Antenna Probes for Power Reception from Deep Tissues for Wearable Microwave Thermometry

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***Abstract*—The goal of the research presented in this paper is a design procedure for wearable antenna probes for monitoring internal body temperature using microwave radiometry. Receiving thermal black-body radiation from internal tissue layers is challenging as the human skin dominates the received power due to its high conductivity and permittivity. Therefore, a new design method is needed for probes that receive thermal power preferentially from deep tissue layers, while minimizing the contribution of surface tissues. The design method starts from reciprocity in the near-field, allowing simulations of volume loss power density to be used to predict black-body radiation. Several probes with superstrates are designed in order to maximize the volume loss power density in a specific buried layer. The experiments are performed in the 1.4-GHz quiet band, and temperature tracking is demonstrated and compared to thermocouple direct measurements on a skin-fat-muscle phantom.**

I. Introduction and Background

Currently there is no method for monitoring internal body temperature in a wearable non-invasive device. Applications include tracking muscle temperature for people under heavy training or emergency personnel for detecting onset of heat stroke, monitoring core body temperature during sleep for patients with sleep disorders, as well as tracking internal temperature during hyperthermia for cancer treatment. Radiometry in the lower microwave frequency range can be used to measure temperature from total black-body radiated power (Fig.1). An antenna probe in direct contact with the skin receives power from the tissue stack and is followed by a sensitive receiver, in our case a Dicke radiometer. An algorithm is then required to retrieve the temperature of a specific tissue layer based on the total received power and appropriate weighting functions [1].

Receiving very low level of black-body noise power from buried tissue layers is very challenging. The human skin dominates the received power due to its high conductivity and permittivity, and hence its black body radiation significantly dominates the radiation from the deeper layers (e.g., muscle layer). Therefore, a new design method is needed for probes that receive thermal power preferentially from deeper tissue layers, while minimizing the effect of surface tissues. Additionally, the wearable probe needs to be planar/conformal and should be immune to radio frequency interference (RFI).

Previous works on radiometer probes include waveguide [1]-[2], cavity-backed slot [3], ring slot [4], dipole [5] and cavity-back log-spiral [6] probes. These probes are not wearable and do not optimize power reception from a specific deep tissue layer, or do not take skin-fat-muscle layers into account. Most are also wideband in order to collect more power, but that makes them more susceptible to RFI and therefore not

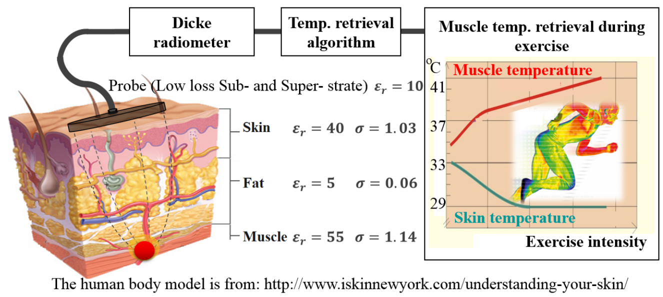

Fig. 1. Skin and muscle temperature follow different trends during exercise. The goal of microwave radiometry is noninvasive muscle temperature tracking.

applicable to long-term monitoring. This paper presents a design method, implementation and validation of an antenna probe that can be used in a wearable thermometer.

II. Design approach

Analysis of a near-field antenna probe can be done in the reciprocal case by analyzing absorbed power. This is typically quantified by the Specific Absorption Rate (SAR), which is a measure of the volume Joule loss density, p_J (in W/m^3). The probe should be engineered to provide a high value of p_J in the muscle layer while minimizing it in the skin and fat layers. By considering the boundary conditions for the electric field vector and high dielectric contrast between skin, fat, and muscle layers, it becomes apparent that the desired component of the electric field vector produced by the probe is the one tangential to the skin surface, since E_{tang} is continuous across the interface of tissue layers. Therefore, good probe candidates are patch and slot antennas, which can be designed to have dominant E_{tang} over E_{norm} and also can be made flexible and conformal to the skin.

Based on this idea, a coaxially-fed circular patch on a Rogers 6010 1.58-mm thick substrate (ϵ_r=10.2) is designed (Fig.2(a)). When the patch is placed on the tissue stack from Fig.1 and fed with 1 W in a full-wave simulation (HFSS), the resulting volume loss power density in the cross-section at the center under the probe shows that 33% of the total power is absorbed in the muscle layer, while the skin layer absorbs 50% of the power. To improve the power delivered to the muscle, and by considering boundary conditions, a superstrate is added to the probe, Fig.2(b). The resulting absorbed power in the muscle increases to 61% for a 1.58-mm thick superstrate with ϵ_r=10.2.

Fig.3 illustrates the effect of the superstrate in the near field. The transverse component is continuous at the boundary

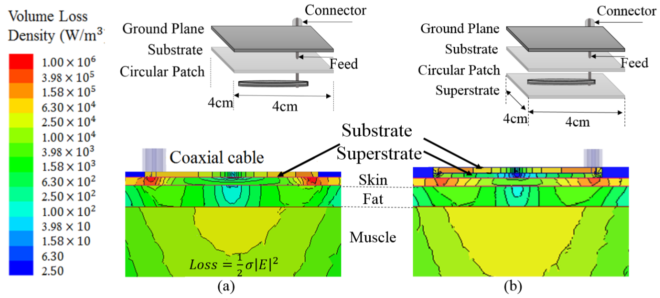

Fig. 2. Volume loss density of circular patch with and without superstrate are compared. (a) Patch is designed to maximize power deposition into the buried muscle layer. (b) Adding appropriate superstrate matches the probe to deeper tissue layers and doubles the power transfer to the muscle layer.

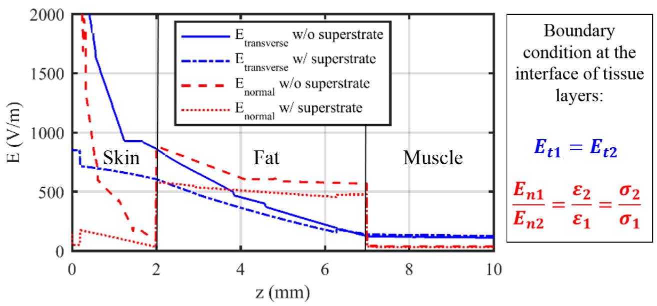

Fig. 3. Simulated E_{tang} and E_{norm} in different tissue layers with an without probe superstrate. The skin surface is at z=0.

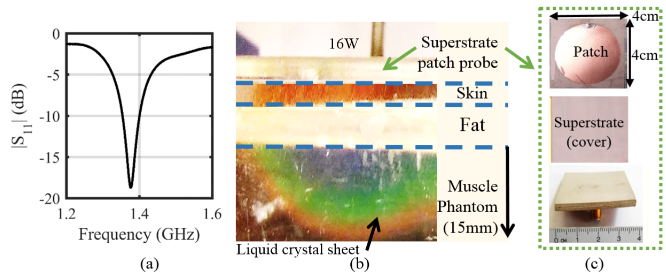

Fig. 4. (a) Measured S_{11} of the probe on skin, fat, and muscle phantom. (b) Temperature profile of superstrate patch measured with a liquid crystal sheet placed in the transparent muscle phantom under the transmitting patch. A ZHL-15W-43 power amplifier is used for 60 s to heat up the tissue phantoms. (c) fabricated superstrate patch probe.

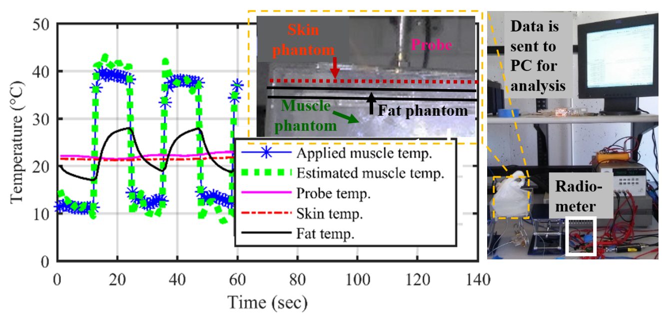

Fig. 5. Measured radiometric temperature of the muscle phantom (green) tracks the actual temperature (blue). Probe and skin (red) and fat (black) temperatures change at a much longer time scale.

between tissue layers, and adding the appropriate superstrate can reduce the absolute value of the electric field, and therefore the absorbed power, in the top skin layer. The normal E-field component attenuates at the interface of fat and muscle proportionally to the ratio of the permittivities ($\approx$ 11) and conductivities ($\approx$ 19). Adding a superstrate introduces a high dielectric contrast at the probe-skin interface, which results in confining E_{norm} to the low-loss superstrate and thus reduces the contribution of the skin in the total thermal noise power absorbed by the probe.

III. Measurements and Next Steps

To validate the simulations in Fig.2 and characterize the sensing region, the superstrate patch is tested in transmitting mode. The superstrate patch is placed on a layered phantom gel and 16 W of power is fed to the probe 50-Ω connector. A liquid crystal sheet placed perpendicularly through the phantom stack displays the heating profile (directly proportional to loss) in the transparent Agar muscle phantom. Fig.4 shows that the field penetrates 15 mm into the muscle layer following the profile from Fig.2(b).

Fig.5 shows the capability of the superstrate patch in tracking the temperature of the muscle with a radiometer connected to the probe. A thermocouple is placed directly on the muscle layer as a reference measurement of temperature. The muscle phantom in this case are two plastic bags filled with hot and cold saline, alternated every 15 seconds. Even though the physical temperature of the probe and skin layers are constant (red), the buried muscle phantom temperature measured by the radiometer (green symbols) tracks the thermocouple direct measurement with no delay (blue symbols). The fat layer shows a thermal conductivity time constant on the order of seconds, which is much longer than the practically instantaneous radiometric measurement.

In addition to patch probes, several slot antennas with superstrates have also been designed for this application, given the tangential E-field nature of their radiation. Patch antennas have the slight advantage that the ground plane allows for easy integration with receiver circuitry. Additionally, a phased array of probes is fabricated to increase the SNR in temperature retrieval in case of having thick layer of fat. Initial measurements with a 2×2 patch array show increased sensitivity to small temperature variations of the muscle under a thick layer of fat. The design approach presented here can be applied to different tissue stacks for a range of applications, e.g. power transfer to embedded tissue implants, and RF heating of deep tissue layers for wrinkle reduction with reduced surface layer damage.

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