Measurement and Simulation of Heat Transfer into a Human Skin Phantom

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***Abstract*—Reliable in-vitro millimeter and sub-millimeter wave exposure investigations need well characterized radiation sources, accurate phantom models and calibrated SAR/temperature-rising probes. A practical setup is presented for studies regarding the human skin exposure at frequencies above 30 GHz. A standard-gain horn antenna is used to provide a Gaussian beam and known field-intensity on the sample, together with an infrared camera to monitor the temperature variations. The measurements of the temperature distribution in the gel phantom, including uncertainty, are presented and compared with Finite Element simulations.**

I. INTRODUCTION

IN the context of fast development of millimeter and sub-millimeter wave technology and concerns related to its ecologic and biologic impact, this paper studies the human skin interaction with the electromagnetic radiation from the thermal point of view. This is particularly important for the standardization of millimeter wave scanners and the prospective 5G wireless systems. Actually, to be able to observe the temperature rising with a conventional infrared camera and establish repeatable measurements, the exploited radiation power should be relatively high, in the order of hundreds of milliwatt. This can increase the sample temperature by a few Kelvin and therefore be detected and analyzed conventionally, helping the validation of numerical methods for human exposure evaluation.

II. SETUP

The setup shown in Fig. 1 includes a standard-gain pyramidal horn antenna (Flann 23240-20 with coaxial-to-waveguide adaptor 23094-VF50) and an RF generator (Agilent E8257D) up to 50 GHz with an external power amplifier (Centellax TA2U50HA, typical gain 24-25 dB, typical output power up to 24-27 dBm). The skin phantom has been prepared as simple as possible: a gel layer (2 mm thick) based on TX151-powder (25%) and water (75%) spread on a Plexiglas™ holder (3 mm thick) [1]. A conventional IR camera (FLIR SC300) images the temperature pattern corresponding to the exposed area. The maximum radiation power density on the sample is set to 40 mW/cm^2 ± 20% and the beam shape is nearly Gaussian [2, 3] with a beam waist $w_0 \approx 2.0 \ldots 2.5$ cm. Both IR camera and horn antenna are positioned at a distance of 10 cm from the sample. Indeed, thermal measurements confirm a quasi-Gaussian profile of temperature on the sample surface.

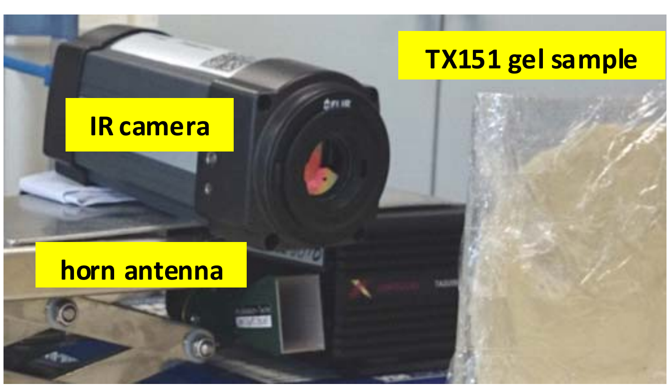

Fig. 1. Exposure setup including horn antenna, IR camera and human skin phantom. The RF generator is not shown here.

III. RESULTS

Fig. 2 shows thermal images of the skin phantom taken before and after the exposure to a nearly Gaussian beam at 35 GHz with a maximum power density of 40 mW/cm^2 ± 20%. The measurements after illumination are taken after 180 seconds, 450 seconds and 900 seconds. Temperature elevations are extracted from the images after subtraction of the background noise measurement (image of the sample without illumination), which is in the order of 0.5 K. Taking into account the capabilities of the infrared camera, the thermal stability of the experimental environment and the

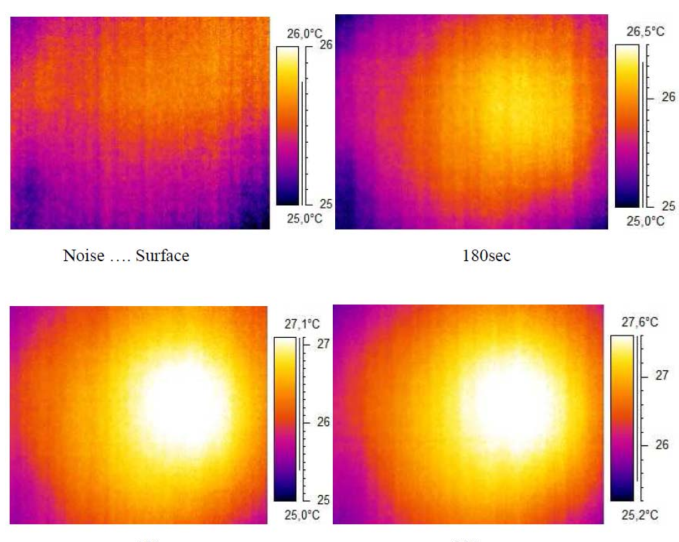

Fig. 2. Thermal images of the skin phantom after illumination with 35 GHz radiation of nearly Gaussian shape with maximum power density of 40 mW/cm^2 and a beam waist of $w_0 \approx 2.0 \ldots 2.5$ cm for different illumination times between 0 s and 900 s.

limited homogeneity of the gel phantoms, we estimate the expanded measurement uncertainty for the extraction of temperature elevations to 0.2 K (k = 2, 95% confidence interval).

The physical properties of the TX151 Gel and Plexiglas are reported in Table 1. The electrical properties of TX151 Gel have been measured with a free-space spectrometer setup based on hon antennas and vector network analysis [4], whereas the other parameters have been found in literature [1].

	Electrical conductivity S/m	Relative Permittivity	Thermal conductivity W / (m·K)	Heat capacity MJ / (m^3 K)
TX151 Gel	100	30	0.588	4.54
Plexiglas support	10^{-10}	2.58	0.193	1.69

Table 1. Electrical and thermal parameters of phantom and support.

IV. Comparison with Calculations

The measurements (as extracted from the thermal images in Fig. 2) were compared to simulations of the temperature elevation based on a finite element model [5]. The Gaussian beam width w_0 significantly affects the thermal behavior of the phantom. In particular it determines the surface distribution and the peak value of the temperature elevation. The computations show that, for given values of the gel parameters and of the heat transfer coefficient, the surface distribution of the temperature elevation normalized to the peak value of the temperature elevation depends on w_0. This allows an a-posteriori verification of the actual value of w_0 (in terms of power density distribution), as presented in Fig. 3, where the normalized temperature elevations given by measurements (phantom after 900 s radiation) have been included. The diagram shows that a value of w_0 = 2.25 cm is most realistic.

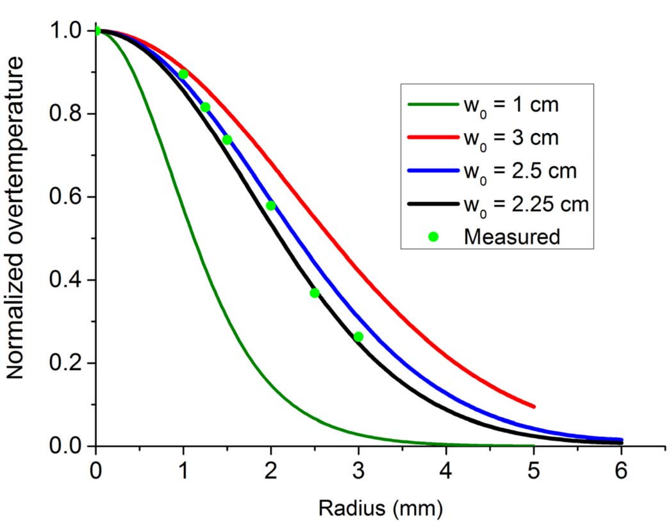

Fig. 3. Spatial distribution of the normalized temperature elevation over the surface of the phantom versus parameter w_0.

The parameter h_{amb} which controls the heat transfer between phantom and surrounding air has a large impact on the maximum temperature elevation, too. Fig. 4 shows the comparison of simulations with measurements for two different values of h_{amb} assumed to be realistic. The simulated temperature elevations are still subject to a large uncertainty. The main contributions to this uncertainty are the antenna input-power (which is in the order of 20% for k = 2), the parameters of the approximated Gaussian beam, and the uncertainty of thermal and electrical parameters of the gel phantom.

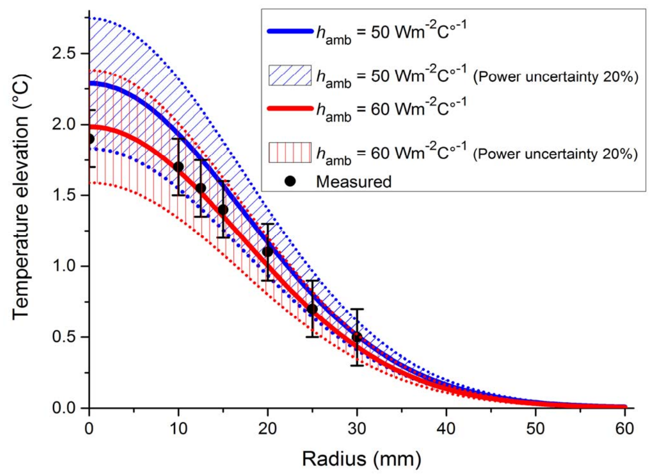

Fig. 4. Simulated temperature increase in comparison to the measured values extracted from the thermal image.

V. Summary

We showed a practical measurement setup that was used to measure the heat transfer into a skin phantom based on thermal imaging. The measurements were compared to calculations and matched well within the expected measurement uncertainty.

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