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Design and Simulation of an Antenna for Non-invasive Temperature Detection Using Microwave Radiometry

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Abstract—A non-invasive thermometry approach for monitoring core (internal) tissue temperature using microwave radiometry is presented. We detail the design and analyses of a microwave antenna capable of detecting core temperature at depth. Performance of the radiometer with a printed dipole antenna is evaluated at frequency of 1.4 GHz in a multilayer 3D computational structure consisting of skin, fat, and muscle. To study this approach, a human tissue model was constructed with skin, fat, and deep muscle tissues having electrical properties at working frequency of 1.4 GHz. One of the main challenges is the Radio Frequency (RF) interface; hence, frequency selection will be important. Moreover, the antenna must be designed for characteristics in close proximity of biological medium in the selected frequency band. The Specific Absorption Rate (SAR) and volume loss density have been used to determine the amount of absorbed power in each tissue layer and thus emitted power from each tissue layer. This approach has been designed to detect thermal emissions radiated from tissue up to 23 mm deep. We present the numerical analysis of 3D tissue-layer power emission and temperature sensing by a microwave radiometric antenna from a single frequency band of 1.4 GHz. Computed results show that this method senses the internal temperature in each tissue layer.

1. INTRODUCTION

The internal environment of the body or core body temperature is an important factor for body health and functionalities. The human body must maintain the right internal temperature, even though core body temperature fluctuates. The core temperature is usually considered to be the temperature of internal body organs which can differ significantly from body surface. Therefore, there is strong interest not only in the medical applications but also in the field of sports and fitness to have noninvasive measurements of body core temperature.

Taking body temperature is a relatively simple procedure and could be done from wide range of methods, such as oral, ear, armpit, and forehead. The primary goal of taking measurements in clinical settings is to obtain an estimate of a patient's core body temperature. In fact, noninvasive methods actually measure only surface temperature or represent an average body temperature, hence, unreliable for the prediction of deep body core temperature [1].

The current methods for body core temperature measurements are invasive, such as rectum, esophagus, and pulmonary artery [2, 3]. The measurement by pulmonary artery is considered the most accurate since the artery brings blood directly from the core and its surroundings [4]. The placement of internal temperature probes is not without risk, uncomfortable, and may require anesthesia [5].

Noninvasive radiometric sensing has been used for thermal monitoring of hyperthermia temperature [6], deep brain temperature in infants [7], and for vesicoureteral reflux [8, 9].

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The law of blackbody radiation indicates that all objects with a temperature above absolute zero radiate electromagnetic emission over all frequencies due to thermally induced vibration. The temperature of the object determines the amount of energy radiated at each frequency. The higher the temperature is, the higher the energy is radiated. The blackbody radiation shows that to stay in thermal equilibrium, it must emit radiation at the same rate as it absorbs it. The measurement of natural electromagnetic radiation at microwave frequencies from human tissues allows the detection of thermal conditions that exist in the human tissues. The principal concept in a microwave radiometer is to compute or measure the thermal emitted power in a given frequency band from a volume in the field of view of the detecting antenna. Microwave remote sensing can be divided into two wide categories: passive, well-known as radiometers, and active, identified as radars [10, 11]. In radiometric sensing, the antenna is in the passive mode that collects power emitted from tissue.

The noise power $P(W)$ at temperature T (K) over a frequency band Δf (Hz) can be written [12]:

$$P = k_B T \Delta f \tag{1}$$

where k_B is the Boltzmann's constant (1.38×10^{-23} J/K).

An antenna beam pattern with a solid angle $d\Omega$ will capture an extended brightness source of interest when the antenna is pointed toward the direction of concern. One of the significant parameters to this development is the gain of the antenna. Therefore, the collected power by the antenna with respect to the total gain of the radiometer is given by [13]:

$$P = G k_B T \Delta f \tag{2}$$

where G is the antenna or total radiometer gain.

When the solid angle of the object is much larger than the antenna's solid angle as shown in Fig. 1, the radiometric temperature that is captured by a loss free antenna is equal to the object's temperature.

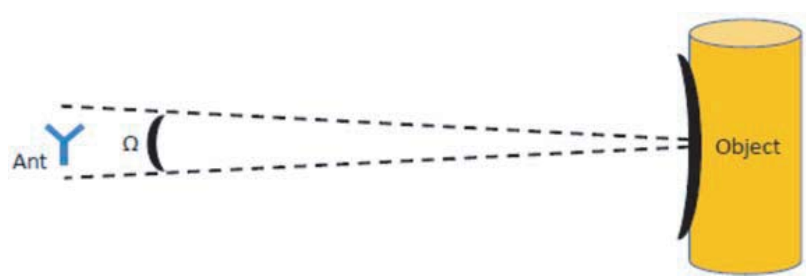


Figure 1. Antenna solid angle.

The antenna temperature T_{Ant} can be written [14]:

$$T_{Ant} = \frac{1}{d\Omega} \int_0^{\pi} \int_0^{2\pi} F(\theta, \phi) T_{Obj}(\theta, \phi) d\Omega \tag{3}$$

where $F(\theta, \phi)$ is the power pattern function of θ, ϕ which are the spherical coordinate angles, and T_{Obj} is the effective temperature of the object.

The microwave radiation from the human body has extremely low power levels; therefore, it is important to have a steady and sensitive radiometer to be able to detect the small variations of temperature [15].

This paper focuses on the design and optimization of a microwave antenna capable of sensing temperature at each tissue layer, i.e., skin fat, and muscle, using a 3D multilayer tissue model for computational studies.

The rest of this paper is organized as follows. In Section 2, we present the frequency band selection and radiometer probe design. Numerical analysis, results, and discussions are presented in Section 3. Finally, Section 4 provides conclusions and the future works.

2. FREQUENCY BAND AND PROBE DESIGN

As the microwave radiometry does not need to operate in an active mode or generate microwave signal, there is a huge flexibility in the selection of the frequency band. However, in the case of noninvasive body radiometer, the frequency of operation has strong impact to have estimation of the temperature with minimum errors. The operation frequency of the microwave radiometer should avoid interference from wide range of terrestrial wireless systems. Besides the Radio Frequency (RF) interference effect, the frequency selection is a tradeoff between antenna size and penetration depth into biological tissues. Higher frequency will give chance to have a smaller antenna at the cost of low penetration depth, while lower frequency band provides deeper penetration depth with larger size antenna [16]. Moreover, the choice of a frequency band is determined not only by the tissue electrical properties (e.g., penetration depth), but also by the possible amount of the radio interference in the surroundings.

One of the possible candidate frequencies is the frequency band of 1.4–1.427 GHz which is allocated to the Earth Exploration-Satellite Service (EESS), radio astronomy, and space research services on a primary basis and allows for sufficient detection of emissions deep within the body. All emissions are prohibited in this band according to the International Telecommunication Union-Radio communication (ITU-R) [17].

Many factors may degrade the RF-wave in radiometers, and as antenna is in close proximity of body tissues, electrical properties of tissues are one of the main concerns to make sure that antenna is properly matched to the tissue properties for maximum sensitivity in the selected frequency band. Table 1 provides human tissue electrical properties, i.e., relative permittivity (ε_r), conductivity (σ), loss tangent ($\tan\delta$), and penetration depth at the frequency of 1.4 GHz [18, 19].

Table 1. Electrical properties of tissues at 1.4 GHz.

	Relative Permittivity	Conductivity (S/m)	Loss Tangent	Penetration Depth (mm)
Skin	39.661	1.035	0.335	32
Fat	5.395	0.064	0.154	190
Muscle	54.112	1.141	0.270	34

The antenna will be placed on the body surface, as a result of direct contact with skin tissue, hence, there is no air gap to design an antenna in the free space environment; therefore, tissues' electrical properties provided in Table 1 were used in the time of antenna design. The design goal is to have a small form factor, light weight and thin antenna that can be held in any location on the body surface. In [20], a printed dipole antenna for total power radiometer is investigated for antenna and body tissue effects such as antenna-body impedance mismatch, resonance shifts, pattern, and bandwidth degradation. A dual-band microwave radiometer with a multiple folded dipole antenna was proposed in [21]. A circular microstrip patch due to its size and simplicity, as well as partial radio frequency interface shielding by the ground plane at frequency band of 1.4 GHz is presented in [22].

A folded arms printed dipole antenna is presented here. The antenna is a three-layer structure; substrate, single side metalized and superstrate. The antenna has been built on an FR4-Epoxy substrate with the thickness of 2 mm which has relative permittivity of $\varepsilon_r = 4.4$ and dielectric loss tangent of $\tan\delta = 0.02$. The copper cladding, radiating element, has the thickness of 0.036 mm.

The antenna has been covered with an FR4-Epoxy superstrate layer with thickness of 2.54 mm. The proposed antenna is shown in Fig. 2, with the total dimension (including feedline) of 19 mm × 20 mm × 4.576 mm. The antenna is placed on the top of a 3D tissue layer structure, consisting of skin with thickness 1 mm, fat with thickness 2 mm, and muscle with thickness 20 mm.

The antenna characteristics in close proximity to the body tissue are studied, to make sure that the antenna resonates at required frequency, as electrical properties of tissues might affect the input impedance of antenna and therefore disturb the antenna scattering parameters. One of the most critical parameters of a radiometric antenna is its beam efficiency. Beam efficiency may be defined as the

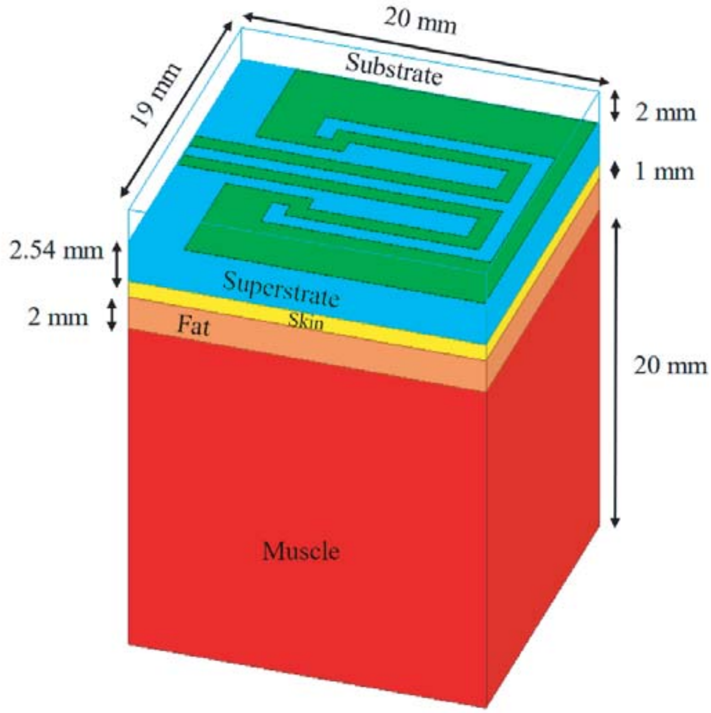
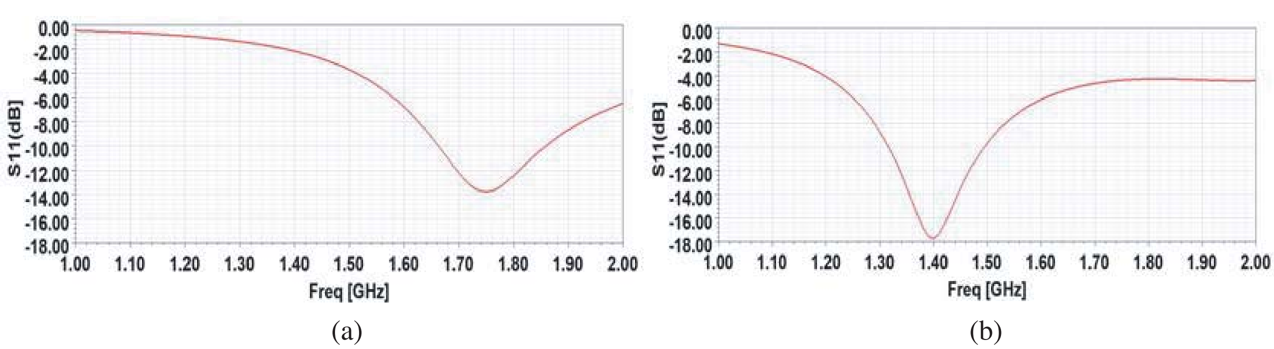
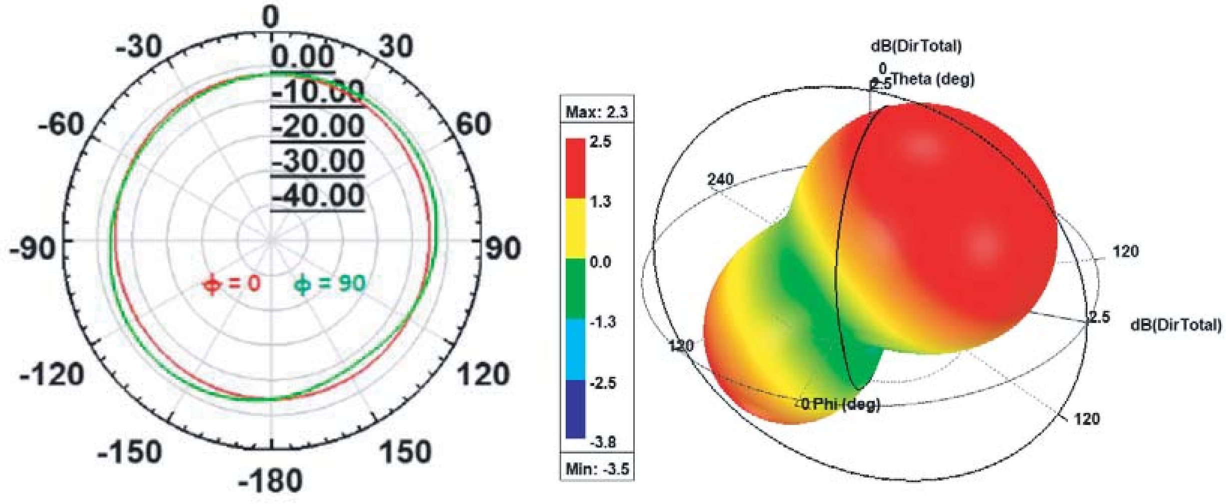


Figure 2. Antenna configuration and dimensions with three-layer tissue structure.

total radiated power that lies within the main beam when the antenna is viewed as a transmitting antenna. Conversely, according to the reciprocity theorem, as a receiving antenna, it is the total received power from a source, all at one temperature (single frequency), which comes through the main beam. It is a measure of how well the antenna differentiates against sources outside the main beam [23]. The directionality of the antenna allows focusing on the incoming radiation. The return loss, 2D radiation pattern, and 3D total directive gain pattern of antenna in close proximity to the skin tissue are presented in Fig. 3. It shows that the antenna has an impedance bandwidth of -15 dB in the selected frequency band of 1.4–1.427 GHz. To demonstrate the effect of electrical properties of tissues on antenna characteristics, the antenna's return loss without three-layer tissue is also shown in Fig. 3.

It is required to have a directive gain as much as possible for focused sensing due to low power emitted of core tissue. The proposed antenna design with a small size of $19 \times 20\,\text{mm}^2$ provides a good directive gain of 2.3 dB as shown in Fig. 3(d). It should be noted that the output voltage of a total emission received by the antenna is directly proportional to the overall gain of the antenna, hence, it is of interest to have a gain with minimum fluctuations and close to a constant value.





(c) (d)

Figure 3. (a) Antenna return loss without three-layer tissue; antenna (b) return loss, (c) 2D radiation pattern, and (d) 3D total directive gain, while on touch to the skin tissue.

3. NUMERICAL ANALYSIS AND RESULTS

Despite that Specific Absorption Rate (SAR) is normally used to determine how much power absorbed by tissue from a RF-wave source, due to reciprocity, the received power in the passive mode is the same as radiated power in the active mode. Therefore, computational studies are valid for the active as well as passive modes. Computational model and studies have been implemented using the High Frequency Structure Simulator (HFSS), based on the Finite Element Method (FEM) from ANSYS electronic desktop (2019 R2) [24]. To begin with, the simulations were performed in the active mode, when the antenna acts as transmitter, and energy is radiated to the three-layer tissue structure and as a result absorbed by the tissues underlying the antenna. Simulated SAR fields at frequency of 1.4 GHz for skin, fat, and muscle are shown in Fig. 4.

The antenna feed lines are an integrated part of the radiating element; hence no port matching is required. This will support the canceling of a possible source of heat that could affect the temperature measurements. The ideal impedance match does not support and assure best efficiency to collect emitted power from a particular object at depth. The antenna radiation efficiency is shown in Fig. 5.

As pointed earlier, from the reciprocity theorem the power deposition by the antenna is the same as the received emission pattern by the antenna. The antenna brightness temperature, the temperature sensed by an antenna, is a volumetric measure of the temperature seen by the antenna. Therefore, the amount of electromagnetic power concentrated into a volume of the tissue to produce a thermal emission is considered. The radiation from selected area is the sum of the power radiated at all frequencies, and captured emission is within the antenna bandwidth.

The antenna power density pattern can be written [25]:

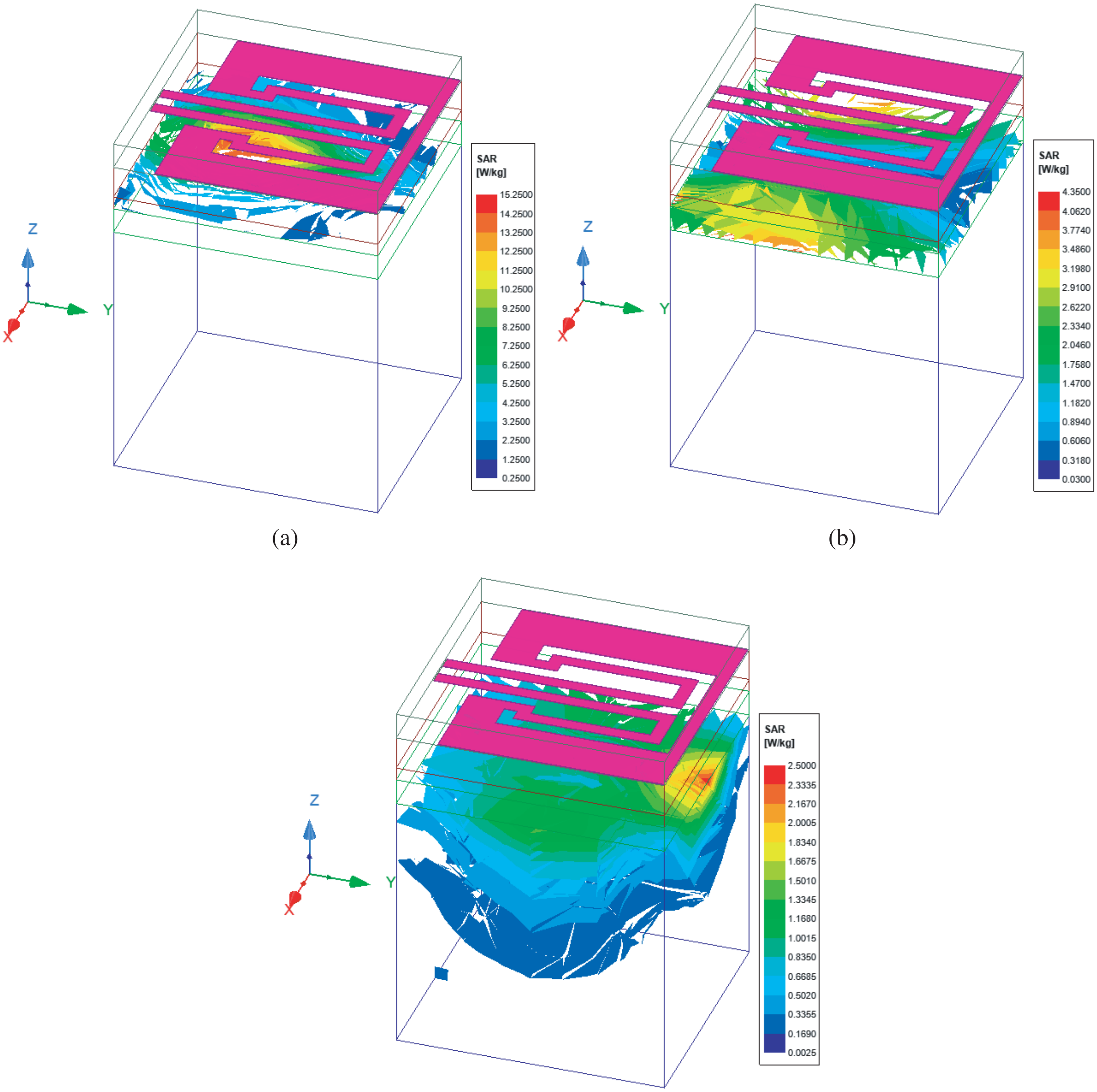
$$P_d = \frac{1}{2}\sigma\left(\vec{r}, f\right)\left|E(\vec{r}, f)\right|^2 \tag{4}$$

where P_d is the power density (W/m^3), σ the conductivity of medium, and E the electric field (V/m) inside the sensing volume V.

Simulated volume loss density (W/m^3) in the three-layer tissue model when antenna is fed with 1 V of input voltage and antenna port has the input impedance of 50 Ω, shown in Fig. 6.

The volume loss density can be calculated by considering the point form of the complex Poynting vector as:

$$\rho_v = -\frac{1}{2}\text{Re}\left\{\nabla\cdot\left(E \times H^*\right)\right\} \tag{5}$$



(c)

Figure 4. Simulated SAR at frequency of 1.4 GHz for (a) skin, (b) fat, and (c) muscle.

where ρ_v is the volume loss density, and H is the conjugate of the magnetic field.

In the computational analysis, the volume loss density was calculated by [24]

$$\rho_v = \frac{1}{2}\mathrm{Re}\left\{E \cdot J^* + j\omega B \cdot H^*\right\} \tag{6}$$

where J^* is the conjugate of the volumetric current density, and B is the magnetic flux density.

The volume loss density is a useful measure for predicting relative heating emission from a volume. Analysis and simulations of temperature are based on the tissue thermal properties from [26]. Table 2 provides tissue density (ρ), specific heat capacity (k), and thermal conductivity (C_p) used for numerical analysis.

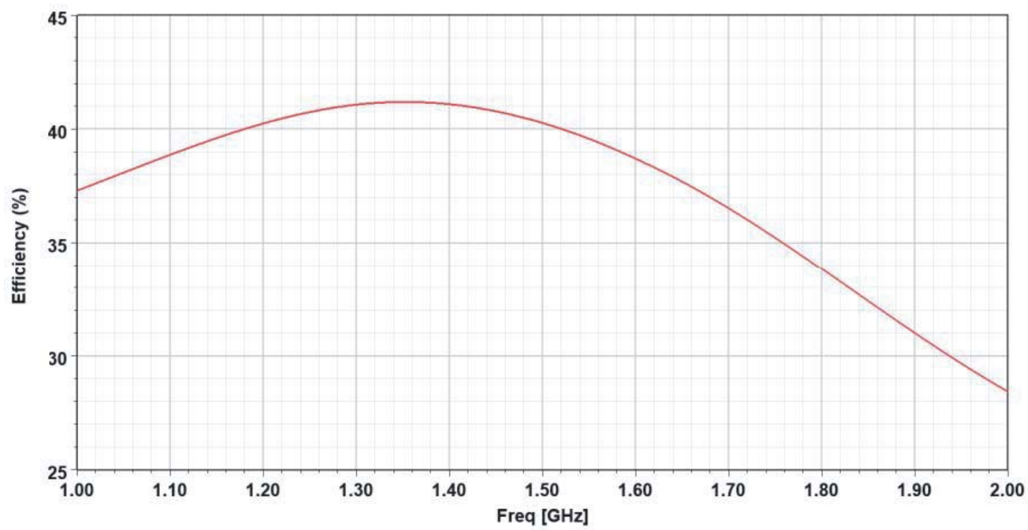


Figure 5. Antenna radiation efficiency.

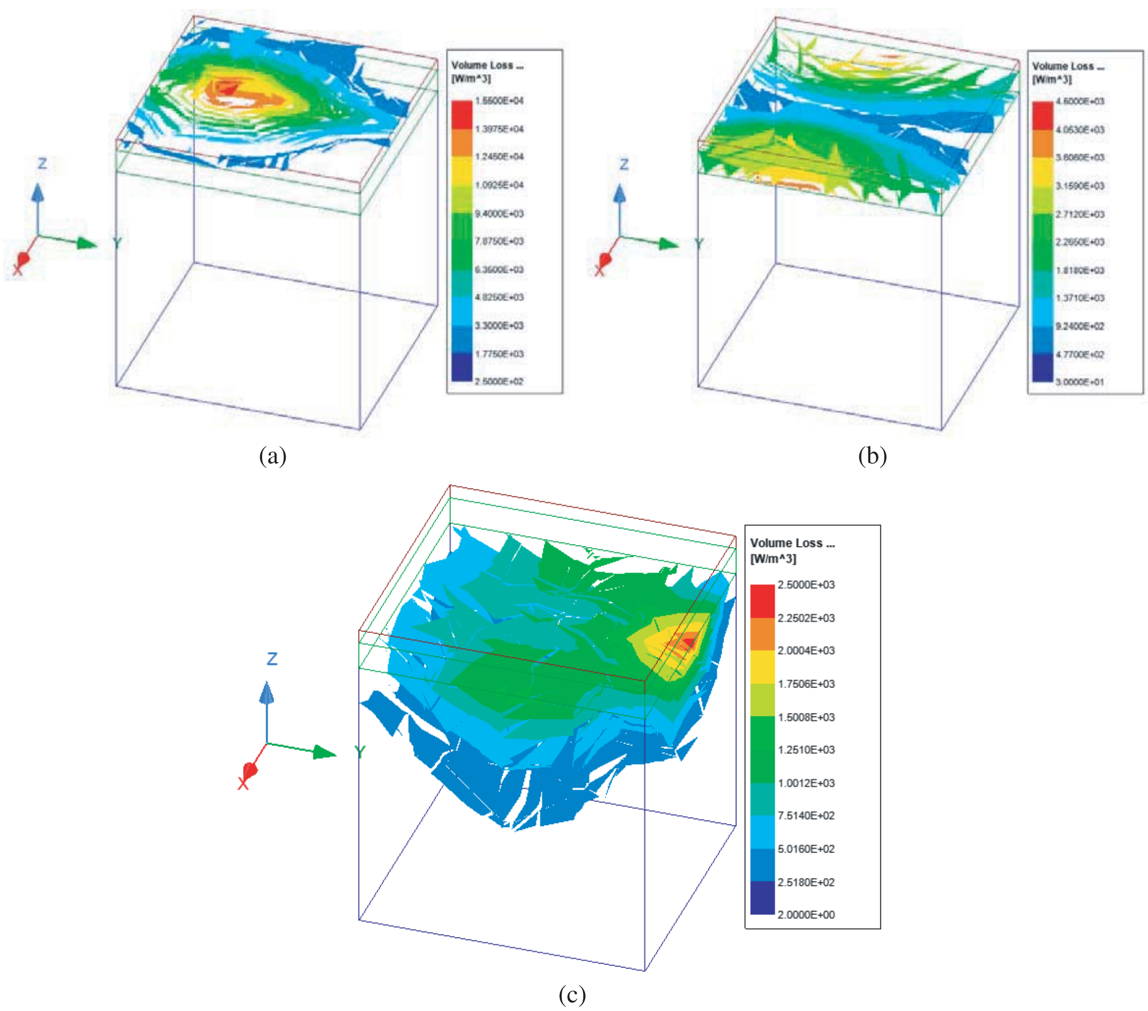


Figure 6. Simulated volume loss density for 1 V of input voltage at the antenna port, (a) skin, (b) fat, and (c) muscle.

Table 2. Tissues thermal properties (Average).

	Density (kg/m^3)	Thermal Conductivity (W/m/C°)	Specific Heat Capacity (J/kg/C°)
Skin	1109	0.37	3391
Fat	911	0.21	2348
Muscle	1090	0.49	3421

The antenna brightness temperature is a volumetric measure of the temperature seen by the antenna; however, the microwave radiation from the human body has extremely low power level. The amount of thermal radiation emitted by an object depends on its surface and core temperatures, area, and characteristics of object. To evaluate the microwave emission and radiometric performance, we have performed an extensive numerical simulation. We have used tissues' thermal properties from Table 2 while tissues' initial internal temperature was set at 37 C° with the ambient temperature of 22 C°. The penetration depth at frequency of 1.4 GHz is 34 mm for muscle (Table 1). However, 3D tissue model has the height of 23 mm, with 1 mm for skin, 2 mm for fat, 20 mm for muscle, and with separation gap of 2.54 mm between the antenna and skin. Fig. 7 shows the temperature distribution in each tissue layer at frequency of 1.4 GHz that can be seen by the surface antenna, while the antenna is in a passive mode with no input power. The lower part of the muscle layer is assumed at a core body temperature. The temperature decreases through the tissue towards the skin surface. The blood perfusion rate, the cooling effect induced by blood vessels, is not considered for thermal analysis. The ambient temperature or environmental conditions mostly affect surface temperature and as a result can influence the core to skin temperature gradient [27].

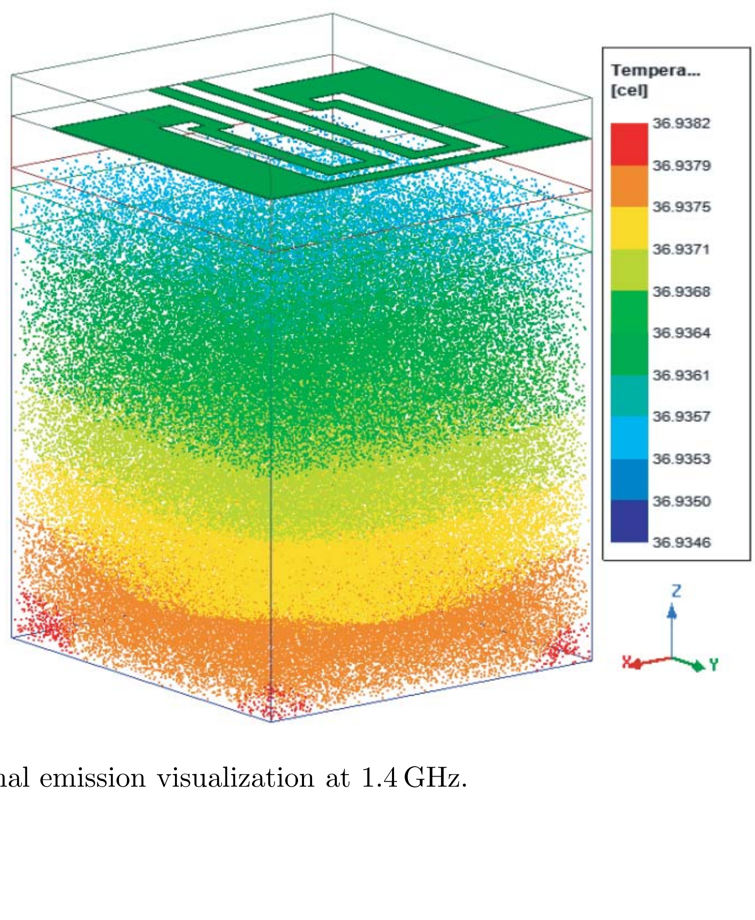


Figure 7. 3D thermal emission visualization at 1.4 GHz.

4. CONCLUSIONS AND THE FUTURE WORKS

The present work presents a noninvasive body temperature sensing antenna able to detect thermal radiation from a small body surface area up to 23 mm deep. The small size radiometer antenna ($19 \times 20\,\text{mm}^2$) has been designed for a single frequency band of 1.4–1.427 GHz.

The amount of microwave energy received by an antenna on the body surface increases with increasing tissue temperature which can be used to quantify internal tissue temperature. The accuracy of the brightness temperature estimation for biological tissues depends on the characteristics of the antenna and on the matching with the body.

This approach is noninvasive, painless, and could be consider as a comfortable way and capable of long-term continually monitoring to follow any changes on core temperature. Simplicity, low cost, and ease of manufacture make the proposed method attractive with the possibility to read temperature non-invasively at depth.

The initial results and outcomes of this ongoing work presented in this paper highlight the possibility of detecting body core temperature at the frequency of 1.4 GHz using microwave radiometer. The research work is still ongoing to complete a prototype and experimental investigations. As human body has a complex anatomy, a conformal antenna might be needed to accurately capture emission from body core.

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