Circular polarization induced by the three-dimensional chiral structure of human sweat ducts

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The upper part of the human eccrine sweat ducts, embedded within the epidermis layer, have a well-defined helical structure. It was recently suggested that, as electromagnetic entities, the sweat ducts interact with sub-mm waves [Y. Feldman *et al.*, Phys. Rev. Lett. **100**, 128102 (2008)]. Although correlation between changes in the reflectance spectrum in this frequency range and physiological activities has been shown, a direct link between the electromagnetic reflection and the helical structure itself has remained to be established. The fact that the sweat ducts manifest natural homochirality is henceforth used to produce this link. We report the detection of circular polarization asymmetry in the electromagnetic reflection from the human skin at sub-THz frequencies *in vivo*. We compare the results to numerical simulations and to measurements of a fabricated metamaterial. We argue that the observed circular dichroism can be interpreted uniquely as the signature of the helical structure itself. By twisting reflected electromagnetic waves, the human skin exhibits properties which are usually discussed only in the framework of metamaterial science.

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I. INTRODUCTION

It was recently found that changes in biometric parameters such as the blood pressure and the pulse rate after sessions of physical activity, are manifested in the electromagnetic response of the human skin at sub THz frequencies [1,2]. In addition, it was shown that occurrences of mental stress also induce changes in the reflection of the skin at these frequencies [3]. The investigations that led to these findings were motivated by the observations that the ducts of the upper part of the eccrine sweat ducts have a well-defined helical structure [4,5] (see Fig. 1). This brought forward the supposition that the ducts may behave as low-Q helical antennas. By applying basic antenna theory using typical dimensions of the ducts, and taking into account known dielectric and conductivity characteristics of the surrounding tissue, the effective frequency range for the ducts-antennas was found to be in the sub-THz region. These results have later been verified [6], and research groups worldwide have addressed different aspects of this phenomenon [7–9]. Moreover, it was also observed that the induced changes in the skin reflectivity were significantly reduced when the activity of the perspiration system was inhibited [1]. However, all the experimental results were obtained using a "black box" approach. Despite that a correlation between the sweat system activity and changes in the reflection spectrum has been found [1,2,6], the link between the electromagnetic reflection properties of the skin and the helical structure of the duct was still to be determined. The key to identifying such a necessary link can be found in an important property of the sweat ducts helical structure—homochirality. By studying dissected slices of human skin, it was revealed that the coiled sections of the sweat ducts have, with a pronounced preference (approximately 90%), a right-handed turning direction [10,11].

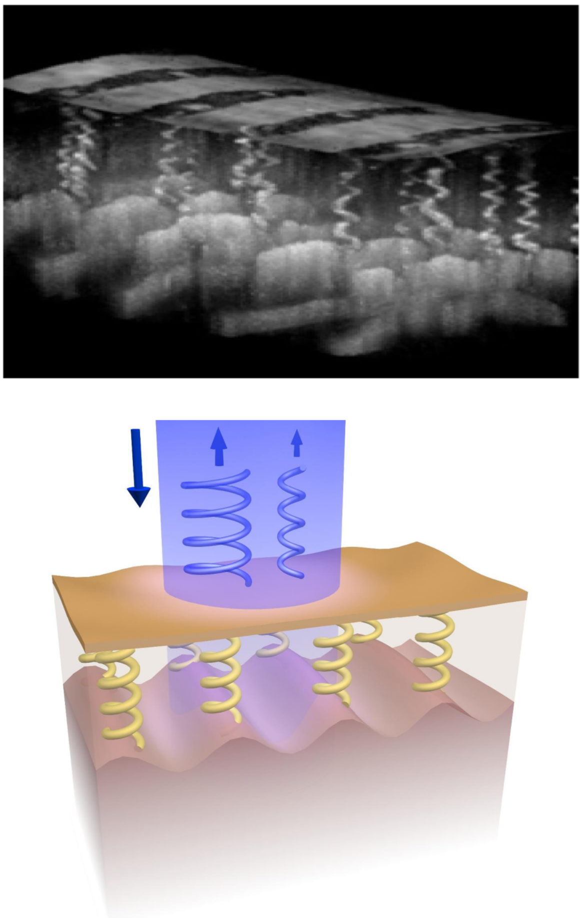
Homochirality is a well-known feature of biochemical life at the molecular level and can be detected using circular dichroism (CD) spectroscopy [12]. Even though the structures concerned here are of submillimetric size, a similar approach can be applied. In this work, the parameter representing CD is calculated according to the following:

$$\frac{\Delta R}{R} = \frac{R_+ - R_-}{R_+ + R_-}. \tag{1}$$

Here R_+ is the reflection coefficient from the sample when excited by left-handed circular polarization (LCP), and R_- is the reflection coefficient when excited by right-handed circular polarization (RCP). Since circular polarization reflection obeys the rule $R_{++} = R_{--}$ (here R_{ij} represents the reflection of a field in the polarization state i when excited with polarization state j), the contribution to the reflection difference arises from the polarization conversion terms $\Delta R = R_{-+} - R_{+-}$ [13]. Hence, a negative value of $\Delta R/R$ is expected. It was shown recently that the frequency for the optimal detection of CD, which is identical to the axial mode frequency of a classical helical antenna, is calculated according to the following [14]:

$$C \approx \lambda \Rightarrow f_{\text{axial}} \approx \frac{c_0\sqrt{\epsilon}}{C} \approx 380 \text{ GHz}. \tag{2}$$

Here C is the circumference of the helical sweat duct ($\sim 140\pi$ μm) [2], c_0 is the speed of light in vacuum, and ϵ is the relative dielectric permittivity of the epidermis (~ 3.2) [2,8,15]. It is clear from (2) that a variation in the epidermis dielectric permittivity or the helical sweat duct dimensions can yield different frequencies. Therefore, it is important to evaluate the effect of these parameters on CD detection and its bandwidth. Using a finite-element simulation for a three-layer skin model with helical sweat ducts embedded in the epidermis [14], we have constructed the expected reflection circular dichroism spectrum of the human skin (Fig. 2). The results of the simulations with two different excitation sources, right and left circular polarizations, were compared and the circular dichroism was calculated according to (1). In the vicinity of 380 GHz, one can observe the well-pronounced dip in the CD spectrum. Note that the conductivity of the sweat determines the magnitude of the CD signal, but it does not effect the location of this minimum in frequency domain (see discussion). From the width of the dip it is



(a)

(b)

FIG. 1. (Color online) (a) The helical structure of the human sweat ducts as visualized using OCT *in vivo* [5] (Gabor domain optical coherence tomography. Image by Jannick P. Rolland, University of Rochester). (b) Homogeneity of the helices turning direction will create a difference between the reflection of left and right circular polarizations.

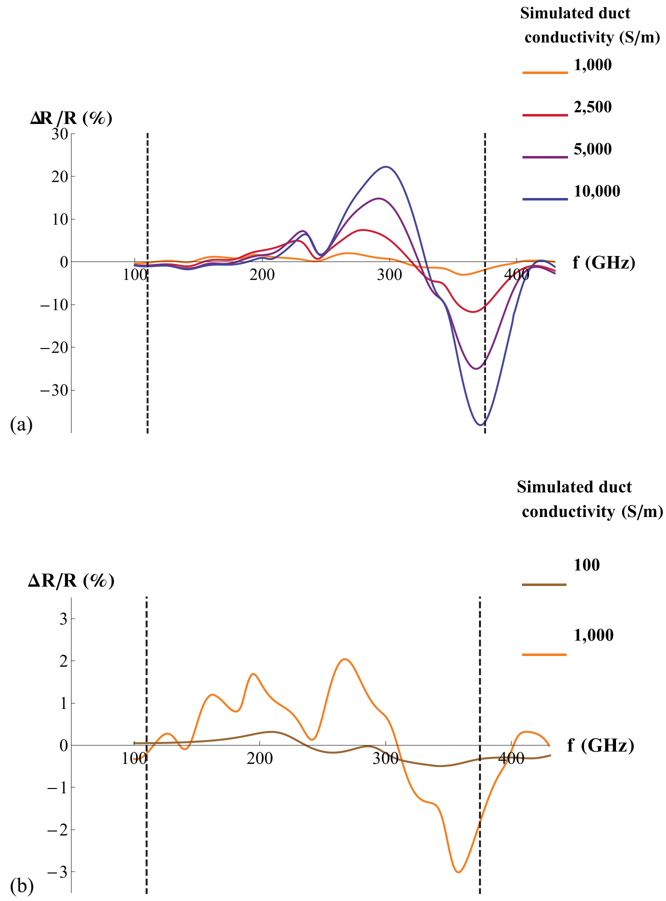


FIG. 2. (Color online) Finite-element simulation of a three-layer skin model with embedded sweat ducts. The results show circular dichroism in the reflection from the skin. The spectral shape is mainly determined by the radii of the sweat ducts and the permittivity of the epidermis. (a) The conductivity of the sweat determines the magnitude of circular dichroism. The two straight lines mark the frequencies that were used in the experiment (110 and 380 GHz). Around 380 GHz, the lowest line (strongest effect) represents a result from a model with duct conductivity of 10 000 S/m, and the highest line (weakest effect) represents a result from a simulation with 1000 S/m. (b) Results from the simulations using moderate conductivity values shows lower CD amplitudes but with a similar spectral shape.

clear that variations in the skin (in skin permittivity or coil diameter) will still lead to the prediction of significant CD around this frequency. However, there are serious challenges in measuring the polarization-dependent reflection of the skin *in vivo*. Muscle tremor, small changes of the incident angle, and the need to acquire a sufficient amount of data dictate suitable system requirements.

II. METHODS

A. Alternating circular polarization generator

The experiments were conducted using an AB-Millimetre vector network analyzer (MVNA-8-350, Paris, France) [16,17]. The experimental approach is based on creating alternating left and right circular polarizations by controlling the phase difference between two orthogonal linear polarizations. We utilize a reflective circular polarizer, consisting of a free-standing wire grid placed at 3/8 wavelength in front of a mirror (Fig. 3). Half of the radiation is immediately reflected by the grid, while the other half, in the orthogonal polarization, is reflected by the mirror and delayed by 3/4 wavelength, resulting in a conversion from linear to circular polarization. A reflecting shutter is placed between the grid polarizer and the mirror and serves as a second mirror (located 1/8 wavelength from the polarizer) when closed. Thus, a 1/4-wavelength phase difference between the two orthogonal polarizations is created, resulting in circular polarization in the opposite rotation direction. The shutter is opened and closed repeatedly, generating alternating circular polarizations.

The system had to be calibrated separately for every frequency, due to the dependence of the necessary optical path on the wavelength. The phase differences of the two orthogonal polarizations at two different system states had to be accurately adjusted. Additionally, the amplitudes of both polarization components had to be kept similar. Standing waves within the system, as well as other technical limitations,

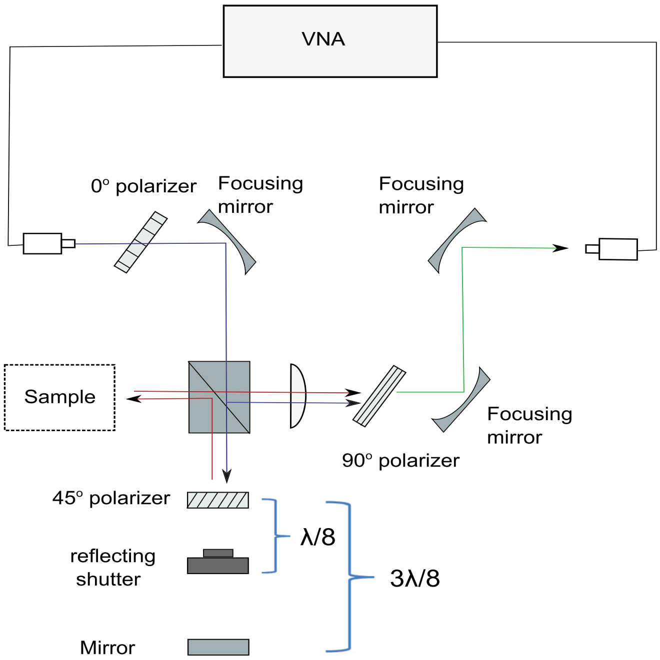


FIG. 3. (Color online) The experimental setup. Opening and closing the shutter is creating alternating left and right circular polarizations. The EM radiation reflected from the sample is measured. The difference between the reflection coefficients when excited by the two circular polarization states is calculated.

made this possible only in specific system positions and at specific frequencies. The measurements were done at two frequency points, 380 GHz, which is estimated as the approximate axial mode of the helical structures, and 110 GHz for comparison (only negligible CD is expected at 110 GHz, as can be seen in Fig. 2). The reflection from, or transmission through, the sample was measured for each one of the two circular polarizations and the difference was calculated. Each comparison between two system states was considered as a measurement, for which the CD value was determined according to Equ. (2). A single experiment was composed of between 500 and 1000 measurements continuously collected, of a single sample (material or human subject), over a 4-min period. An elimination of fixed system error was done by measuring a reference metal plate and calibrating the measured reflection using $R_+ = R_{+,\text{measured}}/R_{+,\text{metal}}$ and $R_- = R_{-,\text{measured}}/R_{-,\text{metal}}$.

B. Fabricated metamaterial as positive control

In order to verify that the system can actually detect CD, a reference sample with well-known CD properties was required. For this purpose, a metamaterial that exhibits chirality depending on the incident angle [18,19] was fabricated. Although this is only possible in transmission mode, the ability to control the expected response using the incident angle makes this method optimal for examining the system sensitivity and the data processing method.

The transmission through the metamaterial was measured, and the CD values were calculated according to $\Delta T/T = (T_+ - T_-)/(T_+ + T_-)$ [here T as the transmission coefficient replaces the reflection coefficient R used in Eq. (1)]. The metamaterial was designed to act slightly off-resonance at 380 GHz in order to check the ability of the system to detect weak CD values. By changing the incident angle, an alteration in the circular polarization direction preference was detected. Histograms of the collected data are presented in Fig. 4. Each histogram shows a mean value of CD which switches its direction when the incident angle is changed from -30° to 30°, confirming the ability of the system to correctly gauge the measure of CD in the sampled signal.

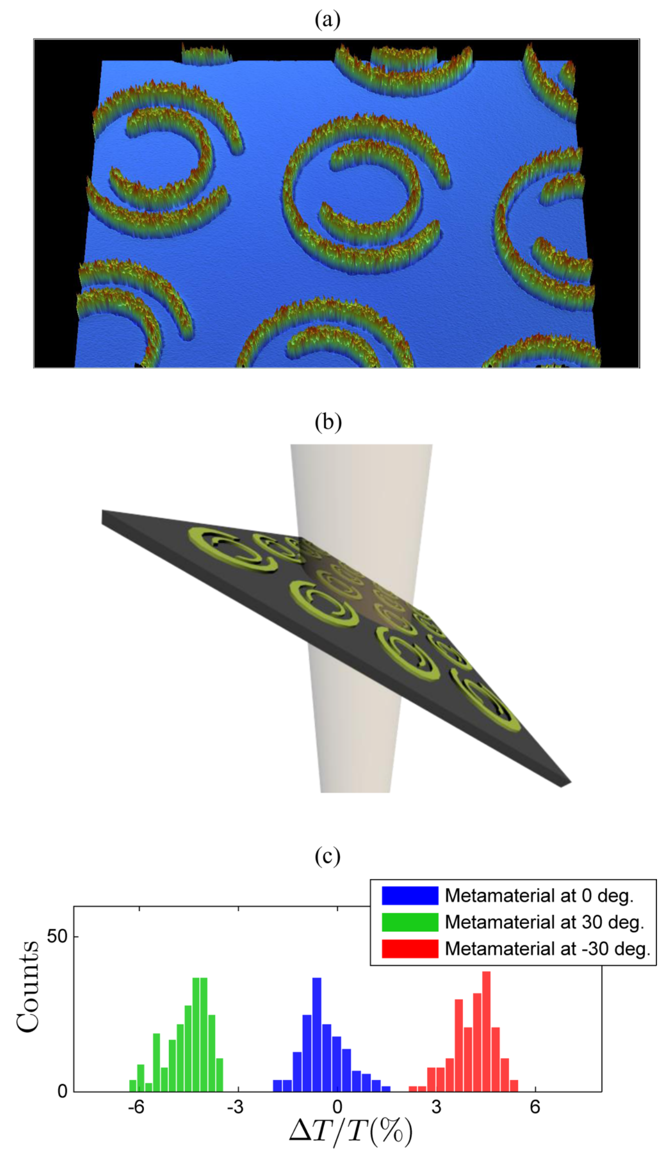


FIG. 4. (Color online) Measurements of the circular dichroism in the transmission through a fabricated metamaterial were used in order to verify the accuracy of the experimental setup. (a) Scanning microscope image of the metamaterial. (b) A change in the direction of circular dichroism was measured when the incident angle has been altered (schematic diagram). (c) The histograms of the measured CD at incident angles of 0° (middle histogram), 30° (left histogram), and -30° (right histogram) are presented. The y axis is the number of measurements (counts). The CD value and direction are listed in the x axis.

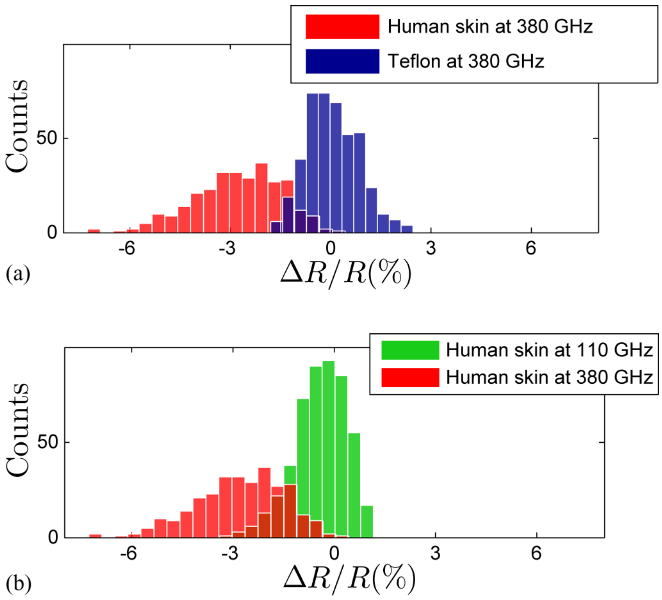


FIG. 5. (Color online) (a) Histograms of the CD reflection measurements from the skin of one typical subject (left histogram) and from a Teflon plate (right histogram). Significant nonzero circular dichroism is detected in the reflection from the human skin. (b) Histograms of the CD measured in the reflection from the skin of one typical human subject at 380 GHz (left histogram) and from the same subject at 110 GHz (right histogram).

III. RESULTS AND DISCUSSION

We conducted a series of *in vivo* measurements of the reflection coefficient of the palm skin of 10 subjects (3 women and 7 men), ages 25–47, in normal health, with the approval of the Ethical Committee of the Hebrew University of Jerusalem. The subjects were not under the influence of any external stimulus. A typical histogram showing the pronounced CD effect for one subject is presented in Fig. 5.

No significant CD was detected when using a Teflon plate as a sample [Fig. 5(a)]. In addition, no CD was found in the reflection from the human skin at 110 GHz [Fig. 5(b)], confirming the frequency dependence of the phenomena, as predicted by the simulation (see Fig. 2). The results of the CD study for 10 subjects show a marked preference of right circular polarization in the reflection properties of the skin. Statistically significant results were detected in 9 of 10 subjects individually [see Fig. 6(a)]. Moreover, in spite of some variations in the exact magnitude of the phenomena [0.5–3.5%, see Fig. 6(b)], the same preference in the direction of CD remains.

The conductivity of electrolytic solutions was previously measured and found to be 100 S/m around 100 GHz [20]. From the simulation results (Fig. 2) one can see that the detected value of CD matches sweat conductivity values of 100–1000 S/m, which does not strongly diverge from the measured value. The slightly higher value can be explained by the fact that the conductivity of electrolyte solutions was only measured in bulk and not near surfaces as within the sweat ducts. It is clear that the noticeable detected CD can only be caused due to the presence of the helical sweat ducts. There are no other submillimetric sized structures, which exhibit homochirality, in the upper skin surface. Moreover, inter-layer interferometric effects, which were previously argued to have a possible influence on the linear reflectance spectrum of the skin [7], cannot account for the creation of CD. Hence, CD can be regarded as the unique signature of the helical structure itself and thus providing, for the first time, a direct confirmation of the antennalike behavior of eccrine sweat ducts.

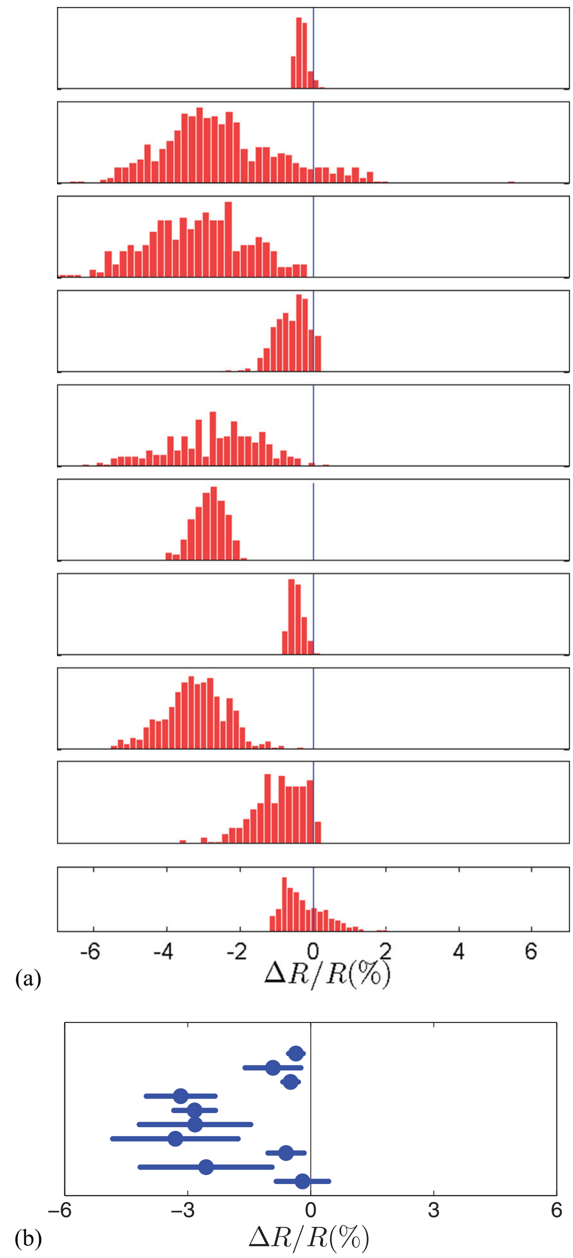


FIG. 6. (Color online) (a) Histograms of the reflection circular dichroism measurements from the skin of all 10 human subjects at 380 GHz exhibit 0.5–3.5% circular dichroism. (b) The calculated CD values means are presented with their STD. A preference to RCP at 9 of 10 subjects is clearly detected (one subject shows a less significant result).

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