Dual-Band On-Body Near Field Antenna for Measuring Deep Core Temperature With a Microwave Radiometer

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ABSTRACT Deep core temperature is the most basic and important information about health conditions. Non-contact infrared thermometers are widely used for human body temperature measurement. However, infrared thermometers are not suitable for deep core temperature measurement. To overcome this limitation, measuring deep core temperature with a microwave radiometer is gaining attention. In this study, we propose a dual-band on-body near-field antenna for measuring deep core temperature with a microwave radiometer application. The proposed antenna has a compact size of 20 mm × 30 mm × 1.52 mm. The negative (-) radiator is located at the top of the substrate and the positive (+) radiator is located at the bottom of the substrate. The dual-band is proposed for high temperature resolution and is achieved by a meander slot on the radiator. The antenna is fabricated on a high dielectric substrate and the stubs are proposed to reduce the size of the proposed antenna so that it can be used on various human body parts.

INDEX TERMS Deep core temperature measurement, dual-band antenna, on-body antenna, microwave radiometer.

I. INTRODUCTION

Bioelectronic devices or biosensors are becoming increasingly important in the medical field as they are used to detect diseases and monitor medical information [1]–[8]. Among the important medical factors, body temperature is the most important indicator of health problems and is often used for early detection of health problems. Recently, the spread of COVID-19 has caused fever, cough, shortness of breath, muscle pain, and headache to numerous people. Among these symptoms, fever and body temperature are the easiest and earliest indicators of COVID-19 infection, so early body temperature detection is of extreme importance.

Currently, non-contact infrared thermometers are widely used to check body temperature. However, they cannot measure the deep core body temperature, that is, in organs and muscles [9]. When the body temperature changes, the muscle temperature changes first, and the skin temperature changes afterward [10]. Therefore, it is important to measure the deep core body temperature, such as that of the muscles, to quickly detect health problems.

There are two types of deep core temperature measurement, invasive and non-invasive [11]. Invasive methods penetrate through skin, fat, and muscle to measure deep core temperature. Therefore, invasive methods injure skin, fat, and muscle. In contrast, non-invasive methods do not penetrate through skin, fat, and muscle, they only come into contract with the skin and do not cause any damage. For this reason, non-invasive methods are preferred for measuring deep core temperature.

However, deep core temperature measurement is difficult via non-invasive methods. To overcome this limitation, deep core temperature measurement using microwaves is brought into focus. The main theory for measuring deep core body...
FIGURE 1. (a) Planck’s law of blackbody radiation, (b) microwave radiometer block diagram for measuring the deep core temperature, (c) antenna on the forehead, (d) antenna on the wrist, and (e) proposed antenna on muscle, fat, skin and thin PVC film.

temperature is Planck’s law for blackbody radiation, as shown in Fig.1 (a). All objects with a non-zero absolute temperature radiate electromagnetic energy. According to Planck’s law for blackbody radiation, an object that absorbs energy perfectly, radiates an electromagnetic field [12]. We can apply this theory to the human body. The deep core tissue of a human being absorbs energy and radiates an electromagnetic field. In this electromagnetic field, most of the infrared radiation is reabsorbed by the deep core tissue, but microwave radiation is transmitted through the deep core tissue to the skin. By receiving these microwaves, the deep core temperature can be measured. Consequently, the antenna of the microwave radiometer system must be able to receive the microwaves from the deep core tissue well.

Dicke proposed a radiometer with one reference load for calibration with the antenna temperature and measured thermal microwave radiation [13]. Goodberlet and Mead [14], used two reference loads, a hot and cold reference, for higher calibration resolution. Fig.1 (b) shows the microwave radiometer block diagram for measuring the deep core temperature. In this block diagram, hot and cold reference loads are constantly calibrating with the antenna temperature. An envelop detector modulates the input signal to DC output. Then, a switch sorts out the antenna and reference signals. However, the signal is too small to use. Therefore, an adder and integrator increase the output to use this signal.

Deep core temperature measurement systems using microwave radiometry have been studied before. However, most previous studies did not focus on the antenna for deep core temperature measurement using microwave radiometers [15]–[18]. If the antenna is designed without considering the human body, it may not work properly. Due to the influence of the human body, the operating frequency of the antenna can be interrupted or shifted [19]. When designing an antenna for the human body, three things must be considered.

First, it is difficult to design an antenna due to the high relative permittivity and conductivity of the human body. We can divide the components of the skin, fat and muscle. The relative permittivity and conductivity of the skin, fat, and muscle have been studied [20]. Based on these studies, we developed an antenna for muscle \( (\varepsilon_r = 54.112, \sigma = 1.142 \ \text{S/m}, \tan \delta = 0.279) \), fat \( (\varepsilon_r = 5.395, \sigma = 0.065 \ \text{S/m}, \tan \delta = 0.154) \), and skin \( (\varepsilon_r = 39.661, \sigma = 1.036 \ \text{S/m}, \tan \delta = 0.335) \).

Second, the different thickness of skin, fat and muscle on different parts of the body such as forehead and wrist should be considered. People always expose their forehead and wrist even when they are wearing clothes. This makes easy to attach...
the antenna to the wrist and forehead. Therefore, forehead and wrist are selected as the target area of the human body. Thus, we consider thickness of the skin, fat and muscles at forehead and wrist [21]–[24]. Fig.1 (c) and (d) show the antenna on the forehead and wrist.

Finally, the antenna must have a low profile and volume. As the area of a person’s wrist is not large, a small antenna is preferred.

The placement of the antenna on the human body has already been studied [25]–[28]. Most body-worn antennas are focused on wearable or internet of thing (IoT) devices. In addition, most body antennas focus on the 2.4 GHz industrial scientific, and medical (ISM) bands for communications. However, ISM bands are often used for communications. This increases the possibility of radio interference. The operating frequency of on-body antenna for deep core temperature measurement with a microwave radiometer must take into account the penetration depth of microwaves into tissues (muscles, skin, and internal organs). Microwaves have a penetration depth of about 1 cm to 3 cm between 0.1 GHz and 3 GHz [29]. The microwave penetration depth decreases significantly above 3 GHz.

If the frequency is low, the microwave penetration depth increases. However, this increases the antenna size and makes it application to the human wrist and forehead difficult. If the frequency is high, the antenna size becomes more compact. However, this, in turn, decreases the microwave penetration depth.

Considering the microwave penetration depth and antenna size, the operating frequency of the body antenna for deep core temperature measurement with a microwave radiometer should be selected between 1 and 3 GHz. Previous studies have proposed measurements for human tissue but using animal skin, fat, and muscle [30]–[33]. However, animal tissue thickness and relative permittivity are different from those of human tissue [34]. To achieve accurate results, our measurements were performed on the human body.

In this study, a dual-band body antenna for microwave radiometer is proposed. The proposed antenna achieves the dual-band by meandered slot on the radiator and compact size by using a stub located on the side of the radiator and a high relative permittivity substrate. The proposed antenna is simulated using Ansys HFSS 2021. In the simulation, antenna impedance matching was simulated over different skin, fat, and muscle thicknesses on the forehead and wrist. The proposed antenna was attached to the wrist and forehead of individuals to measure the reflection coefficient of the antenna. The proposed bio-matched antenna has sufficient impedance bandwidth and volume loss density for measuring deep core temperature with a microwave radiometer.

The remainder of this paper is organized as follows. Section II describes the antenna configuration and design. Section III presents the simulated and measured results of the proposed antenna. Finally, our main conclusions are drawn in Section IV.

II. ANTENNA CONFIGURATION AND DESIGN

The antenna for measuring deep core temperature with a microwave radiometer must be able to be placed on the wrist and forehead. Therefore, a low-height and small-size microstrip antenna is preferred. The total power received from the deep core body tissue can be analyzed with the radiometric temperature of the antenna. The radiometric temperature of the antenna can be calculated using (1), where \( P \) is the total power received from the tissue, \( k \) is the Boltzmann constant and \( B \) is the bandwidth of the antenna.

\[
T = \frac{P}{kB}
\]  

(1)

This shows that the antenna for radiometry should have sufficient bandwidth to achieve high temperature resolution.

In an ideal situation, an ultra-wideband (UWB) antenna can receive more power than dual and single-band antennas. In real-world situations, many wireless devices communicate with each other with different frequency bands. This unwanted frequency can cause radio interference and the antenna can receive unwanted signals from ISM, long-term evolution (LTE), and 5G new radio (NR) bands, among others. Therefore, it is important to avoid popular frequency bands and have sufficient bandwidth for receiving dep core signals. UWB antennas are very likely to receive unwanted signals due to their ultra-wide bandwidth.

Conventional microstrip patch antennas have a narrow bandwidth, and it is difficult to achieve sufficient bandwidth for a microwave radiometer. To achieve sufficient bandwidth, a printed antipodal bow-tie antenna is chosen.

Fig.1 (e) shows the overall view of the proposed dual-band on-body antenna for measuring deep core temperature with a microwave radiometer. The antenna is placed on the human wrist and forehead. The antenna is located on muscle \( (\varepsilon_r = 54.112, \sigma = 1.142 \text{ S/m}, \tan\delta = 0.279) \), fat \( (\varepsilon_r = 5.395, \sigma = 0.065 \text{ S/m}, \tan\delta = 0.154) \), skin \( (\varepsilon_r = 39.661, \sigma = 1.036 \text{ S/m}, \tan\delta = 0.335) \), and replaceable thin polyvinyl chloride (PVC; \( \varepsilon_r = 2.7, \tan\delta = 0.007, \text{ thickness} = 0.1 \text{ mm}) \). The thin PVC is used for hygienic reasons. The antenna is built on a high dielectric constant substrate Taconic RF-10 \( (\varepsilon_r = 10.2, \tan\delta = 0.0025, \text{ thickness} = 1.52 \text{ mm}) \) to reduce the volume of the antenna.

The bow-tie antenna design equation can be approximated by (2) and (3) [35].

\[
a = \frac{2c}{2f_r\sqrt{\varepsilon_r}}
\]  

(2)

\[
a_{eff} = a + \frac{h}{\sqrt{\varepsilon_r}}
\]  

(3)

In (2) and (3), \( c \) is the speed of light, \( a \) is the side length of the bow-tie antenna, \( a_{eff} \) is the effective value of the side length of the bow-tie antenna, \( f_r \) is the resonant frequency of the antenna and \( \varepsilon_r \) is the relative permittivity of the substrate.

Fig. 2 shows the detailed view of proposed biologically matched dual-band antenna for a microwave radiometer. The overall size of the proposed antenna is 20 mm \( \times \) 30 mm \( \times \) 1.52 mm. The (-) radiator is located on the top side of the
The dual-band antenna for temperature measurement by microwave radiometry can achieve higher temperature resolution than a single band antenna. There are several ways to achieve dual-band in a microstrip patch antenna. The most common methods to achieve dual-band in printed antennas are using slots \([36]-[40]\) and multiple layers \([41]-[44]\). The multilayer method is not cost effective and difficult to apply to a printed bow-tie antenna. The folded slot is located in the center of the radiator and is designed to resonate at 1.35 GHz. The length of the folded slot is 45.04 mm \((\approx \lambda_r \text{ at } 1.35 \text{ GHz})\). Fig. 3(a) shows the \(S_{11}\) simulation of the proposed antenna with and without the meandered slot. It shows that the slot is in resonance at 1.35 GHz. Furthermore, slots also resonate around 1.8 GHz.

The effective calculated value of the side length of the bow-tie antenna is 23.24 mm for 2.75 GHz. To reduce the size of the antenna, we added a 6 mm stub to the side of the bow-tie antenna. The side length of the radiator is reduced from 23.24 mm to 8.35 mm by using the stub. Fig. 3(b) shows the simulation of \(S_{11}\) of the proposed antenna as a function of stub length. The antenna is simulated on muscle (thickness = 41.6 mm), fat (thickness = 10.35 mm), skin (thickness = 1.87 mm) and PVC film (thickness = 0.1 mm). This shows that the stub length determines the resonant frequency.

Fig. 4 shows the current distribution of the proposed antenna at 1.35 GHz, 1.8 GHz, and 2.75 GHz. As can be seen, a strong current flows around the slot located on the center of the radiator at 1.35 GHz and 1.8 GHz, but not at 2.75 GHz.

Fig. 5 shows the bottom and top view of a prototype of the proposed antenna fabricated on Taconic RF-10 (\(\varepsilon_r = 10.2, \tan\delta = 0.0025, \text{ thickness } = 1.52 \text{ mm}\)). The bottom side of the antenna, which is a positive radiator, is in contact with the human body, while the top of the antenna, which is a negative radiator, is in contact with the SMA ground.

### III. SIMULATED AND MEASURED RESULTS

The main objective of this study is core temperature measurement by touching the forehead or wrist. However, the thickness of the skin, fat, and muscles on the forehead and wrist are different. Therefore, the proposed antenna should be able to work on both the wrist and forehead. Fig. 6 shows the proposed antenna on the wrist and forehead with different.
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FIGURE 6. The proposed antenna on (a) wrist (b) forehead thickness.

FIGURE 7. Simulated and measured $S_{11}$ on the wrist, forehead and free-standing.

FIGURE 8. Simulated and measured (a) peak gain and (b) radiation efficiency of the proposed antenna.

FIGURE 9. Simulated and measured normalized radiation patterns in free-standing status at (a) 1.64, (b) 1.98, and (c) 2.98 GHz and on the wrist and forehead at (d) 1.35, and (e) 2.75 GHz.

muscle, fat, and skin thickness. Fig. 7 shows the simulated and measured $S_{11}$ when the antenna is placed on the wrist and forehead. The proposed antenna has simulated resonant frequencies of approximately 1.64, 1.98, and 2.98 GHz and measured resonant frequencies of approximately 1.66, 1.97 and 2.33 GHz with not enough $S_{11}$ values when antenna is free-standing. However, it has a good $S_{11}$ value when the antenna is on the wrist and forehead. The simulated results show an impedance bandwidth of 25.18 % (1.18 – 1.52 GHz) and 12.2 % (2.54 – 2.87 GHz) when the proposed antenna is on the wrist and 26.67 % (1.17 – 1.53 GHz) and 11.85 % (2.54 – 2.86 GHz) when the proposed antenna is on the forehead. In contrast, the measured results have an impedance bandwidth of 92.88 % (1.28 – 3.5 GHz) when the proposed antenna is on the wrist and 94.73 % (1.25 – 3.5 GHz) when it is on the forehead. The simulated and measured results agreed well at 1.35 GHz. However, above 1.5 GHz, the measured results show better reflection coefficient values and wider impedance bandwidth than the simulated results. This is because the area of the human wrist and forehead is larger than the skin, fat, and muscle area assumed in the simulation.

Fig. 8 shows the simulated and measured radiation efficiency and peak gain when the proposed antenna is on free standing status, wrist, and forehead. The proposed antenna at free-standing has a peak gain of 2.14 dB at 3.24 GHz with a radiation efficiency of over 90 %. The proposed antenna’s peak gain and radiation efficiency are significantly decreased by the phantom thick layer when antenna is on the wrist and forehead. Fig. 9 shows the simulated and measured normalized radiation patterns of the proposed antenna according to elevation. It has an omnidirectional radiation pattern when the antenna is free-standing. However, the antenna’s radiation pattern is distorted by a thick layer of skin, fat, and muscle when the antenna is on the forehead. 1.64 and 1.98 GHz are radiated and resonated by the slot on the bow-tie radiator, and 2.98 GHz is resonated and radiated by the bow-tie radiator when the antenna is in free-standing status.

According to Planck’s law for blackbody radiation, thermal noise power is delivered to the deep core body tissue. It is
TABLE 1. Comparison with the antenna applied on a microwave radiometer to measure deep core temperature.

| Reference | Antenna Type          | Measurement                           | Operating Frequency (GHz) | Size (mm) |
|-----------|-----------------------|---------------------------------------|---------------------------|-----------|
| [13]      | Metallic sheet antenna| On powder samples                     | 3.05–3.55                 | 32 x 32 (0.32λ x 0.32λ) |
| [14]      | Cavity back slot antenna | On artificial human core model          | 1.2 – 1.6                 | 45 x45 x27 (0.18λ x 0.18λ x 0.1λ) |
| [15]      | Horn antenna          | Toward water                           | 4 - 6                     | 88.04 x89.05 x4 x 9.08 (1.172 x 1.182 x 0.652λ) |
| [16]      | Circular patch antenna| On salmon and water                    | 1.265 – 1.535             | 45 x45 x27 (0.17λ x 0.17λ x 0.01λ) |
| Proposed  | Printed bow-tie antenna | On human wrist and forehead             | 1.25 – 3.5                | 45 x45 x27 (0.08λ x 0.12λ x 0.006λ) |

FIGURE 10. Simulated volume loss density on the wrist at (a) 1.35 GHz, (b) 2.75 GHz and the forehead at (c) 1.35 GHz, (d) 2.75 GHz.

important to analyze the area that the antenna can detect in the various deep body tissues. This can be analyzed using the power density volume loss [45]. As the skin, fat, and muscle have different volume, relative permittivity, and conductivity, we can assume that the antenna sits on the three different sub-volumes. The volume power loss density is integrated over each sub-volume to determine the power loss in that specific volume.

The volume power loss density can be calculated using (4) where $E$ is the electric field, $J$ is the current density and $H$ is the magnetic field. Fig. 10 shows the simulated volume power loss density at the forehead and wrist at 1.35 GHz and 2.75 GHz.

$$P_v = \text{Re}(E \cdot J^* + j\omega \mu \cdot H^*)/2 \quad (4)$$

The forehead has a much thinner skin, fat, and muscle layer than the wrist. Therefore, the forehead has a very high volume loss density value. Conversely, the wrist has thicker skin, fat, and muscle layer than the forehead, it has low volume loss density value. Therefore, the wrist volume loss density should be considered first. It has peak volume loss density of $7.6 \times 10^4 W/m^3$ at 1.35 GHz and 2.75 GHz on the wrist muscle layer. The wrist muscle layer has volume loss density values between $4.4 \times 10^2 W/m^3$ and $2.1 \times 10^4 W/m^3$ at 1.35 GHz and $4.4 \times 10^2 W/m^3$ and $7.6 \times 10^4 W/m^3$ at 2.75 GHz.

Table 1 shows a comparison with the antenna applied on a microwave radiometer to measure deep core temperature. Most of the research on measuring human deep core temperature with a microwave radiometer did not focus on the antenna and on achieving a compact size.

When antenna is not compact in size and has a large volume, it is hard to apply on the human wrist and forehead. Usually, the human wrist width is approximately 5 cm, so the antenna size should be less than 5 cm. Even if the forehead is wider than the wrist, it has a curved surface. This curved surface makes the full contact between the antenna forehead difficult. When antenna is not in full contact with the forehead or wrist, the resonant frequency can be shifted. Additionally, receiving signals from deep core temperature can be weakened. A small antenna can be easily applied on the wrist and forehead regardless of their width and curved surface. To the best of our knowledge, the antenna proposed in this study has the smallest and most compact size.

IV. CONCLUSION

In this study we propose a dual-band on-body near-field antenna for deep core temperature measurement with a microwave radiometer. Most previous studies on deep core temperature measurement using a microwave radiometer did not consider the antenna's characteristics. They simply design the antenna without considering the human body and compact size. The printed bow-tie antenna was selected because of its sufficient impedance bandwidth and low profile. The antenna is applied to muscle ($\varepsilon_r = 54.112$, $\sigma = 1.142$ S/m, $\tan\delta = 0.279$), fat ($\varepsilon_r = 5.395$, $\sigma = 0.065$ S/m, $\tan\delta = 0.154$), skin ($\varepsilon_r = 39.661$, $\sigma = 1.036$ S/m,
tan δ = 0.335, and a replaceable thin PVC (εr = 2.7, tan δ = 0.007, thickness = 0.1 mm). The proposed antenna is fabricated on high relative permittivity substrate RF-10 (εr = 10.2, tan δ = 0.0025, thickness = 1.52 mm). The most important components of the antenna are the slot and stubs located on the side of the radiator. The length of the meander slot is almost half the wavelength of the lowest resonant frequency and is intended for the dual-band. The stubs located on the side of the radiator are used to reduce the size of the antenna. As the stub length increases, the operating frequency shifts to a lower band. The antenna size is 20 mm × 30 mm × 1.52 mm. The proposed antenna resonates at 1.56, 1.9, and 2.35 GHz when the antenna is free-standing. However, it does not have a good S11 value, as we designed and fabricated the antenna to match the impedance on the human wrist and forehead. It has a measured impedance bandwidth of 92.88% (1.28 – 3.5 GHz) when the antenna is placed on the wrist and 94.73% (1.25 – 3.5 GHz) when it is placed on the forehead. Although, this antenna has low gain on the forehead and wrist, it will receive signals from the near-field area and has sufficient volume loss power density to measure the deep core temperature. Therefore, the proposed antenna is well suited for deep core temperature measurement with a microwave radiometer and will aid deep core body temperature measurement in the future.

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