somewhat visible. Because of the ~ 2 mm edge of laminated TPU around the CFC layer, the waterproofness and washability of the antenna are improved. Furthermore, encapsulating the passive UHF RFID tag between layers of TPU film in the lamination process provides protection to the IC + copper pad -structure of the RFID chip, potentially offering a feasible protection against copper abrasion.

As the passive UHF RFID technology has the potential to create a seamless interconnection between humans and the surrounding world, these TPU and CFC passive tags are one realization that could be used in fashion technology for hidden electronics. Moreover, as originally the CFC is used in composite and industrial applications (i.e. boat coating and such), more studies are needed on whether this fabrication methodology offers a feasible method for unobtrusive identification in a wide range of sectors.

In the future, the development of the antennas will be continued in three ways. First, simulations are made, where also different radiation directions to the antennas are considered. Secondly, new antenna designs are fabricated, which have additional TPU film and CFC layers to improve the insulation and conductivity of antennas, correspondingly. Thirdly, wearable studies will be taken further, and washability and usage demonstrations of the antennas will be made.

IV. CONCLUSIONS

Easily integrable and cost-effective RFID tags have a major role in the making of textiles smart. In this work, manufacturing, and system-level testing of new antennas from the stretchable electronics materials were investigated. The results show that the antenna with the higher amount of conductive CFC has the higher read range (> 100 cm). Moreover, the additional layer of TPU film in an antenna isolates the antenna better, which increases the read range on the skin. The results and tested antenna structures present possibilities and further research considerations for the TPU film and CFC antennas, from which a demonstrator is made.

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