

NON-INVASIVE REFLECTOMETRY-BASED DETECTION OF MELANOMA BY PIEZOELECTRIC MICRO-NEEDLE ANTENNA SENSORS

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Abstract—The electromagnetic characterization of piezoelectric micro-needle antenna sensors for fully non-invasive detection of cancer-related anomalies of the skin is presented. To this end, a full-wave finite-difference time-domain procedure is adopted to analyze the performance of the considered class of devices in terms of circuital characteristics and near-field radiation properties as a function of the curvature radius of the relevant sensing probe. This analysis is, in turn, useful to gain a physical insight into the processes which affect the behavior of the structure and, hence, the accuracy in the detection of possible malignant lesions of the skin. In particular, by using the mentioned modeling approach, an extensive parametric study is carried out to analyze the effect produced on the sensor response by variations of the complex permittivity of the skin due to the presence of anomalous cells and, in this way, obtain useful discrimination diagrams for the heuristic evaluation of the exposure level to the cancer risk.

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1. INTRODUCTION

The development of innovative and efficient electromagnetic techniques for non-invasive detection of melanoma is an important research topic for both the academic and industrial communities [1].

Melanoma is a serious form of skin cancer originating in the pigment-producing cells (melanocytes). These cells become abnormal, grow uncontrollably, and aggressively invade surrounding tissues. The skin has several layers, but the main layers are the dermis (lower or inner layer), and the epidermis (upper or outer layer) where skin cancers originate, and which is made up of three types of cells:

- Squamous cells: Thin, flat cells that form the top layer of the epidermis.
- Basal cells: Round cells under the squamous cells.
- Melanocytes: Found in the lower part of the epidermis, these cells produce melanin, the pigment that gives skin its natural color.

The growth of the melanoma results in a local variation of permittivity and electrical conductivity of the dermis [2]. This in turn provides an effective means for the early prediction of potential malignancy and monitoring of the extension of anomalous cells as a function of time by means of electrically small antenna sensors [1].

In this paper, the performance of piezoelectric needle antenna sensors for fully non-invasive detection of skin cancer is investigated thoroughly by using a dedicated full-wave modeling approach. The considered devices are characterized by good characteristics in terms of return loss and efficiency, and allows for an electronically controllable steering of the near-field radiation pattern which can be profitably used to focus the electromagnetic energy on the cancerous material [3].

2. SENSOR LAYOUT

The topology of the considered piezoelectric antenna sensor for near-field detection of cancer-related anomalies of the skin is shown in Fig. 1. As it can be readily noticed, the device features a micro-needle probe, having width $w_d = 0.15$ mm, thickness $t_d = 36$ μ m, and length $l_d = 1.6$ mm, which consists of an Aluminum Nitride (AlN) piezoelectric film sandwiched between two Molybdenum (Mo) electrodes.

The needle is assumed to be elevated above the skin in such a way as to have the circular metal shield with radius $r_g = 3.4$ mm and thickness $t_g = 0.25$ mm at a distance $h_s = 2.6$ mm from the epidermis for a fully non-invasive survey of potentially malignant

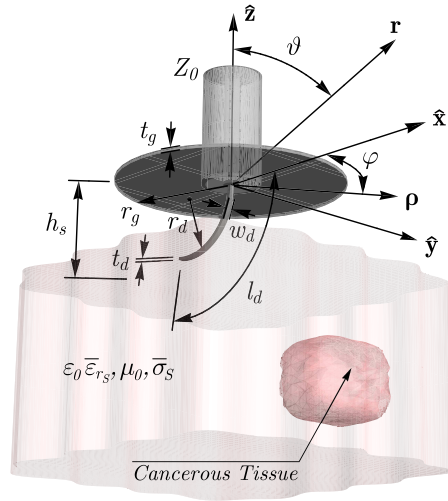


Figure 1. Geometry of the proposed micro-needle probe sensor for near-field detection of cancer-related anomalies of the skin. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_d = 1.25$ mm, $r_g = 3.4$ mm, $t_g = 0.25$ mm. The sensor is elevated to a height $h_s = 2.6$ mm above the epidermis, and excited by means of a coaxial feeding line having characteristic impedance $Z_0 = 50$ Ω . The reference system adopted to express the electromagnetic field quantities is also shown.

tissues. In particular, the curvature radius of the probe and, hence, the relevant near-field beam steering property can be changed electronically by applying a suitable low-frequency control voltage V_c to the *Mo* electrodes, as experimentally verified on physical prototypes manufactured at the facility of the Center of Biomolecular Nanotechnology, Italian Institute of Technology (*IIT*).

3. FULL-WAVE SENSOR MODELING

The complexity of the presented devices poses a non-trivial problem regarding the relevant full-wave characterization, an accurate and fast numerical scheme for solving Maxwell's equations being required. One such widely used technique is the finite-difference time-domain *FDTD* method. However, in the conventional formulation of the algorithm [4], each cell in the computational grid is implicitly assumed to be filled in by a homogeneous material. For this reason, the adoption of Cartesian meshes could result in reduced numerical accuracy where structures

Table 1. Parameters of the Cole-Cole-like Dispersion Model Relevant to the Skin of the Wrist/Forearm [7].

$\varepsilon_{r\infty}$	τ (ps)	$\Delta\varepsilon_r$	σ_i (S/m)	α
0.98.35	7.13	20.5	0.5	0.064

having complex geometry are to be modeled. In order to overcome this limitation, an enhanced locally conformal (*FDTD*) technique has been used [5, 6]. Such scheme provides a clear advantage over the use of the stair-casing approach or unstructured and stretched space lattices, potentially suffering from significant numerical dispersion and/or instability [4]. The adopted modeling approach is based on a suitable normalization of the electromagnetic field quantities, and the definition of effective material parameters accounting for the local electrical and geometrical properties of the structure under analysis. In this way, one can gain an insight into the underlying physical processes affecting the circuital characteristics and radiation properties of the considered class of devices. This in turn is important to improve the sensor reliability, so optimizing the design cycle.

In the proposed study, the skin layer is modeled as a half space having effective relative permittivity $\bar{\varepsilon}_{rS}$ and electrical conductivity $\bar{\sigma}_S$ computed by means of the integral mean value theorem as:

$$\bar{\varepsilon}_{rS} = \frac{1}{B} \int_{f_{\min}}^{f_{\max}} \text{Re} \{ \varepsilon_{rS}^*(f) \} df, \quad (1)$$

$$\bar{\sigma}_S = -\frac{1}{B} \int_{f_{\min}}^{f_{\max}} 2\pi f \varepsilon_0 \text{Im} \{ \varepsilon_{rS}^*(f) \} df, \quad (2)$$

respectively, ε_0 denoting the free-space permittivity and $\varepsilon_{rS}^*(f)$ the complex relative dielectric constant described by the following experimentally extrapolated Cole-Cole-like fitting equation [7]:

$$\varepsilon_{rS}^*(f) = \varepsilon_{r\infty} + \frac{\Delta\varepsilon_r}{1 + (j2\pi f\tau)^{1-\alpha}} + \frac{\sigma_i}{j2\pi f\varepsilon_0}, \quad (3)$$

with the model parameters being listed in Table 1.

4. SENSOR RADIATION PROPERTIES AND CIRCUITAL CHARACTERISTICS

By using the mentioned locally conformal *FDTD* technique, the circuital characteristics and radiation properties of the proposed class of sensing devices have been investigated in detail in the frequency

range from $f_{\min} = 30$ GHz to $f_{\max} = 60$ GHz ($B = 30$ GHz, $f_c = 45$ GHz) where, according to Equations (1)–(3) and the experimental physiological parameters listed in Table 1, the skin of the wrist/forearm exhibits an integral average relative permittivity $\bar{\epsilon}_{r_S} \simeq 13.37$ and electrical conductivity $\bar{\sigma}_S \simeq 19.49$ S/m.

A specific parametric analysis has been carried out in order to determine the impact of the curvature radius r_d of the micro-needle probe on the sensor performance in terms of impedance matching, as well as with regard to the total efficiency $e_a(f)$, given by:

$$e_a(f) = \left[1 - |\Gamma_{in}(f)|^2 \right] \frac{P_{rad}(f)}{P_{in}(f)}, \quad (4)$$

where $\Gamma_{in}(f) = [Z_{in}(f) - Z_0]/[Z_{in}(f) + Z_0]$ denotes the input reflection coefficient. In (4), $P_{in}(f) = \frac{1}{2} \text{Re}\{V_{in}(f)I_{in}^*(f)\}$ is the real input power accepted by the sensor in proximity of the skin, whereas the total radiated power $P_{rad}(f)$ is determined by integrating the real part of the Poynting vector over a surface S_a enclosing the device:

$$P_{rad}(f) = \frac{1}{2} \text{Re} \left\{ \iint_{S_a} \mathbf{E}(\mathbf{r}, f) \times \mathbf{H}(\mathbf{r}, f)^* \cdot d\mathbf{S} \right\}. \quad (5)$$

As can be noticed in Fig. 2, the sensor features a fundamental resonant frequency $f_0 \simeq f_c = 45$ GHz, which is not severely impacted by the curvature radius of the probe. On the other hand, the reactive energy

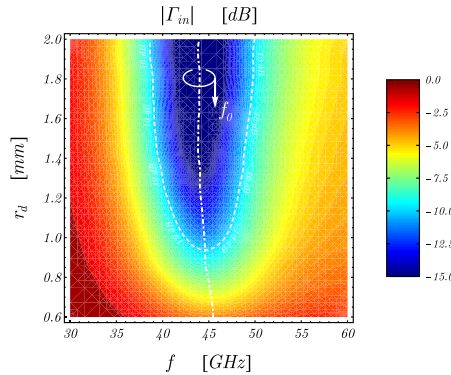


Figure 2. Frequency-domain behavior of the input reflection coefficient featured by the micro-needle sensor as a function of the curvature radius r_d of the probe. The fundamental resonant frequency f_0 of the device is also shown. $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_g = 3.4$ mm, $t_g = 0.25$ mm. The sensor is assumed to be elevated to a height $h_s = 2.6$ mm above the epidermis.

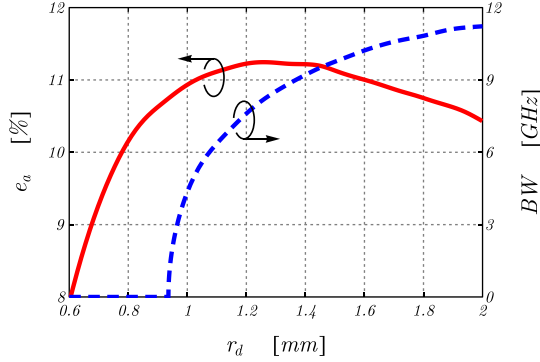


Figure 3. Operating bandwidth BW at 10 dB return-loss level and total efficiency e_a at the central working frequency f_c as functions of the curvature radius r_d of the sensor probe. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_g = 3.4$ mm, $t_g = 0.25$ mm. The sensor is assumed to be elevated to a height $h_s = 2.6$ mm above the epidermis.

storage process occurring in the spatial region between the needle and the metal shield results in a capacitive effect which can significantly affect the impedance matching of the device to the feeding line and, hence, the operating bandwidth BW , whose behavior at 10 dB return-loss level, as a function of r_d , is shown in Fig. 3. It has been numerically found out that the circuital characteristics of the considered sensor rapidly degrade as the curvature radius of the probe decreases, with BW tending to zero for $r_d \rightarrow 0.935$ mm. Inspection of Fig. 3 also reveals that the total efficiency e_a of the sensor at the central working frequency f_c assumes reasonably high values ($\gtrsim 8\%$) despite of the high losses of the skin.

The major benefit of the proposed system stems from the potential for controlling the relevant radiation properties by means of the piezoelectric micro-needle probe. Fig. 4 clearly illustrates some key effects of the curvature radius in this regard; shown is the near-field pattern evaluated along the E -plane of the structure at the interface ($z = -h_s$) of the unaltered skin with nominal complex permittivity. As it appears from Fig. 4, reducing r_d is an effective means to achieve a quasi-uniform distribution of the field intensity over a wider region around the broadside direction. That is in turn important to enhance the illumination and, thereby, the localization of possible malignant tissues. To this end, the selection of the curvature radius value $r_d = 1.25$ mm results in a good performance both in terms of near-field radiation properties and efficiency (see Fig. 3), while keeping

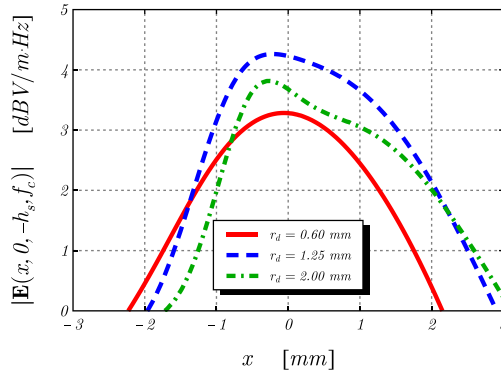


Figure 4. Near-field pattern along the E -plane ($y = 0$) of the sensor at the interface ($z = -h_s = -2.6$ mm) of the unaltered skin with nominal complex permittivity for different curvature radii of the probe. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_g = 3.4$ mm, $t_g = 0.25$ mm. Operating frequency: $f_c = 45$ GHz.

spurious reflection level at the input terminals of the device small over a reasonably wide frequency band around f_0 .

In order to further analyze the characteristics of the electromagnetic field transmitted in the skin, the footprint of the proposed device at the interface ($z = -h_s = -2.6$ mm) of the unaltered medium with nominal material parameters has been evaluated at the central working frequency f_c . The footprint, representing the effective area illuminated by the sensor on the skin surface or subsurface, provides important information in the radio-frequency monitoring of cancer-related anomalies. As a matter of fact, a small or defocused footprint makes the detection of abnormal tissues difficult because of the reduced strength of the target back-scattering response. So, an optimal footprint is of fundamental importance to enhance the assessment and diagnosis of possible health vulnerabilities. As commonly done in the realm of ground penetrating radar (GPR) applications [8–10], the footprint can be determined as the normalized peak-value distribution of the electric field tangential along the observation plane $z = -d \geq 0$, namely:

$$FP(x, y | d, f) = \frac{E_\tau(x, y, -d, f)}{\max_{(x, y) \in \mathbb{R}^2} E_\tau(x, y, -d, f)}. \quad (6)$$

Fig. 5 demonstrates that the radius ρ_{FP} of the -3 dB subsurface footprint featured by the proposed sensor in the near-field region is closely related to the dimension of the device, namely the size r_g of the ground plane acting as a reflector. Furthermore, it has been

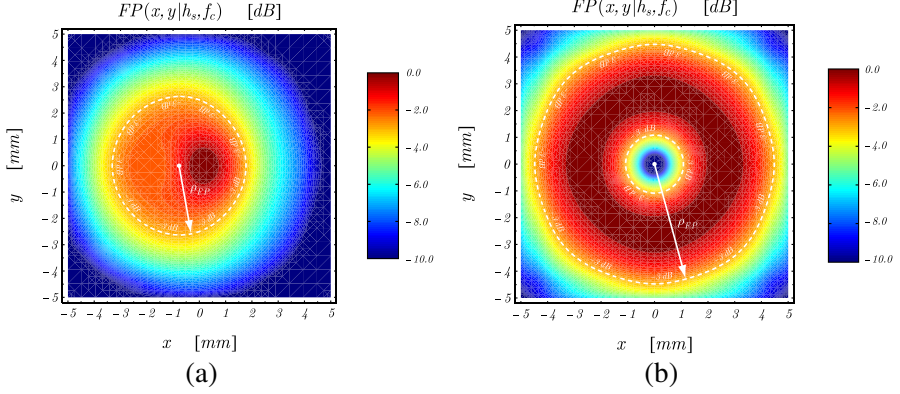


Figure 5. Surface footprint featured by the sensor with curvature radius (a) $r_d = 1.25$ mm and (b) $r_d \rightarrow +\infty$ at the interface ($z = -h_s = -2.6$ mm) of the unaltered skin with nominal complex permittivity. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_g = 3.4$ mm, $t_g = 0.25$ mm. Operating frequency: $f_c = 45$ GHz.

numerically found that, for significant depths of observation in the skin, ρ_{FP} tends to reduce as r_g becomes larger. Although the computed maps are not shown here for the sake of brevity, this property can be readily inferred by considering the Fourier-transform relationship holding between a given aperture current distribution and the relevant far-field pattern [11]. So, one can conclude that the size of the footprint can be adjusted by varying the effective aperture of the structure. This concept forms the basis for developing future-generation class of sensors with electronically tunable characteristics. As pointed out in the time domain, the radiated energy tends to be focused in an angular sector centered on the broadside direction where the curvature radius of the micro-needle probe is properly selected (see Fig. 5(a)). On the contrary, when, in the initial stage of the monitoring procedure, the needle is in vertical position, the sensor footprint assumes, as expected from linear antenna theory, a donut-like shape with a deep radiation null at the boresight (see Fig. 5(b)), potentially resulting in a masking of the target and, hence, an inaccurate diagnosis.

A key role in the design of the considered sensing devices is played by the radius r_g of the metal shield. In order to provide the reader with essential information in this respect, a comprehensive investigation into the structure performance in terms of impedance matching and radiation properties has been carried out. The parametric study of the frequency-domain behavior of the input reflection coefficient has

shown that the ground plane size has a strong impact on the operating bandwidth BW at 10 dB return-loss level (see Fig. 6), the maximum $BW_{\max} \simeq 8$ GHz being obtained for $r_g \simeq 3.4$ mm. On the other hand, as it appears from Fig. 6, the impedance matching of the sensor to the feeding line is severely jeopardized wherein a radius $r_g \lesssim 2.515$ mm is selected. Fig. 6 also demonstrates the important conclusion that the dimension of the metal shield has no significant influence on the fundamental resonant frequency f_0 of the sensor. The total efficiency of the structure has been also computed at the resonance in order to examine the relevant radiation characteristics. As it appears from Fig. 7, e_a tends to increase as the radius of the ground plane becomes larger. However, it is to be stressed out that the level of power deployed in the host medium does not necessarily increase and, conversely, a substantial spurious emission may occur in the air region as r_g becomes smaller. To clarify this point, a dedicated analysis has been carried out by investigating the sensor behavior in terms of near-field front-to-back radiation ratio, defined as follows:

$$FBR(d, f) = 20 \log \frac{|\mathbf{E}(0, 0, -d, f)|}{|\mathbf{E}(0, 0, d, f)|}, \quad (7)$$

d denoting the observation distance from the sensor. As it can be inferred, such figure of merit is conveniently introduced to quantify the electromagnetic-field focusing properties of the device. In Fig. 7

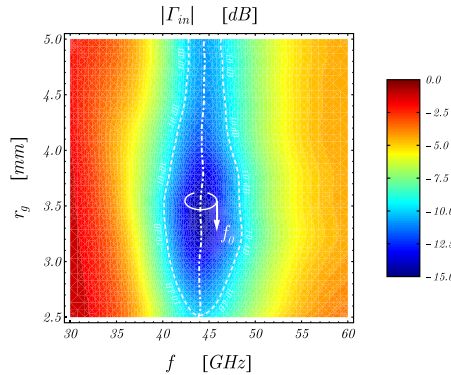


Figure 6. Frequency-domain behavior of the input reflection coefficient featured by the micro-needle sensor as a function of the radius r_g of the metal shield. The fundamental resonant frequency f_0 of the device is also shown. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_d = 1.25$ mm, $t_g = 0.25$ mm. The sensor is assumed to be elevated to a height $h_s = 2.6$ mm above the epidermis.

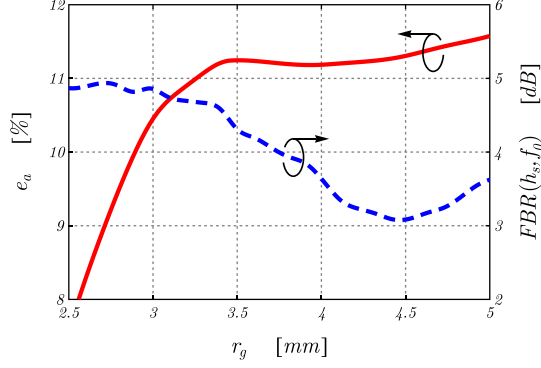


Figure 7. Near-field front-to-back radiation ratio (FBR) along the skin interface ($z = -h_s = -2.6$ mm) and total efficiency e_a at the resonance as functions of the radius r_g of the metal shield. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_d = 1.25$ mm, $t_g = 0.25$ mm.

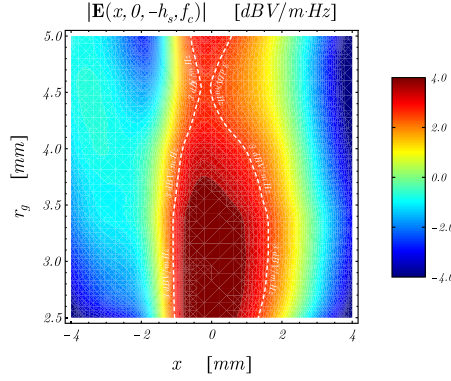


Figure 8. Near-field pattern along the E -plane ($y = 0$) of the sensor at the interface ($d = h_s = -2.6$ mm) of the unaltered skin with nominal complex permittivity as a function of the radius r_g of the metal shield. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_d = 1.25$ mm, $t_g = 0.25$ mm. Operating frequency: $f_c = 45$ GHz.

one can notice that the back-radiation level is actually a non-monotone function of r_g . The computed results clearly reveal that the design value $r_g = 3.4$ mm provides a good trade-off between circuitual characteristics, efficiency, and parasitic energy emission. That in turn is useful to reduce potential electromagnetic interferences ($EMIs$) due to the interaction with nearby electronic equipment.

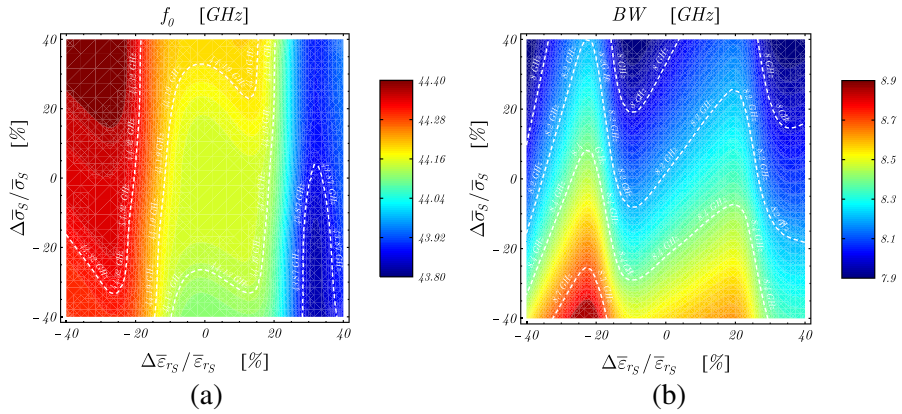


Figure 9. (a) Fundamental resonant frequency f_0 and (b) operating bandwidth BW at 10 dB return-loss level as functions of the variations of the relative permittivity $\Delta\bar{\epsilon}_{rS}/\bar{\epsilon}_{rS}$, and electrical conductivity $\Delta\bar{\sigma}_S/\bar{\sigma}_S$ of the skin due to the presence of anomalous tissues. Structure characteristics: $l_d = 1.6$ mm, $w_d = 0.15$ mm, $t_d = 36$ μ m, $r_d = 1.25$ mm, $r_g = 3.4$ mm, $t_g = 0.25$ mm. The sensor is assumed to be elevated to a height $h_s = 2.6$ mm above the epidermis.

Furthermore, where the suggested ground plane size is adopted for the manufacturing, a superior performance in terms of quasi-uniformity and intensity of the electric field distribution at the boresight is achieved (see Fig. 8), so enhancing the illumination of possible malignant lesions and, hence, the target detectability.

By using the specified optimal geometrical parameters, an extensive parametric study has been finally performed to analyze the effect produced on the sensor response by variations of the relative permittivity $\Delta\bar{\epsilon}_{rS}/\bar{\epsilon}_{rS}$, and electrical conductivity $\Delta\bar{\sigma}_S/\bar{\sigma}_S$ of the skin due to the presence of anomalous tissues with different content of water, salts and proteins (see Fig. 9). The computed diagrams provide useful information in a reflectometry-based detection procedure of the skin cancer [11].

5. CONCLUSION

The electromagnetic characterization of piezoelectric micro-needle antenna sensors for fully non-invasive detection of melanoma has been presented. To this end, an accurate locally conformal *FDTD* procedure has been adopted and, in this way, a physical insight in the processes affecting the circuital characteristics and radiation properties of the

considered class of devices has been gained. An extensive parameter study has been carried out in order to analyze the impact of the curvature radius of the probe on the near-field beam steering property of the structure. The dependence of the sensor response on variations of the relative permittivity and electrical conductivity of the skin due to the presence of anomalous cells has been investigated thoroughly and thus useful discrimination diagrams have been derived. In this way, one can retrieve information about the cancer-related risk level where the considered sensing devices are used in fully non-invasive configuration in proximity of the dermis.

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