The Sub THz Emission of the Human Body under Physiological Stress

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Abstract—We present evidence that in the sub-THz frequency band, human skin can be considered as an electromagnetic biometamaterial, in that its natural emission is a product of skin tissue geometry and embedded structures. Radiometry was performed on 32 human subjects from 480 to 700 GHz. Concurrently, the subjects were exposed to stress, while heart pulse rate (PS) and galvanic skin response (GSR) were also measured. The results are substantially different from the expected black body radiation signal of the skin surface. PS and GSR correlate to the emissivity. Using a simulation model for the skin, we find that the sweat duct is a critical element. The simulated frequency spectra qualitatively match the measured emission spectra and show that our sub-THz emission is modulated by our level of mental stress. This opens avenues for the remote monitoring of the human state.

Index Terms—Black body radiation, Human skin emission, Sweat ducts, Sub THz,

I. INTRODUCTION

THE human body does not present many opportunities for I monitoring its vital state. Despite advances in invasive monitoring and diagnosis, medicine is still limited to the same techniques of yesteryears. Excluding medical imagery, the last major innovation in continuous monitoring is the Electrocardiogram, introduced in 1895 [1]. The visual impression of the person, together with pulse and skin temperature, is major component of any diagnosis, a situation that harks back to the days of Hippocrates and Galen. The skin is a major organ of the body [2] and is a source of information. However, there is a conundrum. Any remote technique requires communication - mechanical or electromagnetic - and the human body is rather quiet. Although visually information can be gleaned, it is a long held view that the human body does not 'shine'. Beyond black body radiation, we do not radiate [3]. Indeed, the human skin temperature of approximately 32°C leads to an equivalent blackbody spectra in the Infrared [4].

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We present results demonstrating that the traditional view is not complete. There is also a marked contribution in the sub-THz region. Furthermore, this contribution is sensitive to the physiological state of the subject, opening a remote diagnostic channel.

The lack of data between 100 GHz and the infrared was partly due to the difficulty of performing radiometry experiments in the sub-millimeter (sub-THz) band [6]. Nowadays, modern heterodyne techniques can cover this range in laboratory conditions.



Figure 1 An Optical Coherence Tomography (OCT) image of human skin showing the existence of the coiled portion of the sweat duct (Gabor domain OCT. Image by Jannick P. Rolland, University of Rochester).

We have conducted a radiometric study of human emissivity around 500 GHz and 507 GHz on 32 volunteers, the preliminary results of which were reported in Ref [7]. In this missive we provided a full and complete description and discussion. The motivation to measure the emission of the human body in this range were experiments linking the morphology of the eccrine sweat ducts to stress based variations in the reflection coefficient of the human palm, conducted in the frequency

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range of 75 GHz to 430 GHz [8-11]. An intriguing finding was the demonstration of circular dichroism [12] in the reflectance of the skin, significant because the helical structure of the sweat duct [13, 14] (Figure 1) is the only candidate in the epidermis that would cause such. Consequently, one must question would there be an implication on the emission of the human body.

II. MATERIALS AND METHODS

A. Experimental setup

The experimental setup is based around a superconducting integrated receiver (SIR) [15, 16] located in cryostat with liquid helium [15, 17]. The general schematic of the system is presented in Figure 2. Concurrent supplementary measurements of the Galvanic skin response (GSR), skin temperature and heart pulse rate were made using a GSR logger sensor NUL -217, a Thermometer DT-670SD and a Pulse Oximeter (CMS50D) respectively. All of these sensors are connected to the data collection system. The subjects' hand was immobilized in stand at a distance of 25 cm from the cryostat window. The radiometry signal was modulated by a chopper placed 5 cm from the cryostat window, rotating at 24 Hz.



Figure 2 The schematic of the measuring setup including a Superconductive Integrated Receiver (SIR), Galvanic Skin Response (GSR), Pulse meter and skin temperature sensors. The abbreviations in the block diagram are FFO: Flux-Flow Oscillator, a local oscillator in the SIR, IF amplifier: Intermediate Frequency amplifier, Superconductor-Insulator-Superconductor (SIS) mixer: the superconductor-insulator- superconductor mixer, PLL: Phase-Locked Loop, LSU: Local Source Unit and HEMT: High Electron Mobility Transistor.

B. Superconducting integrated receiver

The SIR was used to measure the brightness temperature of subject's skin at 500 and 507 GHz for our entire set of participants. Additionally, spectral measurements in the range 480 - 700 GHz were carried out on 3 subjects. Tuning the SIR for each frequency point is a time-consuming process. Therefore, due to time and manpower constraints only three spectra were measured. The SIR integrates into a 4 x 4 x 0.5 mm3 chip a sensitive terahertz range superconductor-insulator-superconductor (SIS) mixer, a highly stable terahertz oscillator, phase-locked by using a harmonic mixer [14, 15]; all these superconducting elements operate at cryogenic temperatures. The SIR is designed to work in the 470-670 GHz frequency range; the noise temperature as low as 120 K and the IF bandwidth 4-8 GHz was demonstrated [15, 17].

C. Supplementary signals

GSR is a measurement of the impedance of the skin. Basic electro-dermal activity theory holds that the impedance of the skin is influenced by the state of the sweat glands and the sweating process is controlled by the Sympathetic Nerve System (SNS). Consequently, changes in the resistance of the skin can be used as a window to the nervous system and an indication of psychological and physiological stress. It is widely used in polygraph tests, and other psychophysiology measurements. Serving as a widely used measure of stress and nervous excitation, the recording of the GSR signal served as a control signal to verify the experimental protocol indeed induced some level of stress. As such, correlation of the received SIR signal and the GSR result is indicative of the effect of stress in the radiometry result. The GSR channel was measured by connecting the electrodes to two fingers tips on the subject's left hand. A thermometer and Pulse Oximeter were also used to monitor the pulse and oxygen content in the blood. These detectors were attached to the subject's left hand. From the heart pulse rate it is possible to derive Heart Rate Variability, another well-established indicator of subject stress.

D. Experimental Protocol

Thirty out of the total 42 measurements were conducted under a protocol that began with 5 minutes of relaxation, followed by 5 minutes of mental stress. Then again 5 minutes of relaxation, followed by 2 minutes of physical stress and finished off by 2 minutes of rest (See Figure 3). The remaining 12 measurements were carried out with a shorter protocol of 5 minutes of relaxation, followed by 3 minutes of mental stress and finished off by another 5 minutes of relaxation. The subjects were requested to avoid coffee and heavy meals for at least 2 hours prior to the experiment and upon arrival were requested to wash their hands with soap, in order to remove hand lotion, if such had been applied. Additionally, they were asked to leave their cell phones outside the measurement room, to avoid sudden interrupts and additional noise in the room. Afterwards, they were brought into the measurement room where they received a general explanation of the goals and procedures of the experiment that they were about to participate in, which also allowed the subject to adjust and relax to the experimental surroundings. After signing informed consent forms, they were requested to sit comfortably in front of the measurement table and place their left hand in the chassis. The hand was then fixed at the point of focus and additional measurement devices, discussed in the next section, were connected as well.



Figure 3 Measurement protocol. 5 minutes rest; 5 minutes of mental stress; 5 minutes of rest; 2 minutes of physical stress; and 2 more minutes of rest.

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E. The subject pool

The subjects were recruited from the staff and student body of the Moscow Pedagogical State University. The criteria for participation were that the subjects be healthy, under the age of 40 with no skin complaints. The participants were 19 female and 13 male volunteers ranging between 18 and 37 years of age (average age 23 years) and the protocols were under the approval of the Ethical Committee of Moscow Pedagogical State University, Russia. They were informed regarding experimental aspects relevant to human health and freely gave their consent.

III. RESULTS

The radiometry experiments show that at 507 GHz the emission of the human skin is substantially different from the blackbody signal of the skin temperature for the sample pool. Radiometry was carried out, using a cryostat based Superconducting Integrated Receiver (SIR) [15], on 3 subjects, for a total of 12 measurements at 500 GHz and for 30 subjects at 507 GHz for a total of 30 measurements (one of the subjects was measured in both frequencies), resulting in a pool of 32 subjects and 42 separate measurements. During the experiment at 507 GHz, the subjects were exposed to a stress protocol consisting of a 5 minute calm state, 5 minutes of mental activity (Colour word test [10]) 5 minutes of relaxation, 2 minutes of physical stress (hand gripping) and finally 2 minutes of calm (The full details of experimental protocol is listed in the SI Appendix). Concurrently, the heart pulse rate and Galvanic Skin Response (GSR), both indications of stress [18, 19], were measured.

The emitted signals were collected from a spot on the palm of the hand of 2.5 cm in diameter. A traditional Lock-in amplifier scheme was employed for data collection using a chopper for modulation [15, 17].

The voltage reading of the sensor is proportional to the brightness temperature [20] of the measured source by a sensor scaling coefficient, K.

$$SIR_{raw}(t) = K[T_B(t) - T_{ch}], \qquad (1)$$

Where $SIR_{raw}(t)$ is the registered voltage, T_{ch} is the chopper brightness temperature and $T_B(t)$ is the subject's brightness temperature. Two dominant factors were considered before each measurement - the ambient background and K, the absolute value of the sensor-scaling coefficient. During the experiments, the environmental conditions were kept constant and the chopper temperature can be equated to the background room temperature.

The coefficient K [*Volt/degree*] was determined by calibration using absolute black body references measured at two temperatures T_{hot} and T_{cold} . The calibration measurements at these temperatures demonstrated a linear dependence of the *SIR* signal on the reference temperature in the range of $77 K \le T \le 293.2 K$. The sensor-scaling coefficient K could then be determined by:

$$K = \frac{SIR_{hot} - SIR_{cold}}{T_{hot} - T_{cold}}$$
(2)

If human skin acts as a perfect black body, then $T_B(t)$ in equation (1) would be equivalent to the measured palm skin

temperature, $T_{hand}(t)$. However, we find that the measured signal is notably higher than the expected values for a blackbody held at the skin temperature, continually measured on the subject's palm throughout the protocol. A representative result is plotted in Figure 4a. This difference of the signal from black body is repeated for all subjects. Furthermore, we find that mental and physical stress of the subject can be correlated to changes in the measured radiometric signal, the correlations being either negative or positive.

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Figure 4(a) A representative SIR measurement for one subject. The black line represents the equivalent black body signal, based on the measured skin temperature of the subject, approximately 32 C. The mental stress protocol period is shaded grey[21]. (b) A representative plot of the normalized SIR/GSR signal against time for the same subject. To compare to the GSR signal the SIR signal was first detrended, using a linear base line [22]. SIR signal is plotted in red and the concurrent GSR signal is plotted in black. The protocol period is shaded [21]. (Copyright 2020 IEEE, Reprinted with permission from IEEE proceedings).

Figure 4b presents a typical result for a concurrent measurement of GSR and a radiometric SIR signal. Figure 5 presents a histogram of the Spearman correlation values [23] between the Heart Rate Variability (HRV), derived from the heart pulse rate measurements, and the simultaneously measured SIR signal, for all subjects.



Figure 5 The histogram of the Spearman correlation between the SIR signal and the Heart Rate Variability (HRV) for 39 measurements, recorded at 500 GHz and at 507 GHz. The histogram divides into two distinct populations of negative and positive correlation. The average correlations are of 0.29 ± 0.2 and -0.36 ± 0.2 . HRV is a more precise indicator of stress than GSR because it is less prone to contact problems and other artifacts. Three measurements from a total of 42 were excluded due to incomplete pulse traces.

There are two distinct populations with average correlations of 0.29 ± 0.2 and -0.36 ± 0.2 . While the reason for these populations is still a subject of debate, it is known that the human reactions to stressful situations fall into two categories; distress and eustress [24, 25]. One could be tempted to suggest that the two distributions are a manifestation of these categories.

Although these correlations are quite low, Student t-testing of the raw SIR signal before and during a period of mental stress revealed that out of 42 measurements, 36 returned a p value of zero for the null hypothesis, implying that the emitted signal was substantially different during rest and during stress.

For this test, two sections from the SIR signal were extracted for each of the 42 measurements – one taken between 120-300 seconds or 0-300 seconds, depending on protocol, representing the very first relaxation period and the other representing the mental stress period, taken between 300-480 or 300-600 seconds, according to the experimental protocol of each measurement. This resulted in 180-300 pairs of samples for each of the 42 measurements. The second relaxation period was not concatenated to the calm section, due to the possibility that it could contain some stress artefacts. The Matlab function, ttest (x, y, Name, Value), was used to calculate a paired Student t-test, with a significance value of 1% for the null hypothesis. The implication is that there is substantial difference in the recorded signal during a calm state as opposed to a stress state. Three subjects were measured repetitively, their results rejected the null hypothesis 3 out of 4 or 5 out of 5 times.

We can conclude that this opens a new avenue for the remote monitoring of stress. While work has been done to recognize stress by image analysis of the human face in the THz range [26] and above [27], this is the first evidence that human stress directly effects the emission of skin.

IV. DISCUSSION

A simple and direct representation of experimental data can be done by binning the $SIR_{raw}(t)$ results into a histogram. Due to differing sensitivities of the heterodyne at different frequencies, this can be done only for single frequencies. The result for 30 subjects at 507 GHz is plotted in Figure 6 as the bars and the upper brightness temperature scale is calculated according to equation (1). One would expect that the maximum of distribution would be around the skin temperature, as is common in the Far infrared [28]. We find that a minimum of 5 Gaussian distributions is required to describe this histogram (see Figure 6).

$$f(x) = \sqrt{\frac{2}{\pi} \frac{A}{\sigma}} \exp \left(-2 \left(\frac{x - \bar{x}}{\sigma}\right)^2\right)$$
(3)

The details are presented in Table 1. The statistical significance of each population was established using the Matlab function ttest2(x,y, 'Vartype', 'unequal') for Welch t-test [29]. The significance values at an α value of 0.01 are all close to zero, implying that the distributions are all statistically distinct. From the results it is clear that population 1 is the dominant feature, comprising of 46% of the total counts. It coincides with the temperature of 310 \pm 0.5 K (37 °C), the human body core temperature. This is not an expected result, as absorption in the

upper skin layers should effectively dampen any radiation produced by the core [26, 27]. The remaining 4 distributions are statistically distinct. However, one feels that the final 5th distribution would fold into the broad background of the first distribution given a larger sample pool. The statistical weight of the 4th distribution (*A normalized* = 0.04) is very low and one must question its relevance to the discussion. The 2nd distribution (2-blue in Figure 6) can be accounted for by the effect of a signal absorption inside the duct, leading to an effective lower brightness temperature. The 3rd population is more intriguing, as it represents an effective increase in signal intensity originating from the hand of our subjects, beyond that expected by the natural variation in the black body signal from the human core temperature. One could speculate that this is rooted in an additional radiative source.

Table 1 - The parameters of the Gaussian distributions defined by equation (3) and used to describe the histogram of Figure 6. The normalized amplitudes were calculated by $A_i^{norm} = A_i / \sum A_i$

Distribution	A	А	\overline{x}	σ
#	$\times 10^{-2}$	normalized	$\times 10^{-2} [V]$	$\times 10^{-2} [V]$
1	11.56	0.46	0.079	0.045
2	3.65	0.15	0.072	0.005
3	5.28	0.21	0.088	0.014
4	0.89	0.04	0.100	0.003
5	3.58	0.14	0.118	0.029

Furthermore, this simple approach cannot account for the signal dependence on mental stress, let alone that the core temperature element is a major contribution to the emission of our skin at 507 GHz. This contradicts the accepted blackbody power spectrum of the human body [26, 28].



Figure 6 A histogram of all raw SIR results for 30 subjects; measured at 507 GHz. Due to differing sensitivities of the heterodyne at different frequencies only one frequency is used. The brightness temperature scale (upper axis) assumes an average room temperature of 297 K (24 °C) and is calculated according to equation (1).A minimum of 5 Gaussian distributions (labelled 1- red, 2- blue, 3- purple, 4- dark grey and 5 dark blue) are required to describe the histogram. Student ttesting reveals statistical significance only for the distributions 1,2 and 3. The broad distribution 1 is centered around the core temperature of the human body of 310 K (37 °C). The second and third Gaussians are situated 1 K lower and 2 K higher than body temperature, respectively.

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Reflection coefficient measurements of the skin at similar frequencies also revealed a dependence on the level of human stress [30] and circular dichroism [12]. This posited the sweat duct as a major factor in the electromagnetic response of the skin at sub-THz frequency band. One may assume a similar importance of the duct in passive emissivity. To explore this concept a simulation study was made.

The electromagnetic response of the sweat duct can be simulated by considering it as a coil embedded in multilayered environment with the dielectric properties of layered human skin [31, 32] (Some details of the model are presented in Appendix). The model, illustrated in Figure 7 consists of three layers with undulating boundaries, mimicking the papillae of human skin as noted in OCT studies [14] (Figure 1). Into this is embedded a helical sweat duct with an aqueous interior. The layer electromagnetic properties were calculated by their water content, provided by Raman Spectroscopy [33]. The resulting simulation led to a model that, at least in terms of a reflection coefficient, predicted a heightened radiometric response around 500 GHz [32]. The influence of stress was introduced by varying the ac conductivity in the aqueous interior of the duct. This assumption is reasonable as stress leads to heightened activity of the sweat duct as the Sympathetic Nervous Response is kicked into activity [18]. As a consequence, there is an injection of charge carriers (protons) in to the duct [34], effectively changing the ac conductivity. In fact pH levels of human sweat have been measured from 4.5 up to 7 [35], indicating a wide variation in *ac* conductivity levels. This mechanism would effect skin emissivity, ϵ , with a temperature of 27-32 °C.

However, this would not account for a black-body signal of 37 °C. A possible explanation is that the human body core temperature produces a contribution that is measurable externally. There are strong arguments against this position as it is accepted that in the Infrared, the upper layers of the skin (the epidermis and stratum cornea) would absorb this component [26]. The transmission coefficient of the duct must be sensitive to the ac conductivity in the duct, as was the reflection coefficient [10, 11, 31, 36]. As the sweat gland, buried in the dermis, is in contact with capillary blood system at 37°C, the duct could influence the emission of the same black body signal in this frequency band. However, at a characteristic frequency of the duct, predicted by its geometry (see Figure 7), there would be a heighten absorption of the black body signal. This dependence on the spiral geometry of the duct is reminiscent of the absorption characteristic of a helical antenna almost like a low Q resonance, narrow band notch filter [37].

In order to test this hypothesis we have made simulation studies using the software package of Computer Simulation Technology (CST) of the transmission coefficient (S_{21}) of the skin as a function of frequency, using our existing skin/sweat duct model [31, 32] with a radiation source embedded in the dermal layer (the details of the Model is presented in Supplemntary materials). Figure 7 also shows the field distribution in the model when excited by a radiation port at the base of the spiral duct.



Figure 7 The simulation model of a single sweat duct embedded in its skin layer with a radiation port (507 GHz) at its base. The colors represent the differing electromagnetic field strengths, with the highest levels registered in the sweat duct.

They confirm the ability of the skin to be a conduit for a Black body signal at 37 °C, modulated by the activity of the duct. In order to test this hypothesis, a frequency sweep from 480 GHz to 700 GHz was made for three subjects. The receiver was tuned and calibrated at each frequency. For the spectral measurements, a shorter protocol (5 minutes rest, 3 minutes mental stress and 5 minutes rest) was used. The coefficient Kwas calibrated per frequency point, maximal at 500 GHz and decreased with increasing frequency. The brightness temperature $T_B(t, f)$ of each subject was evaluated as a function of frequency f using equation (1). The values of $T_B(t, f)$ where qualitatively compared with the results of a CST simulation of the transmission coefficient $S_{21}(f)$ for a uniform source placed at the base of the epidermis below the sweat duct coil (Figure 7). The squared modulus $|S_{21}(f)|^2$ is proportional to the intensity of a transmitted signal and so to the brightness temperature as well. Three different levels of ac conductivity were simulated (2000 S/m, 3000 S/m and 4000 S/m). The simulation results reveal an increasing value of signal with increasing frequency (see Figure 8). This trend as well as the signal shape is maintained for each conductivity. Expressed in terms of the Brightness temperature, T_B , the experimental results qualitatively match the simulation. While these tendencies broadly suit a black body description of the radiation, one must note the dip in both simulation and experiment around 620 GHz.



Figure 8 A simulation of the squared modulus of the transmission coefficient, $|S_{21}(f)|^2$ proportional to transmission radiation intensity, for three different ac conductivity levels (violet – 2000 S/m, dark red – 3000 S/m and dark green -4000 S/m) for a source placed at the base of the epidermis in figure 7 as a function of frequency. On the right hand axis is the measured SIR signal (as an equivalent brightness temperature with accuracy \pm 1.7 degree) for a single subject of the study. The measured result and simulation are qualitatively comparable.

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We conclude that the human skin can be considered as an electromagnetic bio-metamaterial, capable of transmitting the human core black body radiation in the sub –THz range. Furthermore, the efficiency of this mechanism, reminiscent of a low-Q notch filter, is dependent on the effective *ac* conductivity and the morphology of the sweat duct. We speculate that the former is a product of the biochemical injection of charge carriers, itself a direct consequence of the Sympathetic Nerve Response [18, 34], into the aqueous interior of the duct and the latter ensures a narrow frequency band of transmission. Together they offer new and intriguing avenues for medical diagnostics by making both the core temperature and the mental state of a subject available remotely.

V. APPENDIX

A. Model

The model is a unit cell, which consists of two main layers; dermis and epidermis. The latter is further divided into three sub-layers, referred to as E1, E2 and stratum corneum (SC), from the deep most to superficial, respectively (see Figure A1). Although the dermis layer depth is 1-2 mm, only its upper 300 μm were considered in the model, because we are interested in the "transmitted" EM field toward the skin outer surrounding. The helical section of the sweat duct was embedded in the epidermis layer, to correspond with the position of the duct noted by OCT [32]. The boundary between the dermis and the epidermis was modeled as a two-dimensional sinusoidal surface with an amplitude of 150 µm, which corresponds to the papillary dermis in human skin [12, 38]. The moisture profile of skin as a boundary between the sub layers of the epidermis (E1 and E2) were also modeled sinusoidally with amplitudes of 50 µm. The dielectric permittivity of each layer was calculated using the mixture formula presented in equation (1) of reference [9].

$$\varepsilon_{layer} = \varepsilon^{bm} \frac{(2\varepsilon^{bm} + \varepsilon^w) + 2x(\varepsilon^{bm} - \varepsilon^w)}{(2\varepsilon^{bm} + \varepsilon^w) + x(\varepsilon^{bm} - \varepsilon^w)},\tag{A1}$$

where ε^{bm} is the permittivity of the dry biological structural components, approximately 2.2 [39], ε^{w} is a permittivity of water (approximately 5 at f=500 GHz [40]) and x is the volume fraction of the water component [8, 41]. In the considered frequency range, i.e. hundreds of GHz, dielectric losses for water are low and for the dry biological components are negligible. Consequently, the permittivity can be represented by a single, frequency independent value.



Figure A1 Multi layered skin model. On the right, the interior of the model - The coiled sweat duct.

The model parameters are summarized in Table A1. The ac conductivity of the sweat ducts was considered to vary from 100 S/m (the value for pure water at 100 GHz [10]) to 4000 S/m.

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Table A1 Estimated skin dielectric permittivity and ac conductivity, which were used in the simulations model. The ac conductivity of the sweat ducts is considered to be much higher than that of its surrounding epidermis.

Component	Relative	AC Conductivity
	Permittivity	[S/m]
Stratum Cornea	2.7	0.001
(SC)		
Middle Epidermis	3.25	0.5
(E2)		
Inner Epidermis	3.8	1
(E1)		
Dermis	3.9	30
Sweat duct	4	2000-4000

B. Computation Method

The EM simulation was conducted using the CST Microwave Studio software package, utilizing a 3D finite-difference or finite-element analysis to solve Maxwell's equations over a mesh of cells covering the model. We used the T-solver (Time domain solver) feature, which based on solution of differential form of Maxwell's equations. The advantage of T-solver over F-solver (frequency domain solver) is the less memory that it consumes, and it is thus faster. The source we used is a plane wave, constructed of Floquet ports, located at the bottom of the dermis layer and directed perpendicularly to the SC. Eventually, the transmission coefficient, S_{21} , was simulated at a distance of 30 cm from the plane wave source to match the experimental setup.

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