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CPW-Fed Slot Antenna for Medical Wearable Applications

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ABSTRACT In this paper, a flexible antenna with a simple structure, small size ($15mm \times 17mm \times 1mm$), and light weight for medical wearable applications is proposed. The antenna consists of slot radiation elements fed by a coplanar waveguide structure and a floating ground. Flexible conductive cloth MKKTN260 is used to fabricate the antenna, while felt with good insulation is used as the substrate. The measured impedance matching bandwidth ($|S_{11}|$less than -10dB) of the antenna is from 5.578 to 5.898GHz, which can cover the whole ISM 5.8GHz band (5.725–5.825GHz) and perform good wearable radiation characteristics. The floating ground structure and the interaction between slots make the antenna radiated efficiently (the measured peak realized gain is 4.85dBi at 5.8GHz) to the +Z direction, which is away from the human body. Meanwhile, without any specially designed reflecting structures, the specific absorption rate value is below the criterion set by the FCC and ICNIPR. The bending configurations are also studied for this antenna.

INDEX TERMS Wearable antenna, floating ground, slot antenna, coplanar waveguide, SAR.

I. INTRODUCTION

Nowadays, the world is facing a serious population aging problem. Take China for example, by 2020, the elderly population aged 65 and above is expected to reach 248 million which is 17.17% of the total population. In order to provide better medical care to the elderly, it is essential to use biological information monitoring systems [1], [2] to transmit the remote monitoring data of elderly people's vital signs, such as heart rate, basal body temperature, blood pressure, respiratory rate, glucose levels and Electro Cardio Gram (ECG) signals [3]. Rapidly developed wearable electronics devices like digital watch, smart ring, eyewear devices, and smart bracelet, etc, can easily be integrated with these systems [4].

As the most important elements for these wearable devices, wearable antennas design have drawn lots of attention in both academy and industry [5]. They all fulfill the design requirements like: compact in size, low profile, easy to fabricate, and robust to maintain stable communication when the location or shape of the antennas were slightly changed due to the change of human positions or body movements.

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Textile antenna is an especially competitive candidate in wearable medical devices. Because of the flexibility, when textile antenna is attached to the patientclothes, it will not cause discomfortableness to the patients, and will not affect the monitoring data. Various types of textile antennas have been reported recently. In [6], a rectangular patch antenna made by conductive textile is assembled to a two layers of denim substrate. The antenna performs a maximum gain of about 4dBi, however, 2dB gain decrease occurs when the antenna is bent. A PIFA with a slot on the top planar radiator and shorting wall structure is proposed in [7], the antenna has a broad bandwidth and the maximum gain is about 1.5dB. In [8], a planar dipole antenna with rectangular reflector is studied. Compared with in free space, when the antenna is mounted on body, the maximum simulated gain reduced from 0.96 to 0.47dBi, but body-centric wireless communications can still perform well. A truncated sinusoidal printed circuit antenna is discussed in [9], even with extreme bending, the antenna performances like bandwidth and resonant frequency are not significantly affected. Planar monopoles can obtain wide bandwidth with simple structure, compact size and low profile, so they are widely used in textile antenna design [10]–[12]. By carefully designing the truncated ground and the radiation element, good impedance matching through a wide band can be achieved when mounted on human body.

For wearable antennas, in addition to the above requirements, since the antenna is mounted on human body, the backward radiation should be minimized to keep the SAR value in an acceptable level which was set by FCC or ICNIPR [13], [14]. Many methods have been proposed for this design goal. In [15], a cavity is loaded at the back of a slot antenna which was designed for 2.45GHz WBAN application, the SAR level can be significantly reduced, but multi-layer structure is needed and the total height of the antenna was increased. Using reflector element [16] is also effective, however this method also introduces multi-layer structure and sometimes the size of the reflector is larger than the antenna element which enlarge the footprint of the whole antenna system. Ferrite materials and metamaterials were used in [17] to decrease the electromagnetic wave propagating to human body, also a increased height is required. Electromagnetic band-gap (EBG) structures [18], [19] and artificial magnetic conductor (AMC) planes [20]–[22] can also be used in SAR reduction. These designs all need specially design and multi-layer structures, and will complex the manufacturing procedure and increase the profile height.

In this paper, a textile CPW-fed slot antenna with floating ground structure for 5.8GHz ISM applications is proposed. Since nowadays most of the wireless equipment used in hospital works at around 2.4GHz, by choosing the 5.8GHz band, less interference occurs [1]. Meanwhile, higher frequency leads to smaller size of the antenna, which can alleviate the patient's stress when the antenna is worn, and enhance robustness of the antenna to the patients' movement. The proposed antenna can obtain low SAR value without any specially designed methods or using multi-layer structure. Also, forward radiation can be enhanced by using the interaction between slot elements. The rest of the paper is arranged as follows: In Section II, design of the antenna is presented. The experimental results and discussions are provided in Section III, SAR assessment with human tissue models and bending influences are also shown in this section. In Section IV, conclusion is performed.

II. ANTENNA DESIGN

Fig.1 shows the geometry of the antenna. The antenna is located on a low cost, high insulate felt substrate, with a relative permittivity $\varepsilon_r = 1.36$, $\tan\delta = 0.02$, and a thickness of 1mm. The radiation element consists of three slots which are placed on the top of the substrate. The antenna is fed by coplanar waveguide (CPW), and the feeding point in this figure is connected to the inner conductor of a 50ohm coaxial line, while the grounding point is linked to the outer conductor of the coaxial cable. The bottom of the substrate is covered with a whole piece of metallic layer, and designed as a floating ground structure, which means it is not connected with the radiation element or the coaxial cable. This structure can suppress the backward radiation without using specially designed reflector. The conductive parts which surround the slots and form the floating ground are made from conductive cloth MKKTN260 with a conductivity of $9.16 \times 10^6 S/m$. The total footprint of the antenna is only $15 \times 17mm^2$.

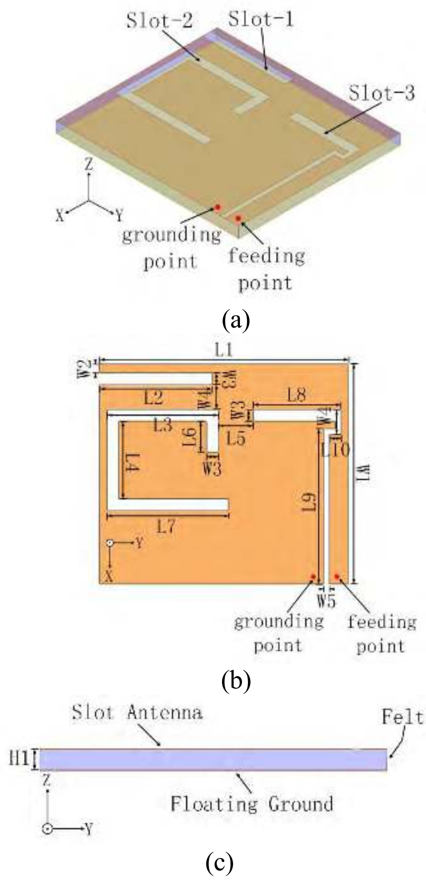


FIGURE 1. Antenna topology. (a) Overall view, (b) top view, (c) side view.

TABLE 1. Antenna parameters (unit: MM).

L1	15	*L9*	1.6
L2	7.5	*L10*	0.8
L3	7.6	*W1*	17
L4	5.3	*W2*	0.6
L5	2.4	*W3*	0.8
L6	2.1	*W4*	1.7
L7	8.3	*W5*	0.4
L8	6	*H1*	1

The simulation is calculated with*HFSS*(Ansys, ver.16), and the optimized parameters are listed in Table 1.

Slot-1 and slot-3 together form the main radiator. The total length of the two slots is 26.4mm, which is about a half wavelength at 5.8GHz. Slot-3 is meandered to make the antenna more compact. In Fig.2(a), the shorten of slot-1(or the shorten of the total length of slot-1 and slot-3) causes the resonance frequency shifts to higher frequency. The width of the vertical part of slot-3 (W5) is decided by the CPW feeding structures. In Fig.2(b), the change of the slots width W3 will cause the shift of resonance frequency, but the bandwidth is almost unaffected. This is because change of W3 mainly affects

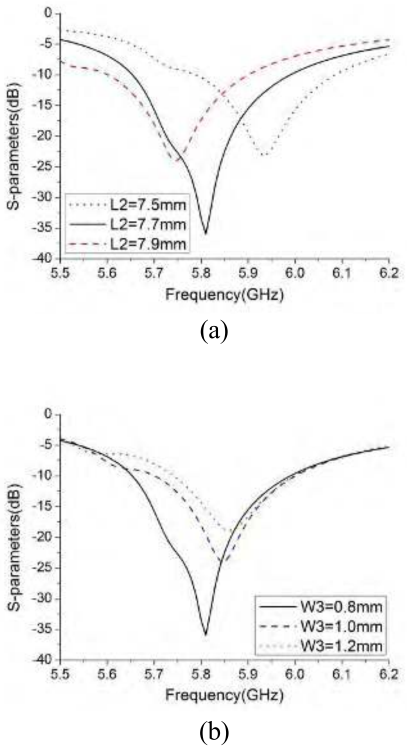


FIGURE 2. Impedance matching analyses for the change of antenna parameters. (a) Change of L2, (b) change of W3.

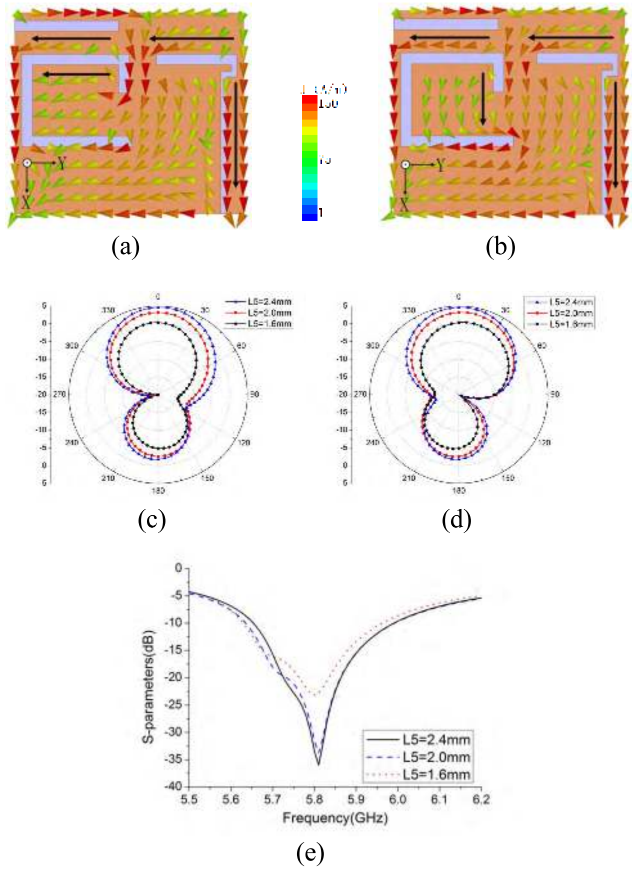


FIGURE 3. Analyses for the change of L5. (a) currents distribution when $L_5 = 1.6mm$, (b) currents distribution when $L_5 = 2.4mm$, (c) radiation pattern in xoz-plane, (d) radiation pattern in yoz-plane, (e) impedance matching with the change of L_5.

the path of surface distributed currents, and generally causes shifts in frequency. While bandwidth is inversely proportional to the quality factor (Q) [23], and the quality factor is related to the radius of the minimum sphere that completely encloses the antenna, which is not affected by the change of W3.

Slot-2 is designed like a split ring. As shown in Fig.3(a) and (b), part of the surface distribution currents can be trapped inside this split ring. By changing the distance between slot-2 and slot-3 (L5), the direction of the trapped currents change accordingly. When $L_5 = 2.4mm$ (Fig.3(b)), the currents flow along the upper edge and inside the split ring just like the currents flow along slot-1 and slot-3. The radiation element works like two antennas with similar radiation characteristics. So the total radiation is strengthened. In Fig.3(c) and (d), we can find that, the forward radiation increases 4.9dB, backward radiation also increases, but compared to the enhancement in the desirable direction, the change is acceptable. As indicated in Fig.3(e), the resonance frequency is not affected by the change of distance between slot-2 and slot-3, while the impedance matching can be affected in some extent.

Since human body has high relative dielectric constant, and may cause influences to the performances of wearable antennas, the proposed antenna is simulated above a cubic human tissue model [24]. As shown in Fig.4(a). The model consists of a 1mm thick skin layer ($\varepsilon_r = 35.11, Conductivity = 3.71S/m$), a 3mm thick fat layer ($\varepsilon_r = 4.95, Conductivity = 0.29S/m$), and a 3mm thick muscle layer ($\varepsilon_r = 48.49, Conductivity = 4.96S/m$). The distance between the antenna and the tissue is H0. In this paper, H0 is set as 3mm and 5mm. In Fig.4(b), we can find that when the antenna is placed in the vicinity of human tissue model, the resonance frequency shifts to higher frequency and the impedance matching is deteriorated. Also, the extent of impact is affected by H0. Radiation pattern is also affected. In Fig.4(c) , for xoz-plane, when with tissue model, the backward radiation (180°) increases about 0.98dB, and the forward radiation (0°) attenuates about 0.8dB. The similar change occurs in yoz-plane. However, the safety of using this antenna can still be proved, and will be discussed in the following section.

III. ANTENNA PERFORMANCES

A. A ANTENNA MEASUREMENTS

Fig.5 shows the photos of the fabricated antenna.

The simulated and measured impedance bandwidth is plotted in Fig.6. The antenna is measured by using *R&S ZNB20* vector network analyzer, while the antenna is mounted on the author's chest and placed in free space, respectively. For both situations, when the antenna is placed on human body, the resonance frequencies shift to higher frequency, and the

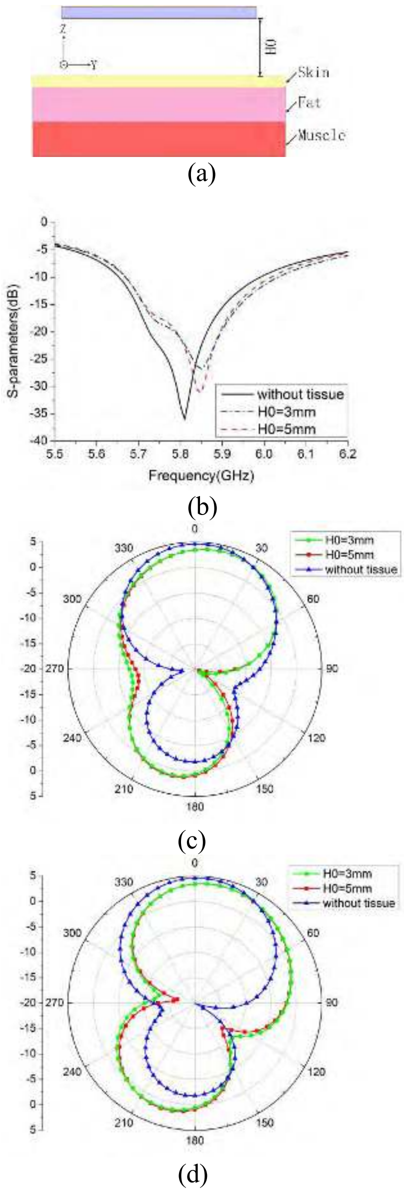


FIGURE 4. How human tissue affects the antenna performances. (a) Simulated human tissues model, (b) S-parameters with tissues model, (c) xoz-plane with tissue model, (d) yoz-plane with tissue model.

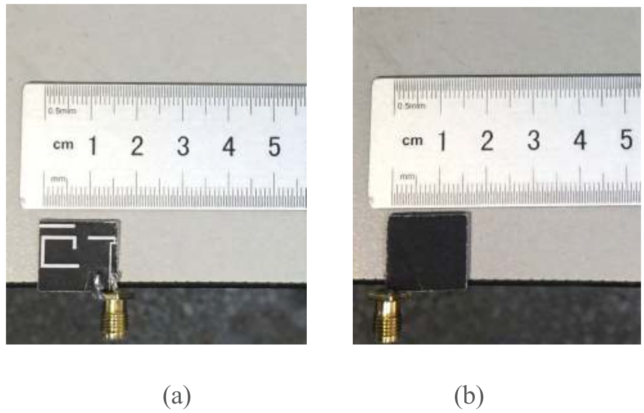


FIGURE 5. Physical map of the antenna. (a) Front, (b) back.

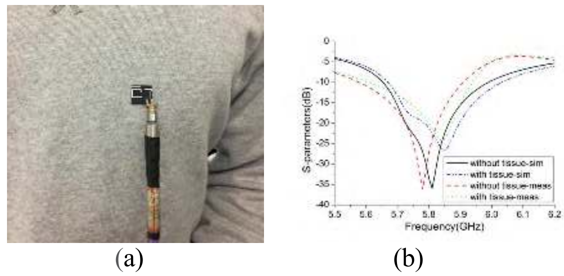


FIGURE 6. Antenna measurement and results. (a) Measure on author's chest, (b) simulated and measured impedance bandwidth.

TABLE 2. Comparisons between this work and recently published papers.

Antennas	Dimensions (λ^3)	Gain (dBi)	Efficiency
[8]	0.33×0.41×0.04	0.47	23%
[13]	0.8×0.8×0.027	3.9	45%
[15]	0.264×0.228×0.064	2.19	50%
[22]	0.77×0.77×0.049	2.22	40%
Proposed	0.278×0.316×0.018	4.85	48%

impedance matching deteriorated, but all of them can cover the aimed 5.8GHz ISM band. The measured results relatively agree with the simulated results, the differences are mainly caused by the fabrication error and the differences of dielectric characteristics between real material and simulation models.

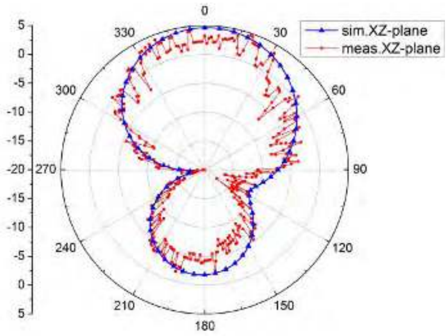
Fig.7 shows the simulated and measured radiation patterns of the proposed antenna. The measured results agree with the simulated ones. Although the use of flexible conductive cloth instead of copper causes higher loss [1], as shown in Fig.8, the measured on-body peak realized gain of our design in the front direction at 5.8GHz is 4.85dBi, and the radiation efficiency is 48%. The comparisons between the performances of our design and recently published wearable antennas are listed in Table 2. From the table we can see that our design is compact in size (small footprint and low height) and has acceptable radiation performances (high gain and relatively high radiation efficiency).

B. SAR

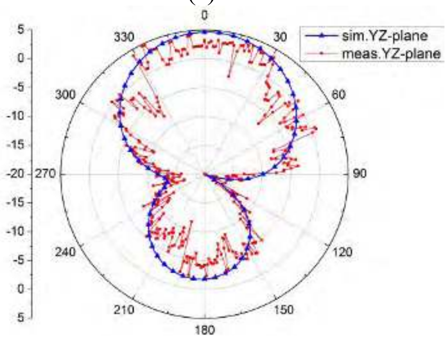
Specific Absorption Ratio (SAR) is a quantitative method for measuring the effect of radiation energy on per unit mass of the human tissues. SAR value can be calculated by using the following equation:

$$SAR = \frac{\sigma E^2}{\rho} \tag{1}$$

While σ is conductivity, E is the electric field intensity,and ρ is the mass density. Fig.9 shows the simulated SAR distributions when the antenna is 3mm away from the three-layer human tissue model [24] (Fig.4(a), H0=3mm), and the input power is set as 200mW. The highest value occurs in the fat layer. As listed in Table 3, the bigger the distance between the antenna and human body, the smaller the value of SAR.



(a)



(b)

FIGURE 7. Simulated and measured radiation patterns. (a) xoz-plane, (b) yoz-plane.

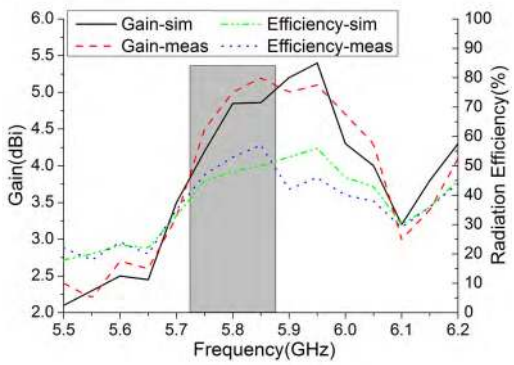


FIGURE 8. Simulated and measured peak realized gain and radiation efficiency of the proposed antenna.

TABLE 3. Peak SAR per 1g tissue values with different distances from tissue model.

H0（mm）	SAR（W/kg）
3	0.61
5	0.37

For all situations, the values are below the IEEE standard threshold of 1.6W/kg per 1g tissue and ICNIPR standard threshold of 2W/kg per 10g tissue.

C. BENDING PERFORMANCES

When a patient is moving or changing positions like bending forward or bending down, the conformal flexible antenna may change from planar to bending configurations. However, the antenna performances are required to remain stable.

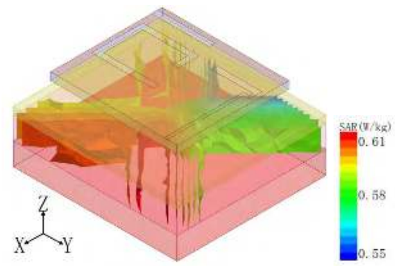
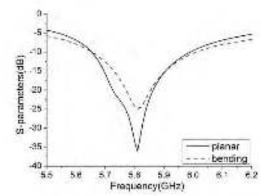
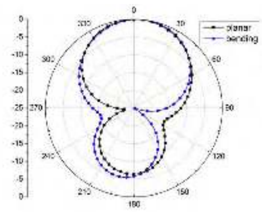


FIGURE 9. SAR distributions when the antenna is 3mm away from the tissue model.

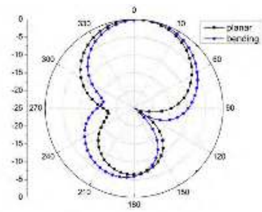
(a)



(b)



(c)



(d)

FIGURE 10. The antenna performances when it is bent. (a) Bent when mounted on the chest, (b) impedance matching, (c) xoz-plane, (d) yoz-plane.

In our design, we assumed that the antenna is mounted on the chest or back of human body, and bending situation occurs as shown in Fig.10(a). The simulated reflection coefficients in the bending state are plotted in Fig.10(b). The bending has nearly no impact on the bandwidth, but impedance matching is deteriorated. However, for the whole 5.8GHz ISM band, the reflection coefficient is below -10 dB, well impedance matching can be realized.

The influences of bending to radiation pattern are shown in Fig.10(c) and (d). The radiation patterns in xoz- and yoz-plane are similar for both configurations. Specifically, bending the antenna changes the forward radiation from 4.93dB to 4.63dB, while backward radiation changes from -1.82dB to -0.83dB.

IV. CONCLUSION

In this paper, a compact, low-profile, flexible slot antenna for medical wearable applications is proposed. Good impedance matching can be obtained when the antenna is mounted on human body. By using floating ground structure and interaction between slot elements, good forward radiation together with low SAR value can be fulfilled. The antenna performances when the antenna is bent show that wireless data transmission can perform effectively during the change of human posture.

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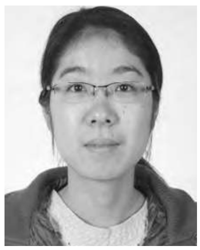

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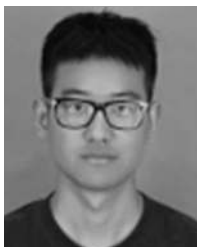

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