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PAPER

Material Selection and Design Methods for Flexible RFID Tag Antenna

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ABSTRACT

In recent years, advancements in flexible printed electronics have significantly propelled the development of wearable devices, especially in areas of integration, comfort, and streamlined manufacturing. By incorporating electronic components and conductive coatings onto flexible substrates, circuits gain enhanced flexibility and some degree of stretchability. Among these circuits, radio frequency identification (RFID) tag antennas have emerged as a focal point in wearable device communication due to their adaptability in power selection and their compatibility with printed circuit technologies. When designing flexible and stretchable RFID tag antennas using printed electronics, two critical factors need to be addressed. The first is the antenna's structural design, which must account for varying environments and usage contexts. The second is the development of the antenna prototype, involving the selection of conductive coatings and flexible substrates, as well as the printing processes and performance evaluation standards. This paper will explore common conductive coatings and substrate materials used in flexible printed electronics, along with the design methods of printed tag antennas for wearable applications. Lastly, a novel approach is proposed in which the flexible and stretchable RFID tag antenna itself functions as a strain sensor for posture or pressure detection. Unlike conventional strain sensors, this design eliminates the need for additional communication modules, offering a simplified structure that can be easily printed onto clothing, thereby streamlining the production process.

KEYWORDS

radio frequency identification (RFID) tag, nanomaterial for printing, antenna design, flexible and stretchable circuit

1 INTRODUCTION

Radio frequency identification (RFID) is a technology that enables contactless data communication using radio waves, allowing for the identification and tracking of objects via RFID tags [1] [2]. In wearable devices, RFID offers several distinct advantages over other communication methods such as Bluetooth, Wi-Fi, or

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cellular networks. These advantages include low cost, passive tags that do not require batteries, simple designs with strong waterproof capabilities, and precise tracking [3]. A complete RFID system typically consists of three components: the tag antenna, reader antenna, and RF front-end processing circuit. The reader continuously emits an electromagnetic field through the reader antenna, and when the tag antenna comes within range, information is exchanged through modulation techniques like inductive coupling or backscattering. After receiving the encoded data, the reader extracts the required information using modulation and demodulation circuits. [4]

Flexible printed electronics further enhance RFID tag antennas by offering additional benefits. One advantage is the high level of integration, making them well-suited for wearable devices due to their excellent flexibility and even stretchability. By using various substrate materials, RFID tags can achieve different mechanical properties, allowing for integration into diverse environments. Another advantage is the environmentally friendly manufacturing process, which allows for simple mass production. Unlike traditional circuits that rely on chemical etching, flexible printed electronics use pre-formulated conductive inks to directly print circuits onto the substrate, making the process efficient and fast. [5] [6] Furthermore, some specialized ink formulations enable rapid recycling, helping to reduce environmental impact. This technology has garnered significant attention in recent years for these reasons. [7]

This paper will explore the conductive inks, substrate materials, and antenna structures used in the design of flexible and stretchable RFID tag antennas. By selecting appropriate materials, a strain sensor array system based on RFID for posture detection will be simulated and designed.

2 MATERIAL SELECTION

In printed flexible electronics, two key material components are conductive ink and substrate materials. The antenna made from conductive ink is responsible for converting electromagnetic signals into electrical currents. To ensure that the antenna achieves high gain, efficiency, wide bandwidth, and other essential characteristics, the conductive ink must exhibit excellent and stable conductivity, appropriate viscosity for printing, and suitable mechanical properties, such as Young's modulus and Poisson's ratio, after solidification. The wide range of substrate material options also distinguishes printable RFID antennas from traditional antennas. By selecting different substrates based on application needs, the antenna's size can be significantly reduced while maintaining properties such as flexibility, bendability, and stretchability. Additionally, the simplified printing process enables the potential for large-scale production.

2.1 Conductive ink

Currently, the three most common types of conductive inks are metal-based, carbon-based, and conductive polymer inks. [5] Each type offers distinct advantages in terms of printing adaptability, conductivity, synthesis complexity, and cost. As a result, hybrid inks that combine these materials have emerged, aiming to maximize strengths while minimizing weaknesses.

Metal-based conductive inks generally consist of three components: a solvent, additives, and metal fillers. Polymer additives like polyurethane (PU) and polyvinyl pyrrolidone (PVP) are commonly used to adjust viscosity and enhance the formation of conductive networks [8]. Metal fillers, which serve as the primary conductive element, are often nanoparticles, nanowires, metal complexes, or liquid metals. The most frequently used metals include gold, silver, copper, and liquid metals composed mainly of gallium and indium alloys. Depending on the formulation, metal-based conductive inks can be divided into two categories: nanoparticle or nanowire suspensions and solutions of metal-organic precursors or compounds. The suspension form provides excellent conductivity due to the abundance of conductive particles, but its long-term stability can be problematic, and printing issues such as clogged needles may arise. Metal-organic compound solutions, on the other hand, offer superior printing performance thanks to various additives, though this typically results in increased resistivity.

Another way to avoid the possibility of traditional metal nanomaterials clogging the needle is to use liquid metal. Gallium indium alloy, due to its liquid characteristics and low volatility, has been verified to have biocompatibility and is widely used in wearable devices. Its liquid characteristics and excellent conductivity enable it to form a new corresponding conductive network on its own when stretched, ensuring that the resistance remains basically unchanged [9]. Even liquid metal pretreated with PVP can be added to Eco-flex, which can increase viscosity for printing while ensuring high conductivity and also achieve excellent elastic performance. [10]

Carbon black and graphite, as the most traditional carbon conductive materials, have good conductivity, very low prices, and certain printing adaptability. And due to their different sizes, they are often mixed together for better conductivity. Recently, research has found that the different ratios of the two can affect the performance of ink [11]. However, their significant difference in conductivity compared to metals and poor mechanical properties have led to them receiving less attention in recent years.

In order to solve the problems, carbon nanotubes and graphene have quickly become research hotspots as new carbon conductive materials. Their extremely small size brings various advantages in physical properties, such as high strength, better conductivity than carbon black and graphite, and better flexibility at the macro level. Although additional treatments such as ultrasound or chemical treatment are required for them to disperse well in the solution, it can be proven that they can be used for printing wearable electronics [12]. Bougot et al. used sodium dodecyl sulfate (SDS) and N-methyl-2-pyrolidone (NMP) solutions to prepare carbon nanotube suspensions and completed the printing of RFID antennas [13]. Bohan Zhang et al. used graphene assembly film to obtain a UHF RFID antenna with excellent conductivity $(1.6 * 10^6\ S/m)$ graphene [14]. And even high-transparency RFID tags can be achieved by generating graphene through CVD [15]. Although research on new carbon nano conductive materials has made significant progress, overall, carbon materials have poor conductivity compared to metal materials and are not easy to print, which cannot be ignored.

In addition to metal-based inks, polymer-based alternatives, such as poly (3,4-ethylenedioxythiophene) doped with polystyrene sulfonate (PEDOT:PSS) and polyaniline (PANI), are also widely used. PEDOT:PSS, in particular, has shown excellent biocompatibility, making it a promising candidate for wearable device applications. It is also common to synthesize new conductive polymers by adding metals or carbon-based materials to some polymers. Rajveer Mudhar et al. attempted to 3D print recyclable RFID antennas by adding carbon black nanoparticles to polylactic acid (PLA) [16]. Table 1 shows feature of various conductive inks.

Table 1. Comparisons between different kinds of conductive inks

Types	Advantages	Disadvantages	Examples in RFID
Metal material	- Excellent conductivity - Good durability and mechanical properties	- High cost - Opaque - Some materials such as copper may rust - Nanowires or particles may cause clogging of printing needles	Gold [17], [18], [19]
			Silver [20], [21], [22]
			Copper [23], [24]
			Liquid metal [7], [25], [26]
Carbon material	- Low cost - Good mechanical properties for CNT and graphene	- Less conductive than metal - Extra surface treatments for good dispersion	carbon nanotube [27], [28]
			Graphene [14], [15], [29], [30]
Conductive polymers	- Good printing characteristics - Can be customized by selecting polymers for blending according to specific needs	- Less conductive than carbon - Complex production	PEDOT::PSS [31], [32]
			Others [16]

2.2 Substrate materials

In order to ensure good radiation and reception efficiency of the antenna, an ideal substrate needs to have a low permittivity, small dielectric loss, and good high-temperature conductivity. The degree of adhesion between the substrate and ink is also crucial in the selection of flexible substrate materials for printing. For stretchable substrates, factors such as tensile fracture strain and elastic recovery rate are also important considerations. The most common substrate materials include polymers, metal foils, paper, and fabrics. [33] The advantages and disadvantages between them are shown in Table 2.

Table 2. Comparisons between different kinds of substrate materials

Type	Advantages	Disadvantages
Metal foil	- Heat resistant - Shape stable - High durability	- High cost - Rough surface for printing - Not biodegradable - Conductive
Polyimide (PI) [34], [35]	- Wide thermal stability - Good flexibility and mechanical properties	- Opaque
Polyethylene terephthalate (PET) Polyethylene naphthalate (PEN) [36], [37], [38]	- Good flexibility and mechanical properties - Transparency - Good resistance to most solvents	- Low thermostability - Not stretchable
Polydimethylsiloxane (PDMS) [39], [40]	- Stretchable and flexible - Low Young's module - Easy to mold	- Highly hydrophobic, extra pre-process on the surface is needed for the good adhesion
Thermoplastic polyurethane (TPU) [41], [42], [43], [44]	- Highly stretchable - Low Young's module - Hydrophilic property makes it have a good adhesion with some inks	- Relatively poor thermal stability - The surface is not smooth enough
Paper [45], [46]	- Cheap	- Not water-resistant - Low durability
Fabric [47]	- Easy to integrate with clothes - Good breathability and comfort - Can be customized according to needs	- Sensitive to the environment - Poor electrical performance

3 DESIGN OF TAG ANTENNA

Although tag antennas are divided into three categories: active, semi-active, and passive, in the application of wearable devices, passive is one of the unique advantages of RFID as a communication method, and active RFID usually means higher frequency bands and stronger radiation. Therefore, this section mainly introduces non-source RFID tag antennas. Passive tag antennas are divided into two types: chipped and chipless. [48], [49]

The development of traditional chipped RFID technology is relatively advanced. Compared to chipless RFID, chipped RFID can transmit more data and supports both reading and writing capabilities. The typical design process is as follows: 1. Determine the corresponding operating frequency bands, such as low frequency (125 KHz, 134 KHz), high frequency (13.56 MHz), ultra-high frequency (433 MHz, 860–960 MHz), and microwave frequency bands (2.45 GHz, 5.8 GHz). As the frequency increases, transmission distance extends, data transmission rates increase, and the amount of information transferred grows. However, higher frequencies also reduce penetration ability and increase energy consumption. The antenna size must be adjusted accordingly to meet the specific frequency requirements. 2. Select the corresponding chip. There is a wide range of RFID tag chips available, each with different memory capacities, sensitivities, and operating frequencies. The choice depends on the application requirements. Due to the varying input impedances across different chips, an additional impedance matching circuit is often required. Common RFID antenna impedance matching techniques include inductive coupling, capacitive coupling, loading bars, and T-shaped matching circuits. The T-matching structure is advantageous because it allows for some adjustment of both reactance and resistance. However, despite this benefit, the small input resistance of most available chips necessitates further adjustment of the antenna's main radiating element. The most common approach is to add a load at the antenna's end to achieve impedance matching while simultaneously boosting antenna gain.

Chipless RFID tags typically transmit limited information, and common structures can be simplified to the mode of LC resonant circuits. Although the most successful chipless RFID tags currently available on the market are mostly based on the principle of surface acoustic waves, and there are some RFID tags made using SAW to achieve temperature and strain sensing functions [50] [51], due to the difficulty of piezoelectric materials being compatible with tensile properties, they usually do not have a good gauge factor and excellent tensile performance. Therefore, this structure is currently not suitable for stretchable RFID tags. Therefore, the common stretchable tag antenna structure is still winding microstrip lines combined with flexible substrates. Soo Hong Min et al. achieved an RFID-based strain sensor with a gauge factor greater than 0.5 by printing a conductive ink composed of silver nanoparticles and carbon nanotubes onto a polydimethylsiloxane substrate to form finger capacitors and single-turn coils as inductive structures [52]. The Lan Chen team utilized the high q-value and compact bandwidth of U-shaped resonators to design a resonant structure with multiple resonant frequencies in order to achieve information encoding for chipless RFID [53].

4 RESULTS

For tag antennas, circular polarization is generally not considered as it complicates the structure and increases costs. Therefore, a simple half-wave dipole antenna is the preferred structure for RFID tags that require mass production. Due to the fact that the frequency of UHF tags is usually 912 MHz and the half-wave size is still large, winding lines are usually used to reduce the antenna size. By increasing the bending index of the two arms, antennas will be greatly reduced in a single dimension while also bringing inductance to match the input impedance of the chip. The specific model and size parameters are in Figure 1:

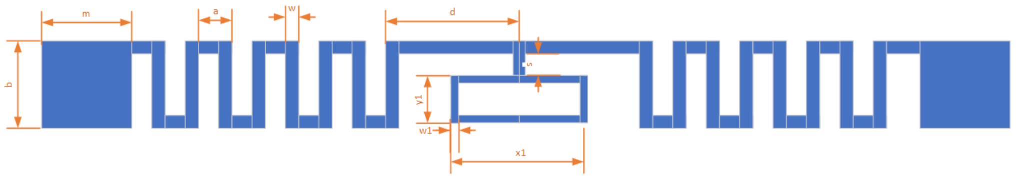

Fig. 1. Design of UHF RFID antenna with winding lines and T-matching

As mentioned earlier, first roughly adjust the resonant frequency of the antenna. For this structure, the most important parameters affecting the resonant frequency are a and b. After calculating the approximate size range using half wavelength, the calculated values are used as initial values for optimization. Although the bending index and parameters a and b can be composed in various ways to achieve the specified resonant frequency, in order to simplify the design process and for the application of strain sensors, the value of b is fixed at 10 mm. Perform parameter sweep analysis on the value of a. The relationship between the input impedance of the antenna and the value of a is shown in Figures 2 and 3. It can be observed that as the value of an increases, in addition to affecting frequency offset, it also has a significant impact on the imaginary part of impedance, while the real part changes relatively small. This is mainly because the value of a determines the distance between the bent fingers, thereby affecting the inductance of the antenna. In fact, the impact of b value changes on the antenna is very similar to that of value a, which can also cause frequency offset and changes in the imaginary part. The substrate is made of 1 mm thick TPU film with a dielectric constant of 5, conductivity of 10^{-13} S/m, Poisson's ratio of 0.49, and Young's modulus of $1.2 * 10^5$ Pa. After scanning the parameters, the ideal value of a is between 1.5 and 1.7 mm.

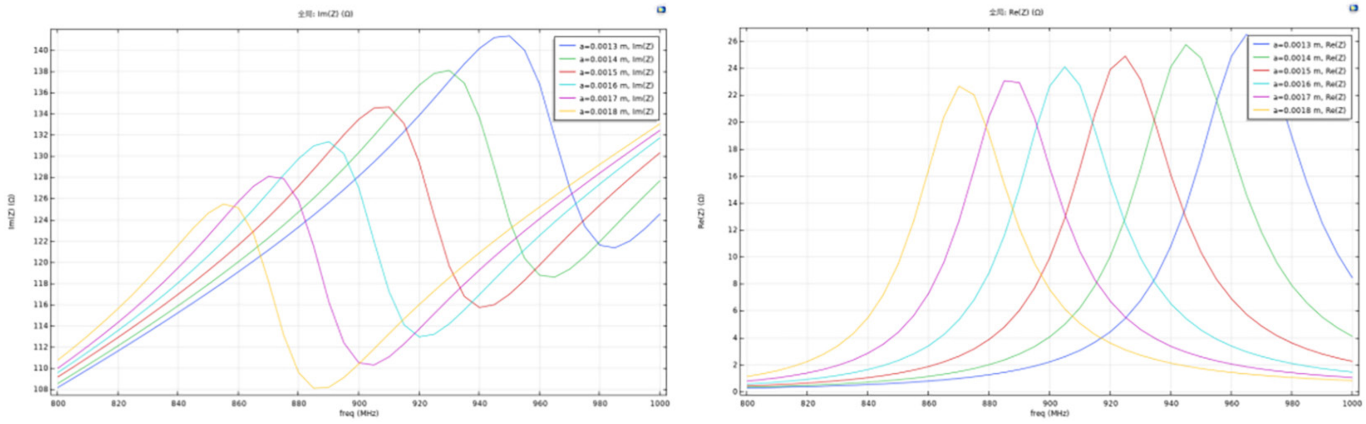

Fig. 2. Diagram of antenna input impedance variation with value a (left is the reactance while right is the resistance)

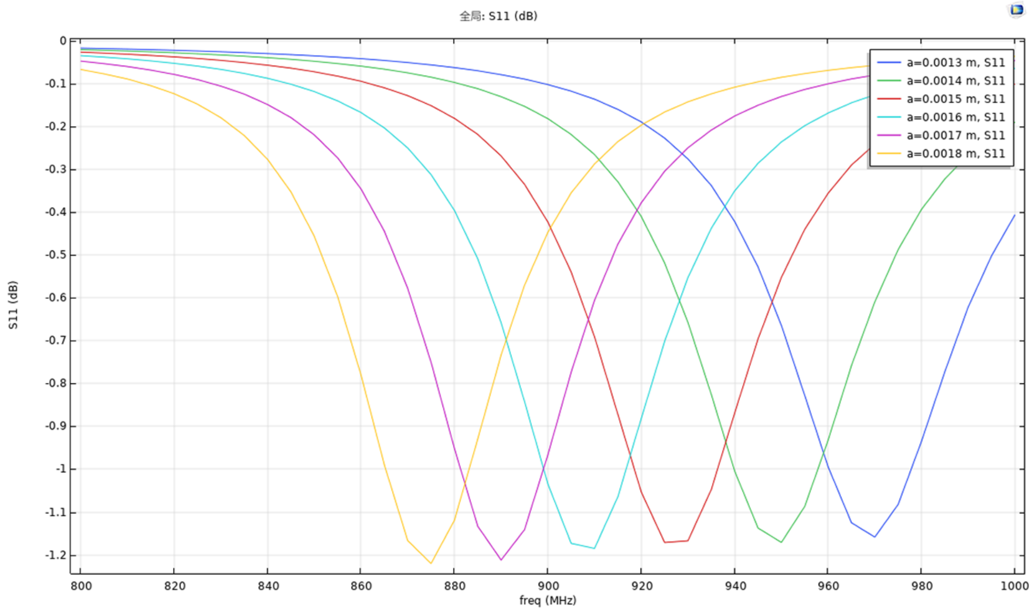

Fig. 3. S11 of antenna when port impedance is not matched

After adjusting the operating frequency, it is necessary to match the port impedance. W and w1 will have the most direct impact on impedance matching; although their parameters can be different in design, considering the simplification of production, they should be made the same in design. For a T-shaped structure, its input impedance is depicted as below:

$$Z_{in} = \frac{2Z_t(1+\propto^2)Z_a}{2Z_t+(1+\propto^2)Z_a}$$

While Z_a is the original impedance of the antenna, and for Z_t:

$$Z_t = jZ_0\tan\left(\frac{kx1}{4}\right)$$

While $Z_0 \approx 276\log\left(\frac{y1}{\sqrt{0.25w*8.25w_1}}\right)$. Therefore, by adjusting the values of s, x1, and y1, the input impedance of the antenna can be adjusted to a certain extent. After optimization, the antenna parameters obtained are as in Table 3:

Table 3. Parameters of the antenna (mm)

a	b	w	w1	d	s	m	x1	y1
1.6	10	0.5	0.5	9	1	10	5	6.5

The antenna is perfectly matched at 930 MHz, with an S-parameter of –33.068 dB. The directional diagram is shown in Figure 4 Based on Figure 5, it can be seen that the antenna has a very high sensitivity to the value a. When the value a changes, the operating frequency changes significantly due to the change in its inductance value. The reader can detect this impedance change to achieve the function of detecting strain.

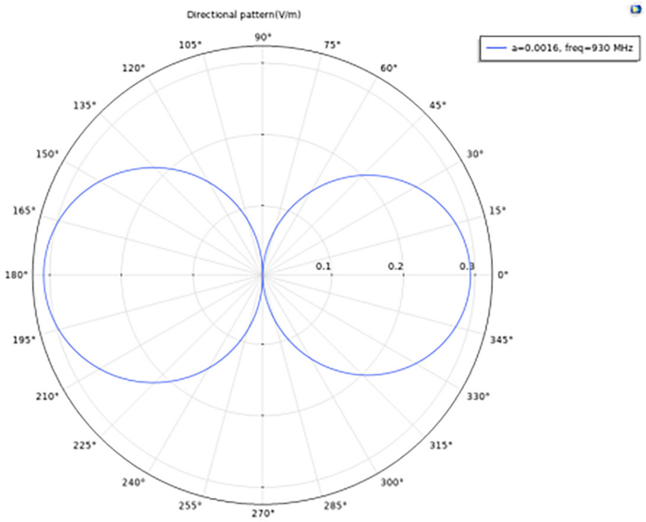

Fig. 4. Directional pattern

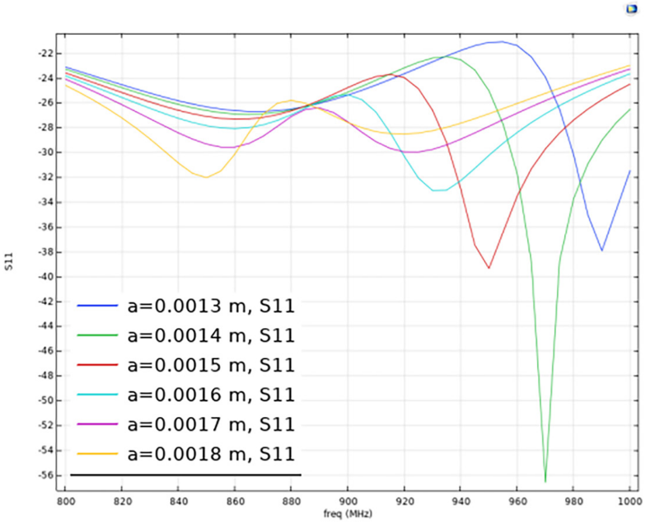

Fig. 5. The influence of variation of "a" on parameters of the antenna

5 DISCUSSION

As shown in Figure 5, with other parameters fixed, the variation of a not only changes the resonant frequency and reflection coefficient but also alters the bandwidth of the antenna. In fact, when considering the possibility of the antenna as a strain sensor, the performance of S11 is not the main factor, and broadband is also very important. For example, when the value of a is set to 1.4 mm, the S11 of the antenna has an extremely low value, but the steepness is extremely high within the bandwidth. This means that when the value of a is fixed, changes in other parameters, such as the distance between the tag antenna and the reader, will have a more significant impact on the efficiency of the system. This increases the difficulty of data analysis, which in turn affects the overall sensitivity of the system. Therefore, when selecting the value of a, it is advisable to sacrifice the reflection coefficient as much as possible to obtain a larger bandwidth and avoid the serious impact of changes in transmission distance on the distance. Therefore, when the environment is changing, the strain detection range of strain sensors based on the RFID principle depends not only on the stretching effect of the material but also on the "distance" between the low S11 narrowband situation and the initial state of the antenna. This also greatly limits the detection range and sensitivity of this type of strain sensor. Although it does not have the advantage of high sensitivity of traditional strain sensors, this design is more flexible in size. Due to the integration of communication modules and sensors, different application scenarios can be quickly achieved by adjusting the bending number and b. In addition, the TPU substrate makes encapsulation extremely simple and provides the packaged sensor with good water resistance. By utilizing heat transfer printing technology, it can also be conveniently integrated onto various types of clothing.

However, there are still many issues in this field. For example, the current conductive ink cannot guarantee sufficient stability under stretchable conditions, which often introduces additional noise to the system and leads to complex information processing. Meanwhile, as discussed above, such RFID-based strain sensors have significant deficiencies in detection range and sensitivity, and antenna structures with high sensitivity and detection range that can resist environmental changes need further research.

6 CONCLUSION

This article mainly introduces the commonly used conductive inks, substrate materials, and design methods in flexible printing RFID applications. Summarized the innovations in materials and structures of flexible RFID in the past two years. At the end of this article, a design example of an antenna is used to illustrate the design process of a chipped RFID tag antenna, and the possibility of using the RFID antenna as a strain sensor is explored. The sensor has a good reflection coefficient (S11 is –33.068 dB) and ideal bandwidth at 930 MHz. And based on TPU substrate design, it has good performance in terms of waterproofing and integration with clothing.

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