A Low SAR, Small size, High gain, Circularly polarized Antenna for Wearable Application

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Abstract. A planar, small size, high gain, low specific absorption rate (SAR) and circularly-polarized (CP) wearable antenna is proposed in this paper. The antenna is fabricated on a substrate with a dielectric constant of 3.5 with a thickness of 0.5 mm and sized at 42×42 mm only. Both the simulation results show that the overlap bandwidth of impedance and axial ratio of the proposed antenna is 13.7% (5.15-5.91 GHz). To isolate the antenna against the influence of the human body, a artificial magnetic conductor (AMC) plane is added on the reverse side of the radiator. The AMC structure effectively isolates the human body from the radiation of the antenna and reduces the specific absorption rate (SAR) of it by more than 96.1% at 5.5 GHz, which improves the antenna gain and the peak gain reaches 5.09 dBi at 5.5 GHz. The wearable performance of the antenna was analyzed, and it is observed that it can sustain good performance even under human body loading. Beside, the antenna has a small size, which makes it ideal for wearable applications.

1. Introduction
In recent years, the wearable device market has grown rapidly, and various types of wearable devices have continuously emerged, which have been widely used in entertainment and leisure, positioning and trajectory tracking, health management, medical assistance, and military fields [1]. In wearable devices, wearable antennas play a vital role, and the performance of antennas directly affects the performance of the entire system. So far, researchers have proposed a large number of wearable antennas. For example, the literature [2] proposed an inverted F-type compact conformal wearable antenna, a flat single unit [3], microstrip [4], etc., which are suitable for wearable applications. However, due to their nearly omnidirectional radiation characteristics, a large amount of electromagnetic energy radiation enters the human body. How to isolate the antenna’s radiation to the human body and reduce the SAR value is a problem that researchers are very concerned about. At present, the commonly used methods are to use a high impedance surface and introduce electromagnetic band gap structures (EBG) and artificial magnetic conductors (AMCs) on the back of the antenna substrate [5 ]-[8], the existence of these structures greatly suppresses the antenna's radiation to the human body, reduces the SAR value, and can increase the antenna gain. However, antennas based on EBG and AMC structures are often large in size and accompanied by narrow bandwidth, and how to reduce the size while obtaining a wide bandwidth is still a problem.
In addition, most of the wearable antennas currently proposed are linear polarization (LP), which may cause antenna polarization mismatch due to continuous changes in human body motion. In the most severe case, due to complete polarization mismatch, invalid transmission may occur. On the other hand, circular polarization (CP) antennas are more robust to polarization mismatch caused by human motion. There have been reports on CP wearable antennas in [9] and [10]. However, their 3-dB axial ratio (AR) bandwidth is very narrow, that is, less than 2.5%, which makes their application in high data rate body area network systems limited.

In this paper, a broadband circularly polarized wearable antenna is proposed. Both the simulation results show that the overlap bandwidth of impedance and axial ratio of the proposed antenna is 13.7% (5.15-5.91 GHz). The AMC structure effectively isolates the antenna's radiation to the human body, greatly reduces the antenna's SAR value, and the antenna's SAR value is reduced by more than 99.2%. In addition, it has very good human body loading performance, compact structure, small size (only 42×42 mm) and high gain (5.09 dBi), which is very suitable for wearable applications.

![Figure 1. Antenna structure diagram (a) The top view of the monopole antenna, (b) AMC structure, (c) the combined effect of the monopole antenna and the AMC structure](image)

2. Antenna design
Both the monopole antenna and the AMC structure are designed on a dielectric material with a dielectric constant of 3.5 and a thickness of 0.5 mm. Coplanar waveguide (CPW) is used for feeding. Figure 1(a) shows the top view of the monopole antenna. The monopole antenna has the characteristics of omnidirectional radiation. In order to obtain the effect of directional radiation, an AMC structure with a period of 3×3 is loaded 5 mm below the monopole antenna. Figure 1(b) is the structure diagram of AMC, and Figure 1(c) is the effect diagram of the combination of monopole antenna and AMC structure. The maximum size of the antenna is only 42×42 mm, which is characterized by compact structure and small size. The electromagnetic simulation software HFSS2019 is used to simulate and optimize the antenna. The final antenna structure parameters are: \( L = 30 \text{ mm} \), \( W = 31.2 \text{ mm} \), \( Ls = 2.4 \text{ mm} \), \( LI = 12.6 \text{ mm} \), \( W1 = 11.2 \text{ mm} \), \( W2 = 13.2 \text{ mm} \), \( W3 = 8.4 \text{ mm} \), \( Li = 12.5 \text{ mm} \), \( Lo = 0.75 \text{ mm} \).
Figure 2. S11 and axial ratio of the antenna

Figure 3. The reflection phase of the AMC unit

Figure 4. Comparison of radiation pattern of antenna with and without AMC structure

Figure 2 shows the S11 of the antenna, it can be observed that the -10 dB impedance bandwidth is 5.10-6.25 GHz. Because ordinary monopole antennas with a symmetrical ground plane cannot produce circularly polarized waves. In this paper, by introducing different heights of the asymmetric ground plane and the vertical stubs of the right ground plane, the asymmetric ground is excited to produce two orthogonal modes with a phase difference of 90°, which makes the current appear a horizontal component, thereby producing the CP mode. Figure 2 shows that the 3-dB axial ratio bandwidth of the antenna has reached 5.15 to 5.91 GHz, achieving broadband circular polarization.

Because the omnidirectional radiation of the monopole antenna will cause a large amount of electromagnetic radiation to enter the human body, in order to isolate the radiation of the monopole antenna to the human body, an AMC structure is introduced directly below the monopole antenna. Through the in-phase reflection characteristics of the AMC structure, when the reflection phase changes from -90° to +90°, the propagation of surface waves can be suppressed and the effect of in-phase reflection can be produced. By adjusting the structural parameters of the AMC unit, the reflection phase bandwidth of 5.55-6.90 GHz can be obtained. Figure 3 analyzes the influence of different Li parameters on the reflection phase bandwidth of the AMC unit. Due to the addition of the AMC structure, the monopole antenna has changed from omnidirectional radiation to single radiation. Figure 4 compares the radiation pattern of the antenna with or without AMC structure. It can be observed that the antenna has a
Table 1. Human tissue dielectric characteristics.

| Layer    | Sizes (mm³) | $\varepsilon_r$ | Conductivity $\sigma$ (S/m) | Density (kg/m³) |
|----------|-------------|-----------------|-----------------------------|-----------------|
| Skin     | $90 \times 90 \times 2$ | 35.114          | 3.717                        | 1090            |
| Skin     | $90 \times 90 \times 8$ | 4.9549          | 0.29313                      | 930             |
| Muscle   | $90 \times 90 \times 23$ | 48.485          | 4.9615                       | 1050            |

Figure 5. Comparison of $S_{11}$ and axial ratio of antenna with AMC in free space and human tissue model

wearable antenna with AMC structure. The design has always wanted to see the unidirectional radiation characteristics. At the same time, the antenna gain has reached 5.09 dBi.

3. Wearable performance analysis

According to research reports, due to the high loss characteristics of the human body, when a wearable antenna is installed on the human body, the performance of the antenna may change drastically due to the near-field coupling effect. This paper approximates the performance change when the antenna is close to the human body. Establish a human tissue model in HFSS.19, which is composed of three layers of human skin, muscle and fat models. The dimensions and dielectric parameters of the model are shown in Table 1. Place the antenna 4 mm above the three-layer human body model for simulation, and compare the simulation results with the results of the antenna in free space. As shown in Figure 5, the compared $S_{11}$ and axial ratio results are shown. It can be observed that the change is very weak. It is even negligible, which shows that the antenna proposed in this paper has very good human body loading performance. This is because the AMC structure isolates the antenna from the human body, so that the high loss of the human body has a sharply weakened effect on the performance of the antenna, which has always been very desirable in the design of wearable antennas.

Another important indicator for evaluating the performance of wearable antennas is the SAR value. It is defined as the electromagnetic radiation energy absorbed by a unit mass of matter per unit time. The SAR value is crucial in understanding the effect of antenna radiation on the human body. There are two main international standards, one is the American standard, and the other is the European standard. The American standard stipulates the threshold is 1.6 W / kg averaged over 1 g of tissue, and the European standard stipulates the threshold is 2 W / kg averaged over 10 g of tissue [11, 12]. In the CST software, the same human tissue model as the above is established, and the SAR value of the antenna with or without AMC structure is simulated. The simulation results are shown in Figures 6 and 7.
Figure 6 shows the SAR value of an antenna without AMC structure. Under the 1 g standard, the SAR value of the antenna is 20.5 W / Kg, far exceeding the American standard of 1.6 W / Kg. Similarly, under the 10 g standard, the SAR value of the antenna is 6.94 W / Kg, which also exceeds the European standard of 2.0 W / Kg. From this, it is known that without the AMC structure, the SAR value of the antenna does not meet the health standards. Figure 7 shows the SAR value of the antenna with AMC structure. Under the 1 g standard, the SAR value of the antenna is 0.67 W / Kg, which is much lower than the American standard of 1.6 W / Kg. Compared with the antenna without AMC structure, the SAR value is reduced by 96.7%. Under the 10 g standard, the SAR value of the antenna is 0.26 W / Kg, which is much lower than the European standard of 2.0 W / Kg. Compared with the antenna without AMC structure, the SAR value is reduced by 96.1%. It can be concluded that the AMC structure greatly reduces the SAR value of the antenna, so that the antenna has a very low SAR value, which is in line with the application standard of wearable antennas.

4. Conclusion
This paper proposes a circularly polarized wearable antenna with low SAR value, small size and high gain. The size of the antenna is only 42×42 mm, achieving a gain of 5.09 dBi, and the simulated overlap impedance bandwidth and axial ratio bandwidth are 13.7% (5.15-5.91 GHz). By introducing the AMC structure under the monopole antenna, the SAR value of the antenna is greatly reduced. The human body loading performance of the antenna is analyzed, and it is found that the reflection coefficient and axial ratio of the proposed antenna are almost unaffected under the condition of human body loading, showing good performance. And a low SAR value, small size, high gain, good human loading performance and circular polarization antenna are very suitable for wearable applications and can be integrated into wearable devices.
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