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Dielectric Contrast Assessment for Skin Cancer Detection in the Terahertz Band

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***Abstract*—In the field of biomedical imaging, Terahertz waves offer significant advantages, such as non-ionizing radiation, excellent spatial and temporal resolution, and compact instrumentation size. Although the high absorption of water at these frequencies limits the penetration into biological tissues, it also serves as a source of contrast between healthy and pathological states, as the latter typically exhibit increased vascularization and, consequently, higher water content. This study addresses the current landscape in which, despite the clinical application of Terahertz waves being far from routine practice due to unresolved challenges, there is a significant focus on skin diseases. The goal of this work is to identify a measurable and distinguishable contrast between healthy and pathological states, in the frequency band $0.4-1.6$ THz, using dielectric property measures of healthy skin and basal cell carcinoma, along with an analytical model grounded in transmission line theory.**

***Index Terms*—biomedical application, plane waves, propagation, transmission lines, terahertz.**

I. Introduction

Terahertz (THz) waves, spanning from 0.1 to 10 THz, represent a promising area of research in the biomedical field. These waves have the potential to address the increasing clinical demand for imaging and diagnostic devices that are non-invasive, cost-effective, and safe for patients, while also providing real-time, high-resolution capabilities. Unlike X-rays, THz waves have low photon energy, preventing tissue ionization. Their frequencies correspond to wavelengths ranging from tens of micrometers to millimeters, which results in higher image resolution compared to microwave-based imaging technologies.

Nevertheless, the strong absorption by water limits the penetration of THz waves into biological tissues to just a few hundred, or even tens, of microns, depending on both the tissue type and frequency band [1], which confines most diagnostic applications to superficial tissues or fluids. As a result, in vivo measurements are often restricted to reflection-mode configurations, further reducing the scope of possible diagnostics.

While water absorption limits the penetration depth, it also enables precise tissue differentiation based on hydration levels, which is particularly useful in detecting malignancies, as they typically have a higher water content compared to surrounding healthy tissue. Thus, THz technology holds potential for label-free tissue differentiation using water as an endogenous marker.

Based on the previous considerations, it is evident why, over the past two decades, the diagnostic imaging of skin diseases has become a prominent application of THz waves, drawing significant attention from multiple research groups as e.g. in [2], [3]. However, the clinical implementation of THz technology remains in its early stages, with several scientific and technical challenges yet to be addressed.

A relevant issue is the lack of a comprehensive electromagnetic model of the skin that can adequately describe the interaction between THz radiation and skin tissue and that is robust across the various techniques currently employed in this research field [4]. This would not only help evaluate the contrast source among various techniques studied but also enhance the understanding of THz wave interactions with skin tissue.

In this work, we assess the dielectric contrast by showing the differences in the reflection coefficients of an impinging plane wave at the air-skin interface, across specific stages of pathological conditions and for varying angles of incidence. The problem is modeled according to transmission line theory, incorporating measured dielectric properties values for both healthy skin and basal cell carcinoma (BCC), as reported in [5].

II. Dielectric properties

While the magnetic properties of biological tissues are negligible, and their permeability is typically assumed to be equal to that of the vacuum, a precise understanding of their frequency-dependent permittivity is crucial for studying how electromagnetic waves propagate, reflect, and are absorbed within tissues, such as skin, and even among the different layers that comprise it.

A current challenge is the limited availability of dielectric properties measures of the skin and its associated pathologies. In addition to the lack of a standardized technique and protocol for measurements, the compilation of a robust database on the complex permittivity of the skin is further complicated by factors such as anatomical differences between individuals or across different body regions, age, and other factors that can affect the skin hydration levels. For example, sweating induced by mental stress alone can alter the skin's dielectric response [6], highlighting the complexity of univocally characterizing human skin from a dielectric perspective.

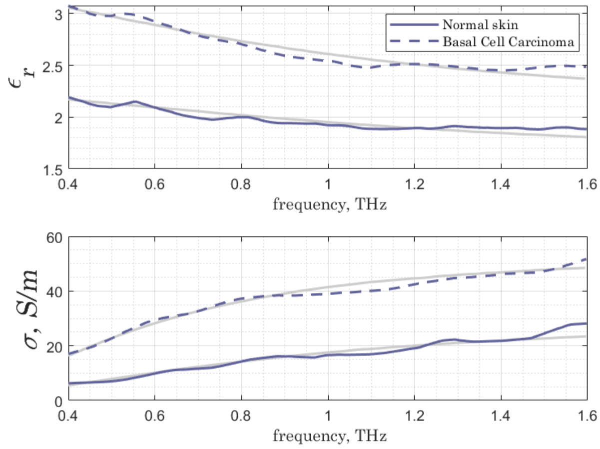

Fig. 1. Measured dielectric properties of normal skin (solid line) and basal cell carcinoma (dashed line): [5] relative permittivity and conductivity. Grey curves represent the corresponding Double Debye fitting curves.

This complexity thus extends to the model of the skin to be used for studying the THz-skin interaction problem and fitting any measurement data.

Bennett et al. in [7] exploited a binary composite model to estimate the hydration levels of skin layers, based on the dielectric properties of water, dehydrated skin, and their respective volume fractions assumed varying linearly in depth. However, the validity of this model can be compromised by factors that break its assumption of skin layers containing homogeneously distributed sub-wavelength-sized particles, such as surface roughness or the anisotropy of the stratum corneum [4].

In [8] data fitted using the Double Debye model based on ex-vivo measurements are provided, whose validity is questionable due to the differences in hydration levels between ex-vivo samples and in-vivo conditions.

For the purposes of this study, we use the complex permittivity values of cultured skin and basal cell carcinoma measured by Nourinovin et al. [5] through THz time-domain spectroscopy, as reported in Fig. 1. Such data, in principle, is expected to be more consistent with in-vivo conditions. Moreover, the availability of reproducible cultured samples, produced in a controlled manner, enables future extensive experimental campaigns that can support both the development of imaging equipment and standardized protocols, as well as justify future clinical trials.

III. Stratified Model

The problem of a plane wave impinging on diseased skin can be approximately viewed as a stratified dielectric structure, meaning a medium that is homogeneous in the plane transverse to a longitudinal z-axis, with relative permittivity defined by piecewise constant functions of z, as shown in Fig. 2.

In this approximation, the structure can be treated as a waveguide with an infinite cross-section, allowing its behavior to be analytically studied using transmission line theory.

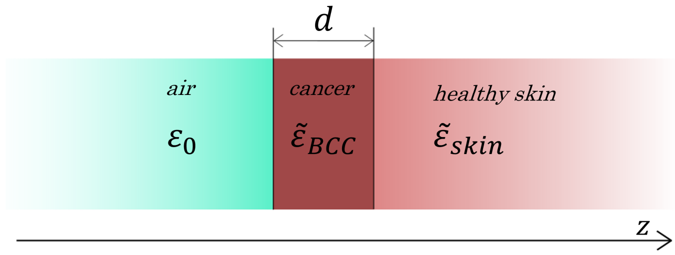

Fig. 2. Air and diseased skin as a multilayered dielectric medium.

Based on this, we implemented a stratified model to evaluate the reflection coefficients S_{11} at the air-tissue interface as referenced in (1):

$$S_{11} = \frac{Z_{tissue} - Z_0}{Z_{tissue} + Z_0} \tag{1}$$

where Z_0 is the characteristic impedance of free space and Z_{tissue} is the impedance of the equivalent transmission line segment modeling the biological tissue. The latter was calculated via transmission line theory using the measured permittivity and conductivity shown in Sect. II, accounting for the wave's angle of incidence, its resulting polarization, and the presence of any internal dielectric layers such as the BCC and the healthy skin.

The analysis thus considers the variation of both the angle of incidence and the thickness, d, of the BCC layer in terms of fractions of the wavelength to simulate different pathological states.

In Fig. 3, the computed reflection coefficient magnitudes are shown for 0.5 THz and 1.5 THz, frequencies near the limits of the available dielectric property data. These results reveal a maximum contrast of approximately 5 dB between the healthy case and the case where the BCC layer corresponds to a thickness of one-quarter wavelength under normal incidence.

Given that the wavelengths within the BCC at the analyzed frequencies are approximately $345\,\mu m$ and $126\,\mu m$, and considering how their fractions compare to the epidermal thickness in areas such as the neck and face —where BCC commonly occurs and ranges from just a few tens of micrometers to around $200\,\mu m$ [9]— these results are encouraging. They suggest that in an experimental setup capable of directly measuring reflection coefficients, e.g. relying on a vector network analyzer (VNA), it may be feasible to discriminate even small BCCs, which can measure just a few tens of micrometers in size.

IV. Conclusion and Perspectives

In this preliminary study, we have highlighted that incorporating the measured dielectric properties of skin and basal cell carcinoma between 0.4 and 1.6 THz into an analytical model of skin as a stratified dielectric structure leads to a clear contrast in the reflection coefficients at the air-tissue interface between healthy and pathological tissues.

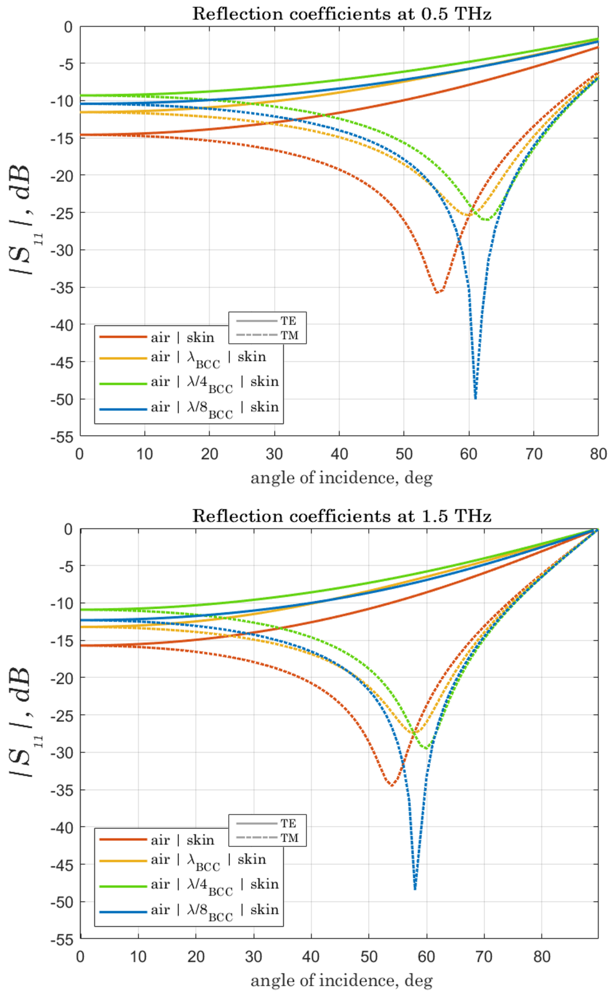

Fig. 3. Magnitude of computed reflection coefficients at the air-skin interface for varying BCC thicknesses and angles of incidence.

This result encourages further exploration beyond the plane wave scenario, adding complexity through numerical and experimental models. While it remains necessary to validate the simplified nature of the used model—which assumes healthy skin as a more homogeneous entity due to the lack of direct measurements of the dielectric properties of the stratum corneum and epidermis—these findings underscore the potential of an external measurement system capable of directly measuring local reflection coefficients. Specifically, a VNA operating in the millimeter-wave band and equipped with a probe could effectively discriminate local contrasts between adjacent areas of healthy and diseased tissue with differing water content.

Our final goal is to design a device that can extract information from the measured reflection parameters, particularly sensitive to the sought-after contrast, and generate a bio-image.

Acknowledgments

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References

[1] O. Smolyanskaya *et al.*, “Terahertz biophotonics as a tool for studies of dielectric and spectral properties of biological tissues and liquids,” *Progress in Quantum Electronics*, vol. 62, pp. 1–77, 2018.

[2] K. I. Zaytsev *et al.*, “The progress and perspectives of terahertz technology for diagnosis of neoplasms: a review,” *Journal of Optics*, vol. 22, no. 1, 013001, 2019.

[3] A. I. Nikitkina *et al.*, “Terahertz radiation and the skin: a review,” *Journal of Biomedical Optics*, vol. 26, no. 4, 043005, 2021.

[4] J. Wang, H. Lindley-Hatcher, X. Chen, and E. Pickwell-MacPherson, “Thz sensing of human skin: a review of skin modeling approaches,” *Sensors*, vol. 21, no. 11, p. 3624, 2021.

[5] S. Nourinovin, M. M. Rahman, S. J. Park, H. Hamid, M. P. Philpott, and A. Alomainy, “Terahertz dielectric characterization of three-dimensional organotypic treated basal cell carcinoma and corresponding double debye model,” *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 3, pp. 246–253, 2023.

[6] K. A. Baksheeva *et al.*, “The sub-thz emission of the human body under physiological stress,” *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 4, pp. 381–388, 2021.

[7] D. B. Bennett, W. Li, Z. D. Taylor, W. S. Grundfest, and E. R. Brown, “Stratified media model for terahertz reflectometry of the skin,” *IEEE Sensors Journal*, vol. 11, no. 5, pp. 1253–1262, 2010.

[8] V. P. Wallace, A. J. Fitzgerald, E. Pickwell, R. J. Pye, P. F. Taday, N. Flanagan, and T. Ha, “Terahertz pulsed spectroscopy of human basal cell carcinoma,” *Applied spectroscopy*, vol. 60, no. 10, pp. 1127–1133, 2006.

[9] D. Lintzeri, N. Karimian, U. Blume-Peytavi, and J. Kottner, “Epidermal thickness in healthy humans: a systematic review and meta-analysis,” *Journal of the European Academy of Dermatology and Venereology*, vol. 36, no. 8, pp. 1191–1200, 2022.