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Analysis of human skin tissue by millimeter-wave reflectometry

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Background/purpose: Millimeter-wave reflectometry is a potentially interesting technique to analyze the human skin *in vivo* in order to determine the water content locally in the skin. Purpose of this work is to investigate the possibility of skin-tissue differentiation. In addition, it addresses the influence of the pressure of the probe on the skin, the influence of an air gap between probe and skin as well as the influence of a bandage between probe and skin.

Methodology: Reflection coefficients at various positions on the skin are measured in the 40–60 GHz range and the examined effects are quantified in terms of magnitude and phase of the reflection coefficient. Also, the possibility to perform tissue differentiation is quantified.

Results: It is indicated that differentiation of skin tissue can be performed on the basis of the magnitude of the reflection coefficient provided that no air gap exists between probe and skin. The

influence of probe pressure can be substantial, in particular for phase measurements. The presence of an air gap between probe and skin reduces the differentiation capability of the considered measurement technique, whereas a bandage between probe and skin did not significantly affect the differentiation power.

Conclusion: The results of this work confirm the potential of millimeter-wave reflectometry for determination of the water content in skin tissue which may lead to interesting applications as early detection of skin cancer and through-bandage monitoring of wounds.

Key words: millimeter-wave reflectometry – tissue differentiation – open-ended wave-guide probe – water content

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THANKS TO the huge worldwide effort in developing low-cost integrated chip technology for operating frequencies in the millimeter-wave range (in particular the 60 GHz band, which is of particular interest for automotive and wireless applications), there might be an opportunity to exploit this already available technology for developing sophisticated and nevertheless affordable diagnostic tools for medical applications. One application of particular interest to be explored is the non-invasive early detection of skin anomalies such as skin cancer and the monitoring of wounds through plaster and bandages. When compared with microwaves at lower frequencies (< 30 GHz), millimeter waves have the advantage of a higher spatial resolution as well as the advantage of penetrating into the skin but not significantly deeper whereas the waves at higher frequencies (> 300 GHz), i.e., terahertz electromagnetic waves, have almost no penetration capability at all. So, millimeter waves have the advantage to optimally interact with the human

skin with minimum disturbance from deeper located tissues. In addition, millimeter waves are non-ionizing and may therefore become a harmless alternative for X-ray. The dielectric permittivity in the millimeter-wave frequency range of skin tissue is directly related to cutaneous free water content of the skin (1). Therefore, millimeter-wave reflectometry may play a role in, e.g., the examination of skin hydration, monitoring of wound healing and early detection of skin cancer. As regards the latter, it is important to note that the water content of cancerous tissues differ from the water content of harmless lesion types (2) and that the commonly applied method of just visual screening lacks diagnostic accuracy so that common benign nevi are often excised for histopathological examination (3).

A literature search of millimeter-wave methods to determine water content in human skin tissue reveals a number of articles. Gabriel et al. (4) used a coaxial probe for reflectivity measurements at the skin surface. Such probe does not radiate and is therefore not suitable for

non-contact measurements. Alternatively, open-ended waveguide probes are radiating and they appear to be promising for contact as well as for non-contact measurements as demonstrated by Alekseev and Ziskin (1) and Kharkovski et al. (5). Feldman et al. (6) used a horn terminated by a Teflon plate for contact measurements. In addition, a horn in combination with a lens was used to perform distance measurements. However, in order to optimize spatial resolution, the relatively small aperture of an open-ended waveguide probe is preferred. Diseased skin may be detected by using a differential probe consisting of two wave-guide probes that detect the different dielectric properties of neighboring skin types (e.g., normal and diseased skin). An inherent advantage of these localized differential measurements is that the possible influence of personal factors such as age, gender, race, physical and emotional state and environmental factors such as location and season is avoided.

In spite of a number of publications on skin measurements at millimeter-wave frequencies we were not able to find in the literature the influence of some important factors that could possibly influence the measurement results, considerably. The aim of this work is to address the following remaining research questions: (i) How far is it possible to differentiate between different types of skin tissue? (ii) What is the influence of the pressure of the probe on the skin? (iii) What is the influence of an air-gap between probe and skin? and (iv) what is the influence of a bandage between probe and skin? Present literature almost exclusively presents reflection coefficient data in terms of the magnitude only. Since a reflection coefficient is a complex figure we also may benefit from the phase information which might be useful to provide distance and thickness information of skin structures. Therefore, all mentioned effects are quantified in terms of magnitude as well as phase.

Measurement Method

The reflectivity of human skin has been measured in the 40–60 GHz frequency range with the help of an HP 85106C millimeter-wave Vector Network Analyzer (VNA) system from Agilent (Santa Clara, CA, USA). The measurement setup is shown in Fig. 1.

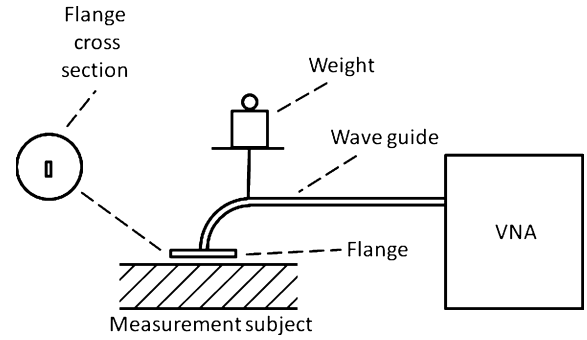


Fig. 1. Measurement setup.

The probe was a standard WR-19 rectangular open waveguide which has aperture dimensions $2.39 \text{ mm} \times 4.78 \text{ mm}$ and a round flange with a diameter of 28.6 mm. The flange dimensions comply with the WR-19 standard. The presence of the flange allows straight-forward calibration with the available calibration tool, i.e., the Agilent U11644A WR-19 mechanical calibration kit. The radiated power was $20 \mu\text{W}$ which implies an exposure level of $0.2 \text{ mW}/\text{cm}^2$. This is well below the maximum allowed exposure limit that holds in the Netherlands where the measurements were performed (7).

A placeholder was mounted on the probe on which different weights were put during the measurements in order to obtain a well-controlled constant pressure of the probe on the skin. Magnitude and phase have been measured in the frequency-step mode at 201 frequencies with steps of 100 MHz from 40 to 60 GHz. One complete run of 201 measurements took about half a minute. Before measurement the VNA was calibrated carefully with a short, quarter-wavelength offset and sliding load. The VNA was put on at least one hour before calibration in order to achieve a temperature-stable measurement system.

Tissue Differentiation

In order to get an idea of the capability to differentiate between different skin types, measurements have been performed at various left-and-right corresponding positions of hands and forearms of one and the same person (53-years-old male with no history of dermatological disease): (i) at fingertips of both middle fingers, (ii) at nails of both middle fingers, (iii) at palms of both hands and (iv) at both forearms. We pre-assume that tissues are similar (i.e., have

similar electromagnetic properties) at left-and-right corresponding positions, whereas tissues at non-corresponding positions may differ due to different layering, etc. Figure 2 shows the magnitude and phase as function of frequency in the 40–60 GHz range at the mentioned positions. The probe pressure has been kept constant by loading the probe with a 300 g weight which gives a constant moderate pressure on the skin. The ripple on the curves is due to residual calibration error.

The magnitude curves of Fig. 2(a) indicate that similar (i.e., left-and-right corresponding) skin tissues give similar magnitude levels whereas different skin tissues give quite different magnitude levels. To quantify the difference in curves we take the (average of) sum of

squares as a metric for the difference in curvature of curves as commonly done in multivariate statistical analysis. So, we determine for each possible pair of curves a kind of difference coefficient F_{mag} as a metric for their mutual discrepancy:

$$F_{\text{mag}} = \sum_{i=1}^N \Delta_{\text{mag},i}^2 \quad (1)$$

in which $\Delta_{\text{mag},i}$ represents the difference in magnitude at frequency position i whereas N is the total number of frequency positions which amounts to 201 for all curves. The difference $\Delta_{\text{mag},i}$ is calculated in terms of dBs instead of ratios to make the weighting independent from the actual magnitude levels. In the same way,

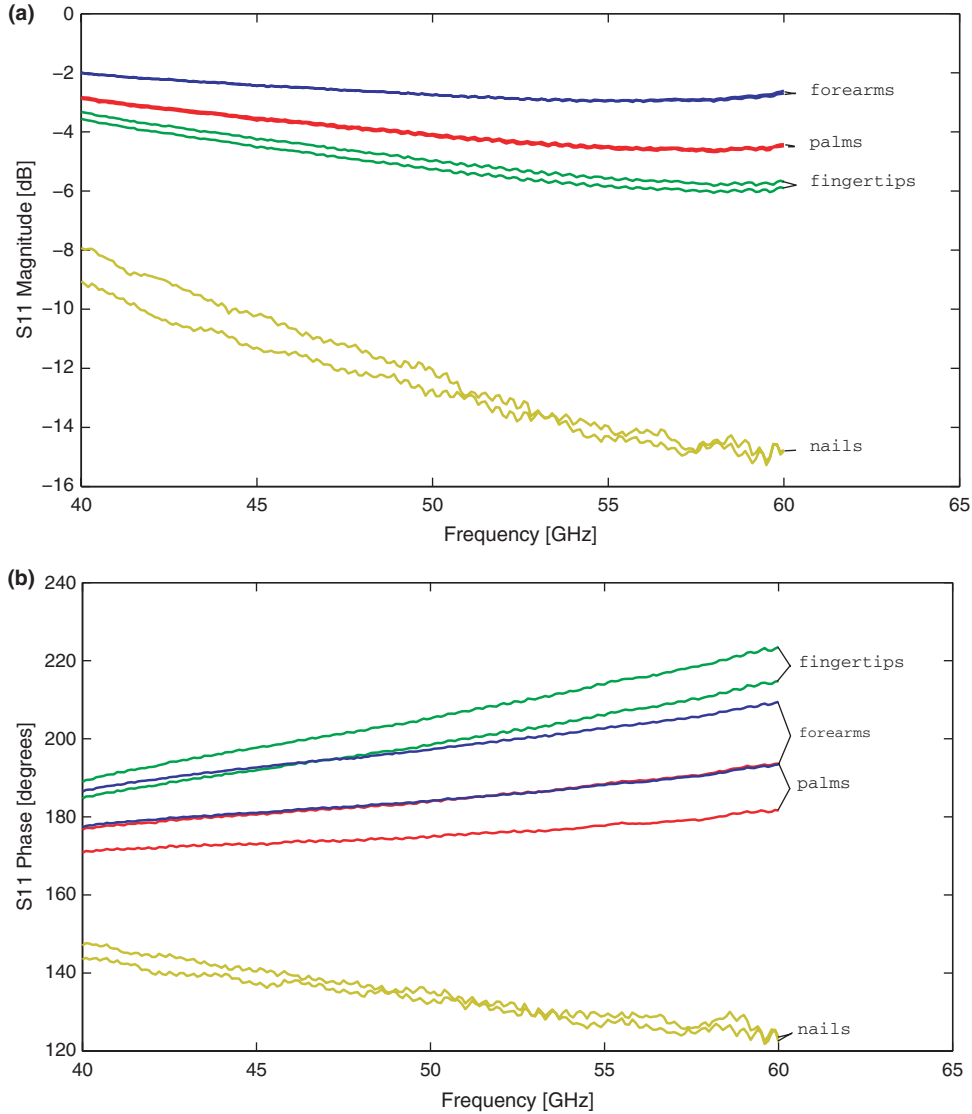


Fig. 2. Reflection coefficient as function of frequency: (a) magnitude and (b) phase.

we determined also the difference coefficient F_{phase} for each phase curve in Fig. 2(b) as a result of $\Delta_{\text{phase},i}$ (in degrees), thus

$$F_{\text{phase}} = \sum_{i=1}^N \Delta_{\text{phase},i}^2 \quad (2)$$

Note that, in this way, we exploit the frequency diversity that is inherently available in the measurement results to differentiate. Table 1 shows the F_{mag} -values as well as the F_{phase} -values for each possible pair of curves. In this table fingertips are denoted as ‘t1’ and ‘t2’, palms as ‘p1’ and ‘p2’, forearms as ‘a1’ and ‘a2’ and nails as ‘n1’ and ‘n2’. The F_{mag} -values are indicated in bold-style below the zeros on the diagonal whereas F_{phase} -values are indicated in italic-style above the diagonal.

Figure 2(a) shows that in particular the forearms and palms have strikingly matching magnitude curves. This large resemblance is reflected by the low values of difference coefficients of pair (a1, a2) and pair (p1, p2) in Table 1; both amount to 0.00. Also the fingertip-curves (t1, t2) show a large mutual resemblance as reflected by the relatively low difference coefficient of 0.07. Although to a lesser extent, this also accounts for the nails. As regards magnitude, similar tissues show clearly small difference coefficients whereas different tissues show relatively high difference coefficients, indicating that, for the considered set of tissues, differentiation with respect to magnitude will be easy to perform, in practice. The difference of 1–2 dB between the forearm curves and the palm curves complies with the measured results published in (1). This difference can be explained by the dominant influence of the surface layer of the skin (Stratum Corneum) which is less conductive when compared with the deeper skin layers. This surface layer

of palm tissue is thicker than the surface layer of the forearm, which makes palm tissue less reflective.

The phase curves of Fig. 2(b) show that, in contrast with magnitude, differentiation with respect to the phase will not be easy to perform. This becomes also clear from the figures in Table 1: the pair of different tissues (p1, a2), for instance, shows the lowest possible difference coefficient of 0.00 whereas the pair of similar tissues (p1, p2) gives the much higher value 1.48.

Figure 2(b) shows that, for all measurements, the phase is nicely linear with frequency. A phase of 180° is theoretically to be expected in case the probe is placed against a half space of homogeneous material which implies one single boundary located at the calibration reference plane. However, the phase-curves show some deviation from 180°. As regards the fingertips, nails and fore-arms this could be explained by a slight popping of the tissue into the open wave guide; the wave propagating in the waveguide reflects back from a boundary that is located slightly closer to the VNA than the reference plane at which the reflection against the short took place at calibration. However, also reflections can occur outside the waveguide, e.g., due to layering, yielding a deviation from 180° in the opposite direction. The curves for the nails, for instance, show a phase difference in the opposite direction since the nails do not pop into the waveguide because of their rigid structure. As a matter of fact they form a second boundary outside the waveguide from which the electromagnetic wave emitted from the probe is reflected back.

Influence of the Probe Pressure

In practice, the pressure of the probe on the skin surface may vary significantly during the measurements. We examined the influence of pressure on the magnitude and phase of the measured reflection coefficient by loading the probe with different weights: 30 g (complying with ‘light’ pressure), 300 g (i.e., ‘moderate’ pressure) and 700 g (‘heavy’ pressure). The results for the right fingertip, palm, forearm and nail are depicted in Fig. 3.

As regards magnitude, the influence of the probe pressure occurs to be insignificant for the fingertips, palms and forearms whereas we

TABLE 1. Difference coefficients of magnitude curves (indicated in bold style) and phase curves (indicated in italic style)

	t1	t2	p1	p2	a1	a2	n1	n2
t1	0	<i>0.81</i>	<i>3.95</i>	<i>10.2</i>	<i>0.13</i>	<i>3.93</i>	<i>79.8</i>	<i>75.3</i>
t2	0.07	0	<i>8.34</i>	<i>16.8</i>	<i>1.37</i>	<i>8.30</i>	<i>96.8</i>	<i>91.8</i>
p1	1.38	0.84	0	<i>1.48</i>	<i>3.05</i>	<i>0.00</i>	<i>48.3</i>	<i>44.8</i>
p2	1.24	0.73	0.00	0	<i>8.75</i>	<i>1.50</i>	<i>32.9</i>	<i>30.0</i>
a1	6.32	5.08	1.79	1.96	0	<i>3.01</i>	<i>75.5</i>	<i>71.1</i>
a2	6.38	5.14	1.83	2.00	0.00	0	<i>48.4</i>	<i>44.9</i>
n1	57.4	61.5	76.6	75.5	102	102	0	<i>0.11</i>
n2	49.5	53.2	67.4	66.3	91.1	91.4	0.54	0

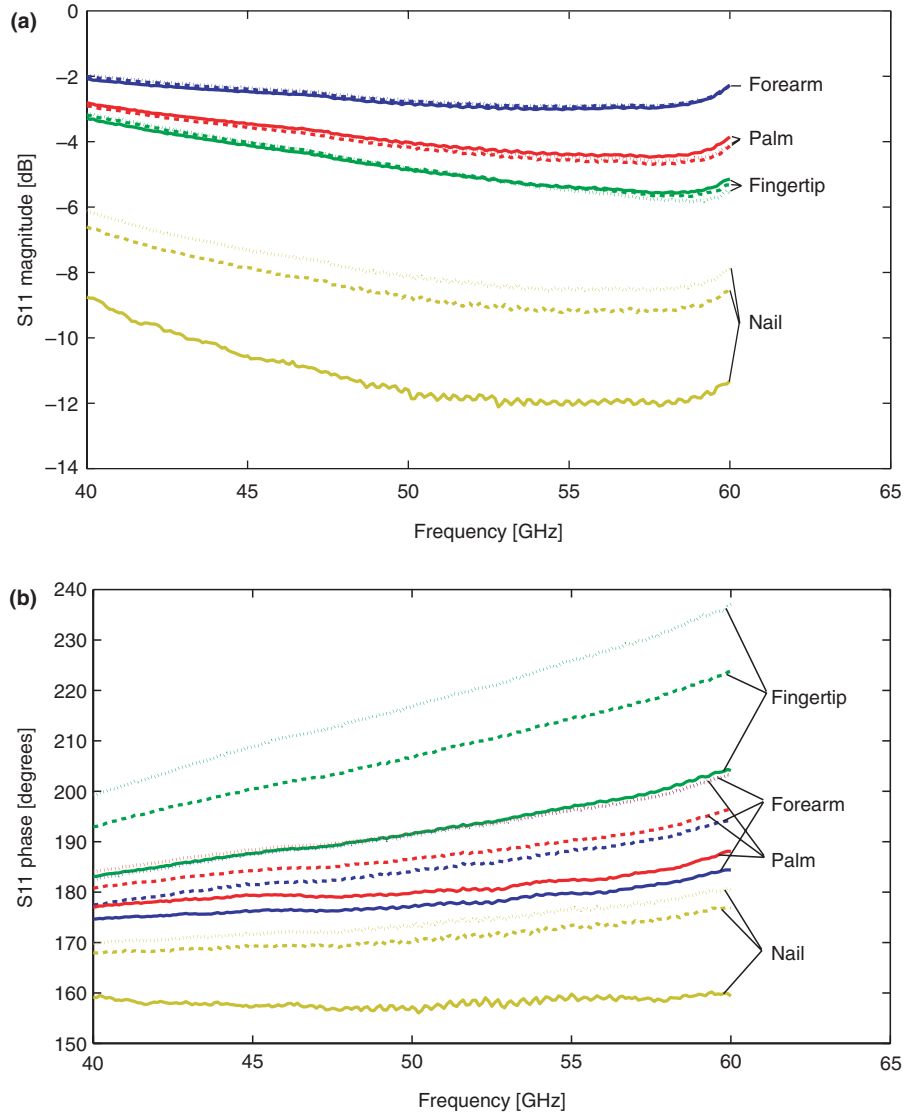


Fig. 3. Reflection coefficient obtained with different weights on the probe; 30 g (solid curves), 300 g (dashed curves) and 700 g (dotted curves): (a) magnitude and (b) phase.

found a substantial influence for the nails. The latter can be explained by the dependence of the curvature of the nail on the probe pressure.

The phase curves reveal a consequent relationship of the phase deviation from 180° with the probe pressure for all cases. As regards the soft tissues this can be understood by noting that an increased pressure causes the tissue to pop deeper into the waveguide so that the VNA ‘sees’ a shorter propagation path in the waveguide yielding an increased deviation of the phase from the 180° reference. The opposite accounts for the nails; the phase difference from 180° tends to decrease with increasing pressure because the nail flattens yielding a shorter propagation path outside the waveguide through the nail.

Influence of an Air gap

Next to contact measurements it would be useful to have the possibility to perform non-contact measurements, e.g., to avoid painful contact of the probe with burning wounds. Therefore, we examined the effects of introducing an air gap between probe and skin. Figure 4 shows the results of measurements with a stand-off distance of 3.4 mm. Note, that the frequencies at which the dips occur in the magnitude curves of both palms, fingertips and forearms as well as the magnitude of these dips are not very specific for the different tissue types. This also accounts for the maxima of the phase curves. Table 2 shows the difference coefficients for the situation with the air gap in a similar way as Table 1.

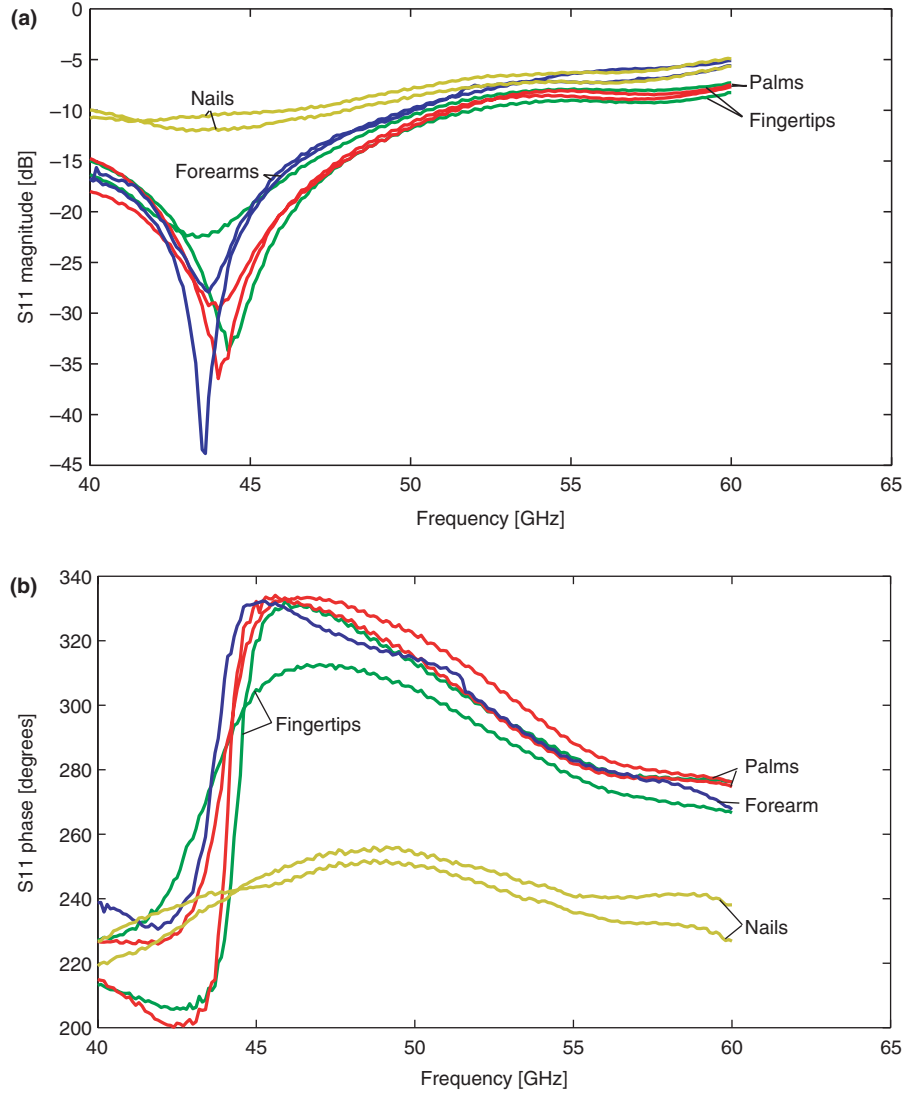


Fig. 4. Reflection coefficient obtained with air gap: (a) magnitude and (b) phase.

TABLE 2. Difference coefficients obtained with an air gap of 3.4 mm

	t1	t2	p1	p2	a1	a2	n1	n2
t1	0	7.72	3.84	7.97	2.35	50.4	30.4	36.4
t2	11.0	0	4.08	0.97	7.36	27.0	42.7	51.6
p1	6.08	2.92	0	3.31	1.25	40.5	51.6	60.0
p2	11.2	1.44	2.34	0	5.61	29.6	46.5	55.5
a1	2.23	11.0	5.45	8.42	0	48.8	46.0	53.2
a2	13.6	17.3	9.27	11.0	6.09	0	87.3	97.2
n1	25.0	55.9	53.1	57.8	30.7	57.1	0	0.69
n2	32.2	67.8	63.6	69.2	37.7	65.3	0.89	0

The intermingling of the curves associated with both palms, fingertips and forearms observed in Fig. 4 indicates that the tight differentiation found for contact measurements is almost lost. This is confirmed by the relatively high difference coefficients for corresponding tissues in Table 2 for, in particular, fingertip-

pair (t1, t2) and forearm-pair (a1, a2) and the lower values for the non-corresponding tissue pairs (p1, t2) and (P2, t2). The nail curves, however, still show a significant characteristic resemblance despite the air gap. This is reflected by the relatively low values for (n1, n2) in Table 2.

Influence of a Bandage

An obviously useful feature would be the capability to sense through bandages which would allow inspection of, e.g., burning wounds without the need for painful removal and application of these bandages each time an inspection is needed. We measured the magnitude and phase with a bandage present between the probe and skin. The bandage was Aquacel Ag

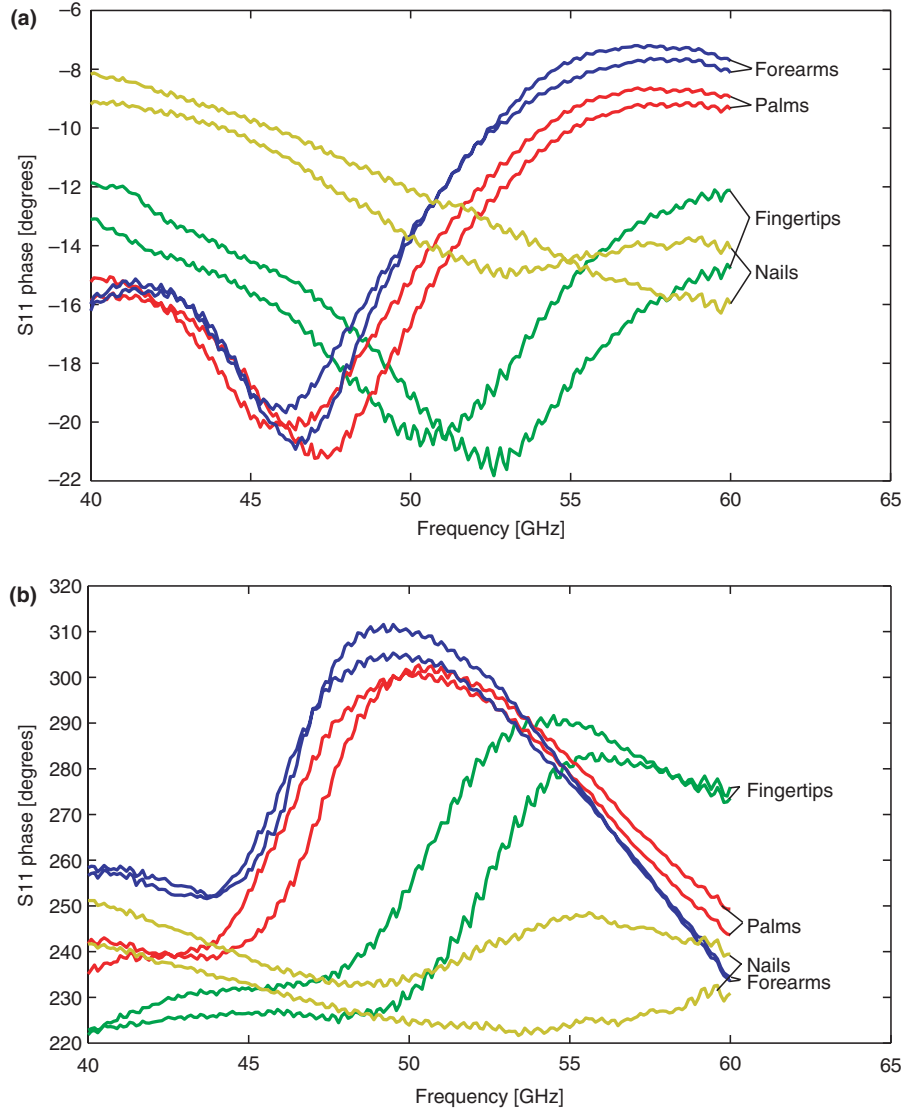


Fig. 5. Reflection coefficient obtained with bandage: (a) magnitude and (b) phase.

from ConvaTec (Skillman, New Jersey, USA) which is indicated for wet wounds including second-degree burning wounds. For the measurements we attached four layers of this bandage resulting in a total thickness of about 3 mm. During the measurements, a weight of 300 g was used to achieve a constant ‘moderate’ probe pressure on the bandage. Figure 5 shows the results. As opposed to the previous case with the air gap, the frequencies at which the magnitude dips occur are reasonably well specific for the different tissue types. This also accounts for the frequency positions of the phase maxima. The observed differentiation power is confirmed by the difference coefficients in Table 3. So, apparently the bandage tends to conserve the differentiation capability of the measurement technique.

TABLE 3. Difference coefficients obtained with four layers of Aquacel Ag bandage

	t1	t2	p1	p2	a1	a2	n1	n2
t1	0	3.28	14.6	10.9	21.8	23.9	28.6	14.4
t2	4.72	0	26.1	22.2	34.6	38.0	19.0	9.30
p1	20.4	39.6	0	0.71	1.18	1.60	41.2	25.2
p2	15.9	34.5	0.95	0	3.17	3.42	40.6	24.3
a1	28.0	48.7	1.23	3.74	0	0.20	45.9	29.2
a2	30.6	53.2	1.47	3.52	0.39	0	50.3	32.8
n1	30.0	25.9	44.5	45.7	43.8	49.9	0	3.29
n2	19.6	18.0	34.9	35.2	35.3	40.7	1.52	0

Conclusions

Reflectivity measurements at millimeter-wave frequencies in the 40–60 GHz range have been performed at the human skin, *in vivo*, to examine the possibility of skin-tissue differentiation and to examine the influence of probe

pressure, air gap and bandage between probe and skin, using a rectangular open-ended waveguide. For the considered set of tissues it is indicated that differentiation of skin tissue can be readily performed on the basis of the magnitude of the reflection coefficient provided that no air gap exists between probe and skin. Phase information seems less useful for this purpose. The influence of probe pressure can be substantial in particular for phase measurements. So, for accurate phase measurements the probe pressure should be kept critically constant or additional measures should be

taken to avoid popping of the skin into the empty waveguide.

As regards non-contact measurements it is demonstrated that the introduction of an air gap between probe and skin may reduce the differentiation capability of the considered measurement technique considerably, whereas a bandage between probe and skin did not significantly affect the differentiation power. So, as regards the specific type of bandage examined, millimeter-wave reflectometry looks also to be a promising option for through-bandage inspection of wounds.

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