Design of High Gain Wearable Antenna Based on Wireless Body Area Network Communications

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Abstract. This paper presents a wearable antenna for Wireless Body Area Network communication. A 3×3 array artificial magnetic conductor structure (AMC) is loaded at the bottom of the antenna to reduce the backward radiation and improve the antenna gain. The simulated results show that the antenna can completely meet the working requirements in the bent state. After the addition of AMC array, the maximum gain reaches 7.53 dB, and the SAR value of human tissue can be reduced by about 94%. In addition, we have also processed and tested the antenna. The measured results are in good agreement with the simulated results, and its working bandwidth includes the low-frequency band of the ISM frequency band for WBAN communication, which can meet the working requirements of the antenna.

1. Introduction

Wireless Body Area Network (WBAN) is a network centered on the human body, consisting of personal terminals, sensors on the human body or clothing and other networking devices, and communicating through wireless communication technology [1]. In recent years, with the rapid development of communication technology, especially the gradual coverage of 5G communication, wireless body area network communication technology has been widely used in military, health monitoring and other fields [2]. As the terminal equipment of the communication system of WBAN, the wearable antenna is particularly important for the signal transmission in the communication system of the body area network. Wearable antennas need to ensure two points: comfort, safety, namely specific absorption rate (SAR).

In order to ensure comfort, the substrate of the wearable antenna is usually made of flexible materials. Currently used materials mainly include Rogers [3], FR4 [4], and other hard materials, but these materials’ bending and folding performance is not good enough. Compared with hard materials, polymer materials such as Polydimethylsiloxane (PDMS) [5] and Polyimide (PI) [6] have good bending properties, wider operating temperature range, corrosion resistance, high insulation and lighter weight.

The antenna in the WBAN system is close to the human body, and the electromagnetic wave radiated by the antenna will cause damage to human tissues. Various countries have formulated safety standards for electromagnetic radiation based on Specific Absorption Rate (SAR). In order to reduce the radiation of the antenna to human body, a metal plate was added to the back of the antenna in the literature [7]. Although this method can effectively reduce the SAR, it will affect the bending of the antenna at the same time, so it is not applicable to the wearable antenna. In Literature [6], a Metamaterial Structure (MS) was added between the antenna and the human body. In Literature [8], a 2×2 Electromagnetic Band Gap (EBG) was loaded at the bottom of the antenna. In Literature [9], a kind of wearable antenna based on floating floor was proposed. All three can increase antenna gain while reducing SAR.
In this paper, a microstrip antenna is designed, and an AMC array is loaded below the antenna. The in-phase reflection characteristics of AMC can effectively inhibit the radiation of the antenna to the human body and improve the gain. Moreover, AMC is made of flexible materials, which is suitable for a wearable antenna.

2. Antenna and AMC structure design

2.1. Structure of the antenna

In this paper, a 2.45 GHz flexible wearable antenna fed by coplanar waveguide is designed. Due to its small size, compact structure, low profile and easy integration, the microstrip antenna is suitable for the field of wearable antenna. The antenna structure is shown in Figure 1. The flexible substrate is made of polyimide material, and the thickness $H$ of the substrate is 1 mm. Copper film of 35 thickness is printed on the substrate, and the connecting floor is designed as a rectangle to reduce return loss and expand bandwidth. According to the basic principle of microstrip antenna, the antenna center frequency depends on the effective current length of the antenna and the effective dielectric constant of the substrate, which can be expressed as:

$$f = \frac{c}{2L_e} \sqrt{\varepsilon_e} \quad (1)$$ where: $L_e = L + 2\Delta L$ (equivalent current length), $\Delta L$ is the antenna compensation length, and $\varepsilon_e$ is the effective dielectric constant. The antenna structure size after optimization is shown in Table 1.

| Name | Size(mm) | Name | Size(mm) | Name | Size(mm) |
|------|----------|------|----------|------|----------|
| L    | 42.0     | L_4  | 12.0     | W_1 | 4.6      |
| W    | 35.0     | L_1  | 15.0     | W_2 | 6.4      |
| R    | 13.2     | L_2  | 27.0     | W_3 | 2.0      |
| L_3  | 7.5      |      |          |      |          |

2.2. Square annular AMC structure

Wearable antenna must consider the following radiation damage to the human body, in order to suppress the antenna backward radiation and reduce the SAR value, this paper designed a square annular structure of Artificial Magnetic Conductor (AMC). By using the in-phase reflection characteristics, the electromagnetic wave can be reflected in the same phase at a specific frequency, so as to suppress the backward radiation of the antenna. The structure uses a Polyimide material, the substrate thickness is 4 mm, and the thickness of 35 $\mu$m copper film is printed on both sides of the substrate (Figure 2 (a)). The structural dimensions of the unit are shown in Table 2. Figure 2 (b) is the equivalent circuit diagram of
the AMC structure. The annular patch can be equivalent to the inductance $L_1$, there is an interpolar capacitor $C_1$ between the top patch and the floor, and there is a coupling capacitor $C_2$ between the metal conductor patches of the two units:

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi} \sqrt{\frac{C_1 + C_2}{C_1 C_2 L_1}}$$

(2)

where: $L$ and $C$ are equivalent total inductance and total capacitance, $L = L_1$, $C = C_1 \cdot \frac{C_2}{C_1 + C_2}$.

| Name | Size(mm) | Name | Size(mm) |
|------|----------|------|----------|
| $L_1$ | 25       | $L_3$ | 9        |
| $L_2$ | 23       | $S$  | 1        |

Table 2. Basic dimensions of unit structure.

Figure 2. AMC structure (a) and its equivalent circuit (b).

When the AMC structure is loaded onto the back of the antenna, its in-phase reflection property is used to suppress the antenna's back radiation and improve the antenna gain. In this paper, the Floquet port method is used to simulate the ±90° reflection phase of AMC structure, and its reflection phase is shown in Figure 3.

As can be seen from Figure 3, the 0° phase reflection point of the AMC structure is around 2.45 GHz, and its ±90° reflection phase band is 2.30 ~ 2.62 GHz. In this frequency band, the electromagnetic wave radiated backward from the antenna will be reflected by the AMC structure to reduce the radiation from the antenna to the human body. The radiation effect of the antenna can be enhanced by the superposition of the reflected electromagnetic wave and the electromagnetic wave from the main radiation direction of the antenna.
2.3. **Antenna system simulation**

In order to analyze the influence of antenna wearing on the human body, the human body is simplified into a three-layer model of skin, fat, and muscle (as shown in Figure 4), and a 3×3 AMC array is loaded at a position 3 mm from the back of the antenna. For the electrical parameters of human tissues, the electrical parameters of human tissues used in reference [2] (as shown in Table 3) were used to establish an antenna system in HFSS software for simulation analysis.

| Material | \(\varepsilon\) | \(\sigma (\text{S/m})\) | \(\delta (^\circ)\) | Density (kg/m\(^3\)) | Thickness (mm) |
|----------|-----------------|----------------|-----------------|-----------------|----------------|
| Skin     | 38.007          | 1.49           | 0.283           | 1001            | 1              |
| Fat      | 5.280           | 0.11           | 0.145           | 900             | 5              |
| Muscle   | 52.729          | 1.77           | 0.241           | 1006            | 20             |

Table 3. Material properties of the human body model.

Figure 4. Schematic diagram of antenna system.

Figure 5 shows the simulated reflection coefficients in three cases. The harmonic frequency of the single antenna is 2.47 GHz, and the working bandwidth of -10 dB is 20.6%. When the antenna is located above the human body model, the harmonic frequency decreased to 2.22 GHz, mainly because the dielectric constant of the human tissue is higher than that of the Polyimide flexible substrate. At this time, the working bandwidth of -10 dB is about 21.4%, and the working bandwidth of the antenna basically remains unchanged after loading the human body model. After loading the AMC structure, the harmonic frequency increased slightly, and the working bandwidth decreased. This frequency band includes the low-frequency band (2.4 ~ 2.485 GHz) of the ISM band of the WBAN.

Figure 5. Comparison of simulated reflection coefficient S11.

Figure 6 and Figure 7 show the SAR value of the antenna with and without AMC structure. According to the limit of specific absorptivity SAR in C95.1 formulated by IEEE, for locally exposed biological tissue, the maximum value of specific absorptivity SAR of any 10 g tissue cannot be higher than 2W/kg [10]. It can be seen that after loading the AMC reflector plate, the maximum SAR value of 10 g tissue decreased from 22 W/kg to 1.42 W/kg, which was within the safety standard level.
Figure 8 is the radiation patterns in three cases. It can be seen that in the case of the single antenna, the maximum gain is about 2.24 dB. However, after loading the human body model, the maximum gain is significantly reduced due to the influence of human tissue. This is because the resonant frequency of water molecules in human tissue is about 2.5 GHz, and the water molecules in human tissue reach resonance near the resonant frequency, thus inhibiting the radiation of the antenna. After loading the AMC structure, the maximum gain is 7.53 dB, which is about 3.6 times higher than that of the single antenna. Moreover, from the shape of the patterns, it can be seen that the AMC reflection plate effectively inhibits the backward radiation of the antenna.

Figure 9 shows the radiation patterns of the antenna in different bending states. When the antenna is bent along the x-axis, the maximum gain is 2.29 dB, and when the antenna is bent along the y-axis, the maximum gain is 2.11 dB. Compared with the unbent state, the antenna gain changes very little. Therefore, the antenna can still work normally in the bent state.
Figure 9. Simulated reflection coefficient S11 in different bending states.

Figure 10. Comparison of the radiation patterns in different bending states (a) along the X-axis and (b) along the Y-axis.

3. Antenna measurement on real human body

In order to verify the actual radiation effect of the antenna, we processed the antenna and AMC reflection plate. Because the dielectric constant of the foam material is close to that of the air, a 3 mm thick foam plate is used as a support between the antenna and the AMC reflection plate.

We used a vector network analyzer to measure the antenna. The measurement set up and results are shown in Figure 11. As can be seen from the figure, when the antenna is placed on the human arm and leg, multiple resonant points appear near the center frequency. The return loss is less than -20 dB, and the working bandwidth is around 2.5 GHz, which can include the low-frequency band of ISM frequency band for WBAN communication.

Figure 11. Measured S11 of the proposed antenna placed on human tissue. (a) Measurement set up. (b) Comparison between simulated and measured S11.
4. Conclusion
In this paper, a wearable antenna loaded with AMC is designed, which can be used for communication in WBAN. A trapezoidal floor is used to reduce the return loss, and a $3 \times 3$ square annular AMC reflector plate is mounted on the back of the antenna to reduce the SAR and improve the antenna gain. The simulation results show that the AMC reflector can greatly reduce the SAR value, and the SAR value is reduced to 1.42 W/kg after loading AMC, which meets the radiation safety standard. The maximum gain of the antenna is 7.53 dB, and the working frequency band of the antenna loaded with AMC reflector plate can still ensure that the antenna works in the low-frequency band of the ISM band of the WBAN. In addition, the bending of the antenna along different directions has little effect on the performance of the antenna, which meets the working requirements. The processing antenna was placed in different parts of the human body for testing. When the antenna was located in different parts, the measured results were in good agreement with the simulation results. The antenna shows that using the in-phase reflection characteristics of the AMC structure can effectively reduce the backward radiation of the wearable antenna to achieve the safety radiation standard and increase the gain of the main radiation direction of the antenna. In addition, its structure is simple and its volume is small, which has reference significance for the research of the communication antenna of body area network.

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