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REVIEW ARTICLE

A review of wearable antenna research

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ABSTRACT

With the rapid popularization of IOT applications, wearable devices have been widely used in many fields such as sports and health, entertainment and medical assistance. In addition to the early wearable form, more attachment and implantable wearable devices are constantly developed, and the development of these new wearable devices is largely due to the development of miniaturization antenna technology. This paper discusses the different realization methods and performance index requirements of wearable antenna, introduces the research situation of wearable antenna at home and abroad in recent years, and analyzes the development trend of wearable antenna.

Keywords: wearable antenna; fabric antenna; button antenna; flexible antenna; specific absorption rate; multi-frequency multimode

1. Introduction

In recent years, the market for wearable devices has grown rapidly, and various forms of wearable devices continue to emerge, which has been widely used in entertainment and leisure, positioning and trajectory tracking, health management, medical assistance, and military fields[1]. Body area network communication and wearable devices have become one of the research hotspots in the field of scientific research. **Figure 1** shows the trend curve of the search quantity keyword "Wearable Technology" with Google search engine since 2013. It can be seen that from 2013 to 2015, the search popularity of wearable technology showed a nearly linear upward trend. With the increasing maturity of wearable technology, various wearable products pour into ordinary lives on a large scale. Wearable devices refer to the application of wearable technology to intelligently configure people's daily wear, and implanted various sensing, recognition, connection and cloud services into people's glasses, watches, bracelets, clothing, shoes and socks and other daily wear. Wearable devices are not only a traditional manufacturing hardware device, but also a kind of cross-border equipment that realizes data interaction and cloud interaction through mobile Internet. Its emergence will bring great changes to people's life and cognition.

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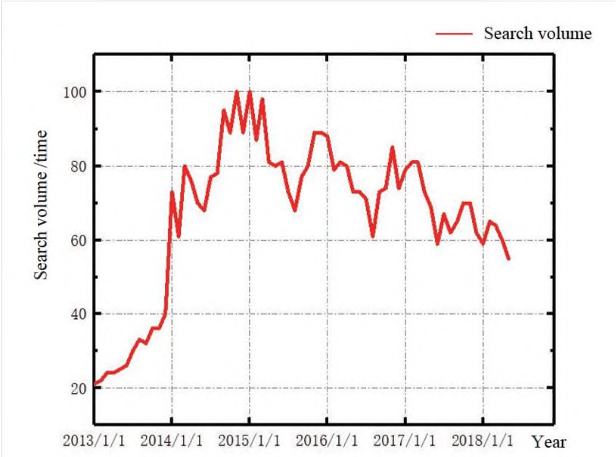


Figure 1. Search volume distribution map of "Wearable Technology" on Google since 2013.

In wearable devices, the wearable antenna plays a crucial role. Wearable antenna plays a role of data transmission, and the performance of the antenna directly affects the performance of the whole system. Wearable antennas originated from military applications, and the earliest individual soldier equipped antenna was the whip antenna. This antenna was exposed to soldiers' head, which could easily reveal the position of soldiers and was not conducive to combat. Subsequently, some antennas hidden in clothes or helmets are gradually removed whip antenna was replaced. Wearable antennas are antennas worn on the human body as the main component of wearable devices, it can be integrated into clothes, shoes, watches and other attachments. In addition to realizing the basic functions of transmitting and receiving electromagnetic waves, the wearable antenna needs to meet the comfort of the wearer to the greatest extent, and ensure the safety of the wearer[3].

This paper investigates the antenna performance, classification of wearable antennas, and future development trend of wearable antenna.

2. Wearable antenna performance

Compared with traditional antennas, wearable antennas have more special requirements in shape and size. When a wearable antenna is worn on the chest or back, it can be a little larger and not limited in shape. However, according to the appearance requirements, the thickness of such antennas should not be too thick. When the wearable antenna is worn at the back of the neck, arm and waist, the appearance can be designed in the form of belt and watch according to the different locations. At this time, due to the activities of the human body, high requirements are put forward for the bending characteristics of the antenna. When wearable antennas are applied in the motion field, the quality and bending characteristics of antennas are relatively higher. For applications in the medical field, wearable antennas require a more sophisticated design in the sensitivity of security and data transmission.

2.1. Antenna efficiency

Communication efficiency is seen as an important component in green radio and mobile communication environments, especially in telemedicine systems, and improving wearable antenna efficiency is expected to be a future research content. Firstly, the wearable device is equipped with light and small batteries to last for a long time. Secondly, when the wearable antenna is installed on the human body, the reflection coefficient and efficiency of the antenna will be affected due to the destructive nature of the human body. Improving the working efficiency of wearable antennas can be used to solve the above problems. Improving the efficiency of the wearable antenna is to reduce the loss caused by the antenna radiation. Choosing the substrate material with the appropriate dielectric constant will help to reduce the loss brought by the antenna material.

2.2. Robustness

Because wearable devices are worn on the human body, human activities will bend the antenna, which will cause the working frequency of the antenna deviation. Then in the design process, we need to consider the robust of wearable antenna nature. The robustness of the antenna is the property of maintaining certain performance when parameters such as structure and size are changed. Increasing the bandwidth of wearable antenna and compensating the frequency through reconfigurable design are the methods used in most studies now.

2.3. Specific absorption rate, SAR

In the process of body domain network communication, on the one hand, because the activities and posture of the human body will change, on the other hand, the position of the communication gateway relative to the device node is not fixed[3], therefore, the antenna is required to have a wide electromagnetic wave radiation angle. However, the radiation of electromagnetic waves is harmful to the human body, and the back radiation of its antenna is not the desired direction. Especially when wearable devices are worn on the human head, health considerations become more important. In the process of energy transmission of wireless communication, part of the energy of electromagnetic field in the transmission process will be absorbed by human tissue, producing a heating effect on the human body. Therefore, semi-omnidirectional radiation is a property pursued by wearable antennas. Wireless communication devices define the specific absorption rate to characterize how much of the radiation dose generated by the antenna is absorbed by the human body. At present, there are two international standards, one is the standard of 1.6 W/kg for 1 g of human tissue designated by IEEE, and the standard of 2 W/kg established by the International Commission on Non-lonizing Radiation Protection (ICNIRP)[4]. Its specific meaning is to take 6 minutes as the timing unit, per kilogram of human tissue absorption of electromagnetic radiation energy should not exceed 2 watts. In most current studies, good conductor ground or metamaterial structure is often used to reduce the back radiation of antenna, improve the main lobe gain of antenna radiation, and reduce SAR.

3. Wearable antenna classification

In recent years, in addition to traditional antennas, three new types of wearable antennas have emerged: Fabric antennas, button antennas, and flexible antennas.

3.1. Fabric antenna

Fabric antenna refers to a wearable antenna composed of fabric material, conductive patch and ground as the substrate plane. It has a planar structure and good integration, and it is a wearable antenna type with great potential. Fabric antennas can be integrated into clothing, furniture, or other fabric materials. Compared with conventional antennas, fabric antennas need to meet the additional requirements of drapability. Drapability means that it can be bent in any direction. Since the flexible substrate has only one specific bending direction, so that this characteristic of the fabric antenna is exactly in contrast with a standard flexible substrate. In addition, in wearable applications, the fabric antenna must be planar without affecting the wearer. Common fabric substrate materials include denim, wool, felt, etc. This material is light in quality, can be bent, similar to the material of clothes, and easy to integrate into clothes. Different types of fabric antenna characteristics are described in the literature[5]. In the wearable fabric antennas, the conductive materials are mainly woven, sewing, printed and copper-coated fabric cloth[3].

Joler et al. proposed an armband polarized wearable fabric antenna with a frequency band of 2.45 GHz, as shown in **Figure 2**[6]. The antenna consists of pure fabric material, which is small and thin enough to facilitate integration into standard armbands. The fabric antenna can reach 5.6% impedance bandwidth, gain 5.04 dBi at 2.5 GHz, and have a radiation efficiency of 55.3%[6], which can well meet the needs of wearable devices.

Figure 2. Plane diagram of sleeve antenna.

Typically, dual-frequency, dual-mode antennas are achieved by integrating two radiators, these radiators are powered by either single-port or two-port systems. Each radiator is operated at a different frequency and provides different radiation modes. Roy B. V. B. Simorangkir proposed a dual-frequency 2.45 GHz and 5.8 GHz dual-mode wearable antenna with the structure shown in **Figure 3**[7]. Two kinds of radiation characteristics are realized by using the inherent TM11 mode and TM02 mode of the circularly polarized patch antenna, namely, patch-like radiation for the external link and unipolar radiation for the internal link. The short pins and two arc grooves are used to tune the two modes to the desired operating frequency. This method can be used to implement a simple structured dual-frequency dual-mode antenna. Another advantage of the proposed antenna is that it uses a silver fabric integrated into a flexible polydimethylsiloxane substrate, making it more suitable for the wearable application[7]. Literature[7] simulated the performance of the antenna when attached to the human surface and showed that the human medium has little influence on the performance of the antenna. When placed on the mannequin, the 84 MHz and 247 MHz bandwidth were measured at the 2.45 GHz and 5.8 GHz frequency bands, respectively, and achieved gains of 4.16 dBi and 4.34 dBi, respectively, indicating their promising applicability to body area network communications.

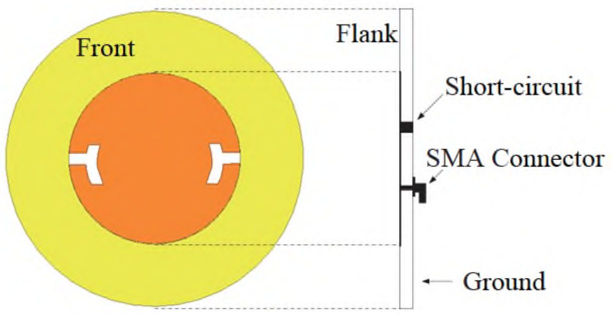


Figure 3. Wearable dual-frequency dual-mode fabric antenna.

Existing literature has disclosed a variety of design forms for wearable antennas, it mainly includes the dorsal cavity type[8] , microband[9] , fall F, flat surface[10], and with a vertical monopole antenna[11,12]. These antennas have narrow bandwidth, large area and high front-rear ratio (FBR), and are strictly affected by the body tissue repeat. Documents [13,16] propose using the electromagnetic band gap EBG structure in a 2.4 GHz metamaterial textile antenna. The introduction of an EBG structure in the wearable antenna design reduces the back-direction radiation, improves the front-rear ratio, and reduces the SAR in the tissue. However, such a structure has the obvious drawback that most EBG-based design sizes are relatively large[17]. Based on these features, Adel Y. I. Ashyap et al. proposed a 2.4GHz compact wearable antenna with a new miniaturized electromagnetic band gap structure, as shown in **Figure 4**[18]. The EBG structure reduces the dorsal radiation, increases the front and rear ratio by 15.5 dB, and separates the impact of the antenna on the human body. When the antenna is attached to the human surface, the antenna resonance characteristics are basically unaffected. The proposed antenna has a 27% (2.17 GHz–2.83 GHz) impedance bandwidth, with the gain increased to 7.8 dBi and a SAR reduction by more than 95%[18]. The resonant frequency and bandwidth are also largely constant in the bending test.

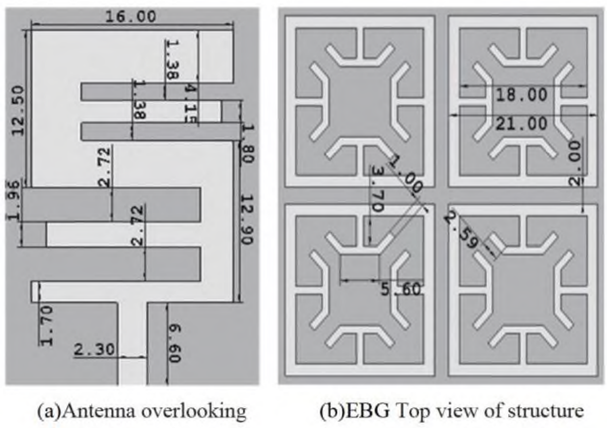
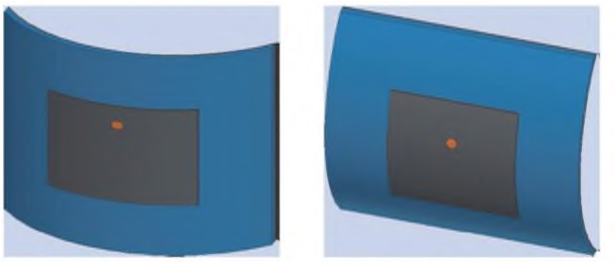


Figure 4. Antenna and EBG structure.

David Ferreira et al. introduced the influence of the bending of a rectangular textile patch antenna working at 2.4 GHz industrial, scientific and medical (ISM) frequency band on the performance. The substrate of the antenna is made of denim textile and conductive layers made of copper and nickel-coated polyester fabric. The substrate of the antenna is made of denim fabric, and the conductive layer is made of polyester fabric coated with copper and nickel. The antenna provides a maximum gain of about 4 dBi and a 70° half power beam width (HPBW) at the plane position. When subjected to wrist equivalent bending, the gain decreased by 2 dB, HPBW increased by approximately 25°, and the anterior-posterior radiation ratio decreased. On the other hand, the antenna shown in **Figure 5** bends in different directions, and the resonant frequency deviates to different degrees according to whether the antenna bends around its width direction or its length direction. When turning the antenna around its width in the bending of the direction, a shift towards low frequency is observed, while bending in the direction of the antenna length results in a frequency offset towards high frequency[19]. Therefore, when designing textile patch antennas for WBAN applications, research should be conducted according to the possible bending degree in the application scenario, as the resonant frequency offset relative to the curvature angle of the antenna may seriously affect the performance of the antenna.



(a) Bending along antenna width (b) Bending along antenna length

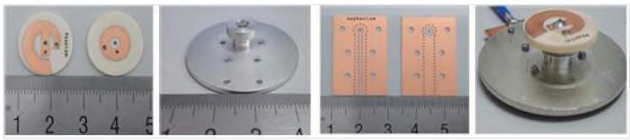
Figure 5. Fabric antenna bending scenario.

It can be seen from the above examples that the research on fabric antenna is particularly important in the selection of substrate materials, and substrate materials have a great impact on antenna efficiency. At the same time, the influence of bending effect on antenna performance will also cause different degrees according to the change of direction. In terms of considering the impact of the antenna on the human body radiation, most studies choose a slightly larger bottom surface or EBG structure to reduce the back direction radiation of the antenna, so as to ensure the safety of the human body. Fabric antenna is a great type of antenna for wearable applications.

3.2. Button antenna

The button antenna is very practical. A hard, wearable antenna with a button-like shape that can be easily integrated into the wearer's clothing. Common button antennas include circular patch antenna and monopole antenna. By designing different sizes of radiation patch, the resonant frequency of the antenna can be adjusted, and multi-frequency characteristics can be obtained when multiple resonant structures are loaded.

Zhang proposes a dual-frequency dual-mode button antenna for human center communication with the structure shown in **Figure 6**[20]. The button antenna in literature[21,23] has only one omnidirectional radiation mode. Zhang designs a dual-mode omnidirectional radiation antenna structure consisting of spiral inverted F antenna and metal reflector. In the low frequency band, the inverted F antenna forms a radiation direction map parallel to the body surface, which can realize the communication between multiple wearable devices on the body surface. In the high-frequency band, the high-order mode forms the radiation direction map of the vertical antenna surface, thus realizing the communication between the wearable device and the in vitro device. At the low and high frequencies, the phantom-measured peak gain was 0.6 dBi and 4.3 dBi, respectively. The antenna has an efficiency of 46.3% in low frequency band and 69.3% in high frequency band. With the overall miniaturization, such button antennas can be integrated into the clothing, so it is expected to become the main form of wearable device antenna design in the future[20].



(a) Two-side metal of dielectric substrate (b) Metal wheel (c) Ground coplanar waveguide feed (d) Overall structure diagram

Figure 6. Button antenna figure.

Compared to the button antenna in the literature[21,28], Hu introduces a new wearable button antenna for wireless LAN. The antenna consists of buttons approximately 16 mm in diameter with patches mounted on the top of the dielectric substrate. The button is located on top of the textile substrate and conductive textile floor and will be integrated into the garment, structured as shown in **Figure 7**[29]. The main feature of this antenna is that it has two different types of radiation direction maps: Monpolar radiation for 2.4 GHz band for bulk communication and broadband radiation for 5 GHz band for in vitro communication. It achieves a radiation efficiency of about 90%, a result higher than the performance of other textile antennas in the literature[29].

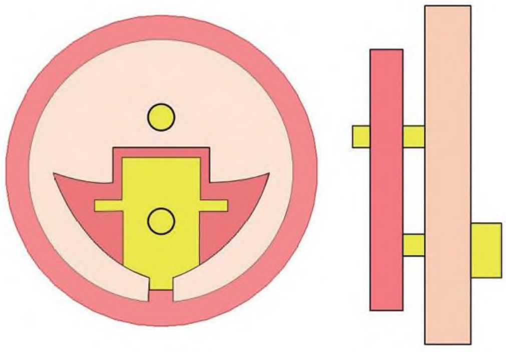


Figure 7. Structure diagram of button antenna.

Chen uses the antenna design concept of removable radiation units to provide the geometric refactoring of modules for wearable applications[30]. Different modular interchangeable microband patch units with snap buttons, whether as RF connections or mechanical fixing mechanisms, obtain specific operating frequency and radiation characteristics. A unique source of the design sharing a common feed structure for all configurations, the feed structure consists of a snap button, a ground plane and a double substrate coupled with the feed. Firstly, a removable patch is proposed that provides an interchangeable right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) at 5 GHz. Secondly, a planar inverted F antenna (PIFA) with an interchangeable resonance frequency of the 2.4 GHz and 5.3 GHz frequency bands used for the wireless LAN is presented. Finally, a patch module was designed for the 8GHz operation to show the versatility of frequency modularity. This antenna design has the advantage of low manufacturing and maintenance cost, realizing the dynamic configurable feature of multifunctional wearable systems in a passive way[30].

3.3. Flexible antenna

One of the main challenges for wearable electronic devices is to achieve flexible, ubiquitous, robust and low-cost wearable antennas, while exhibiting RF properties similar to rigid copper. With this in mind, flexible wearable antennas can address this challenge very well.

Roy BVB. Simorangkir proposed a new approach in 2018 to achieve a robust, flexible, and electronically tunable flexible wearable antenna. The conductive fabric forms a conductive part of the antenna on a polydimethylsiloxane (PDMS) substrate. The aggregate (active and passive) elements required for the antenna, electronic tuning, and RF choke control will be fully enclosed in the additional layer PDMS, as shown in **Figure 8**[31]. Close to the human model, continuous frequency tuning from 2.3 GHz to 2.68 GHz had an average bandwidth of 3.3% and an average peak gain of 2.6 dBi. After extreme bending (bending radius of 28 mm) and washing, the antenna can still maintain the overall antenna performance, including a good frequency refactoring from 2.3 GHz to 2.68 GHz[31].

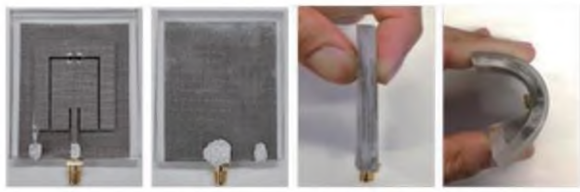


Figure 8. Reconfigurable antenna diagram.

Zahir Hamouda introduces an elliptic monopole flexible antenna fed by a coplanar waveguide that uses a kapton substrate and optimizes for frequencies from 1 GHz to 8 GHz[32] . Maximum gain as measured at 5.8 GHz is 1.86 dBi (without bending) and 3.1 dBi (under bending). Moreover, the conductivity of the polymer is changed by changing the MWNCTs concentration in the PANI matrix to adjust the gain of the proposed organoflexible antenna (PANI / MWCNTs)[32].

4. Future development trend of wearable antenna

The wearable antenna in the bud has large size, poor bending performance and other aspects. In recent years, the wearable antennas appearing in the market have been significantly improved in terms of wearability, intelligence and security, and have their own distinctive characteristics. “Wearable” indicate the need to have very efficient portability and comfort, as well as a stylish look that appeals to users. In the future, the following performance of wearable antenna still need to be studied and improved.

4.1. Small in size, light and convenient

The ideal state for wearable antennas is not to be perceived. When used for wearing occasions, the wearable antenna should be as small as possible, light and easy to carry. When integrating the antenna into clothes, the consideration needs the comfort of the original item and not destroy the comfort experience of the wearer. In particular, the implantable antenna, which has been studied more recently, has put forward new and higher requirements for its safety, digestibility and miniaturization.

4.2. Multi-frequency ultra-broadband

Because the wearable antenna is worn on the human body, the influence of human activities or external environment will affect the working frequency of the wearable antenna, and bending or distortion will shift the working frequency of the antenna, and cannot work normally. In order not to affect the comfort of the wearer, the position of the wearable antenna should be more reasonable, which should not affect the working performance of the system. Especially when the wearable antenna is conformal with the human body, which need the normal connection to the mobile terminal device despite bending to communicate with the data. Therefore, expanding the bandwidth of the antenna and designing wearable antennas that can work in multiple frequency bands are also a direction of concern for researchers.

4.3. Strong anti-interference ability

Wearable antennas are a medium for data transmission and exchange, whose workplace is anytime, anywhere. However, the interference of other radio waves, changeable weather, accidents in the use of waves, will affect the reception and transmission of electromagnetic waves; this requires a wearable antenna with a higher anti-interference capability. For example, waterproof and dust-proof, and not afraid about the interference of electromagnetic are the characteristics of the future wearable antenna pursuit.

4.4. Low SAR

Because the wearable antenna is close to the human body, the radiation of its electromagnetic waves will have a potential impact on the human health. How to reduce the back radiation characteristics of the wearable antenna as much as possible is an important indicator to be considered in the design of the wearable antenna. How to balance the contradiction between enhancing the communication ability of equipment and reducing the radiation to human body needs designers to study and optimize the design.

5. Conclusions

Wearable devices will still grow at a relatively high rate in the next few years, the research on wearable antennas will also continue to deepen and expand. The traditional communication antenna is further planar, miniaturization, and multi-frequency multi-mode design to make it more suitable for wearable devices and body sensor network applications. Combined with new metamaterials technologies, such as electric, magnetic and left-hand materials, you can obtain higher efficiency, better front and rear ratio of wearable antenna. And with the further research of electronic skin and implantable devices, the research of flexible antenna, fabric antenna and digestible antenna will be expected to become the hot spot of wearable antenna research in the future.

Conflict of interest

The authors declare no conflict of interest.

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