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Design and characterisation of a broadband PCB coaxial sensor for non-invasive skin cancer analysis

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Abstract— Biological tissues exhibit varying dielectric properties depending on their composition and physiological state. Broadband dielectric spectroscopy is a valuable non-destructive diagnostic tool for biomedical applications such as glucose monitoring, hydration level detection, and cancer tissue analysis. In the case of melanoma, researches have shown that skin permittivity level varies at the lesion site. Detecting tumors therefore requires imaging the complex permittivity of suspicious areas with a spatial resolution compatible with the small dimensions of these surfaces. However, developing a sensitive sensor capable of detecting small permittivity variations is challenging due to the variability of skin properties for different people and physiological states (e.g. temperature, humidity). This paper presents the design of an innovative detection sensor that can accurately detect variations in cutaneous permittivity between 1 and 6 GHz to identify different types of tumors in their early stage with a good agreement between simulated and measured results.

Keywords— dielectric properties; biological tissues; non-destructive diagnostic; cancer tissue analysis; melanoma; cutaneous permittivity; early tumor detection.

I. INTRODUCTION

The dielectric properties of biological tissues vary according to their composition and the physiological state of the individual. In the case of cutaneous melanoma, a variation in the skin permittivity is found at the location of the lesion related to the modification of the water content of cancerous cells [1]. A sensor that can image the complex permittivity of a suspicious area with a spatial resolution compatible with the small size of interest (an average diameter of 6 mm) is a major challenge [2]. One difficulty in the development of this type of sensor is the sensitivity required to detect the small variations in permittivity in order to correctly differentiate the type and evolution degree of the lesion.

There are several types of sensors that can perform such characterization or detection. The most common probe is the open-ended coaxial probe. It has many advantages, such as its ease of design and implementation and a very good resolution [3]. In the context of melanoma detection, its implementation on a SIW (Substrate Integrated Waveguide) technology allows to consider its integration on a substrate, with millimetre-scale dimensions, opening the way to other perspectives of improvement [4][5].

This paper presents the first results of an innovative RF sensor, able to detect small variations of skin permittivity, in order to consider the detection of different tumour types at the very beginning of their development.

II. PROPOSED SENSOR AND SIMULATION RESULTS

A. Design and fabrication of the sensor

This paper is dedicated to the design, realization and experimental characterization of a broadband microwave probe to determine the dielectric properties of a biological tissue by a direct measurement (in vivo). The probe is composed of two parts: a miniaturized measurement area similar to an open-ended probe and a strip-line for the signal propagation from the connector to the sensitive part. The sensitive part (Figure 1.a) is made of a Roger 3003 substrate holed by a central via acting as a coaxial line central core and metallized vias arranged in a circle to mimic a metallic wall. The strip line (Figure 1. b) uses two Arlon 25N substrates placed one over the other and bonded together (Figure 1). A teflon box is used to limit liquid infiltration during measurement and to apply a pressure reducing the air gap between the two Arlon 25N substrates (Figure 2).

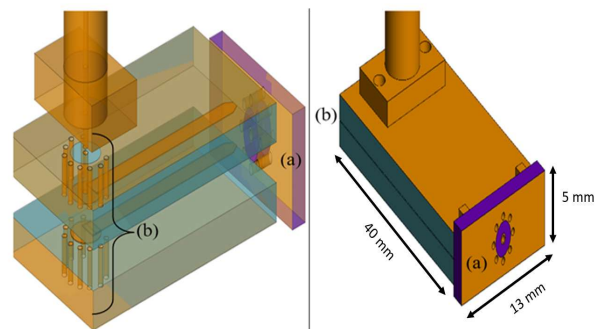


Figure 1: 3D view of the different elements of the proposed probe (a) sensitive part (b) strip-line.

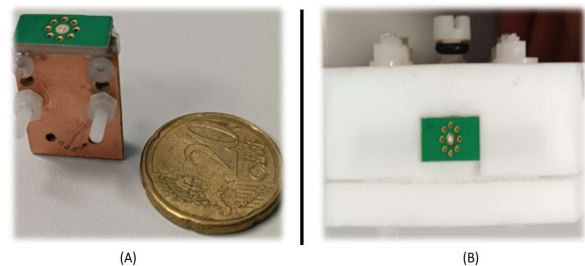


Figure 2: The first prototype unboxed view (A) and boxed view (B)

Material	ϵ_s	ϵ_∞	ϵ_h	τ_1 (ps)	τ_2 (ps)
Water	78.8	3.3	/	7.37	/
Ethanol	25.2	4.68	/	143.18	/
DMSO	45.19	5.984	/	10.07	/
Skin [6]	33.890	4.489	4.460	3.930	0.488
Tumor [6]	58.371	4.343	4.622	4.983	0.488

Table 1: Debye parameters of the models used in simulation

B. Simulation results and extraction method

The 3D simulations are performed using Altair FEKO software where the reflection coefficient (S_{11}) is extracted from 1 to 6 GHz (Figure 3) depending on the nature of the probed material. The material under test is modeled as a box ($20 \times 20 \times 1.5 \text{ mm}^3$) placed in contact to the sensor sensitive part. Its permittivity test is modeled using the Debye relaxation model associated to the parameters indicated in Table 1.

In order to extract the complex permittivity (in real and imaginary parts) from the simulated parameter S_{11} , the following relationship is used [12]:

$$\epsilon_r^* = \frac{C_1 S_{11} - C_2}{C_3 + S_{11}} \quad (1)$$

Where C_1 , C_2 , C_3 are probe-specific constants that are determined, during the calibration step, from the simulated S_{11} obtained for reference materials such as de-ionized water, ethanol, or air. Thus the complex permittivity of the probed material can be deduced using the simulated or measured S_{11} .

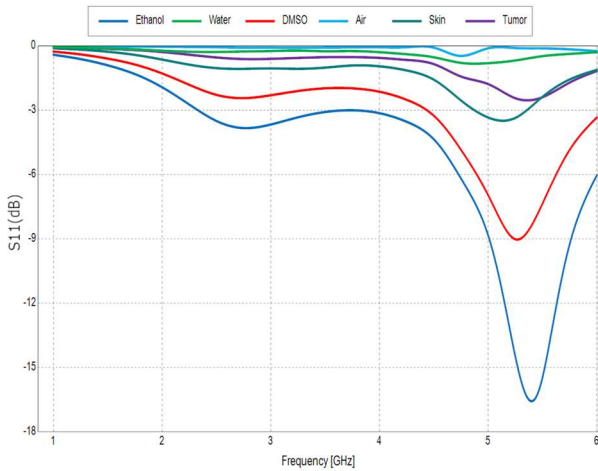


Figure 3: Simulated reflection coefficient (amplitude in dB) for different materials

C. Extraction results

At first, the complex permittivity of the skin/tumor model, extracted from the simulated reflection coefficient using the method explained in (II.B), is compared with the values used in simulation and corresponding to the Debye relaxation model derived from experiments and proposed in [6] (Table 1); indeed, several skin and tumor models are presented in this paper and the ones corresponding to samples S5 and S6 have been chosen as the skin and tumor models. It can be seen that the difference obtained (Figure 4) is quite small, around 1% for the skin and tumor complex permittivity compared to the associated Debye relaxation model. Different scenarios

were simulated, such as the measurement on a multilayer medium (skin, fat, muscle) or the detection of the position of the tumor ($3 \times 3 \text{ mm}^2$) in a wide biological multilayered medium ($6 \times 6 \text{ mm}^2$) (Figure 5). Those scenarios showed the ability of our RF sensor to correctly detect the permittivity variation even if the surface of the tumor model ($3 \times 3 \text{ mm}^2$) is lower than the average melanoma surface ($5 \times 5 \text{ mm}^2$)

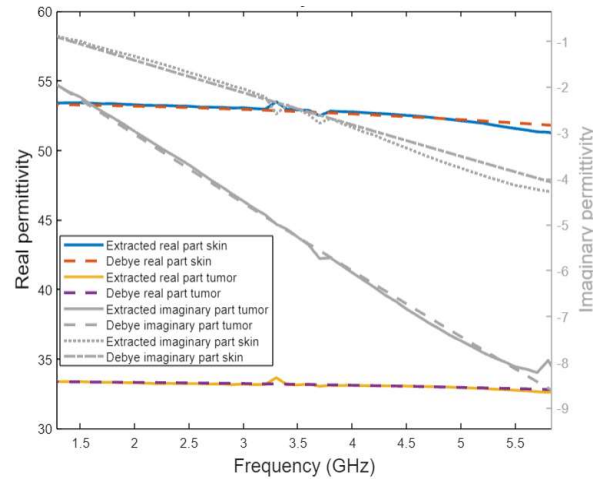


Figure 4: Extracted skin and tumor model complex permittivity from the simulation results

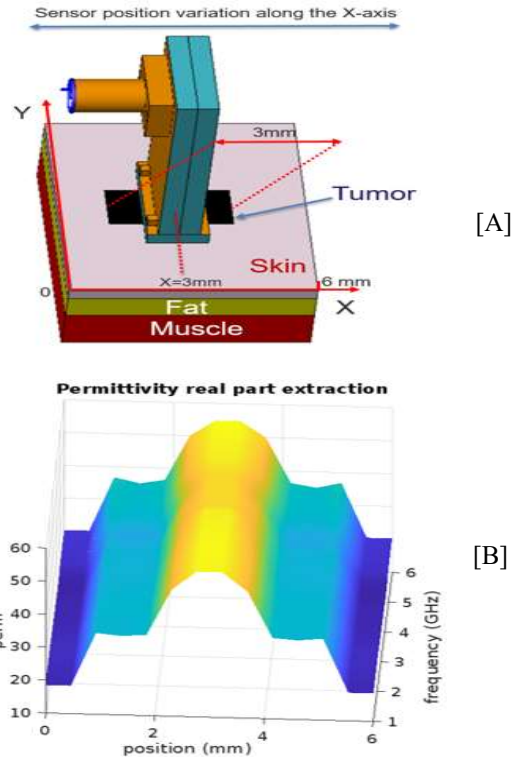


Figure 5: Simulation results for the probe on a multilayered biological tissue model, 3D model [A] extracted real permittivity [B]

III. VALIDATION AND MEASUREMENT RESULTS

A. Skin phantom tissues

In order to properly characterize and experimentally validate the sensor, it is necessary to perform tests close to *in vivo* measurements. The most widely used method is that of phantom tissues, which have electromagnetic properties close to those of human biological tissues [7]. Phantom tissues have been developed to reproduce the dielectric properties of healthy skin and melanoma tumor using non-toxic and biodegradable materials such as gelatin, agar-agar, water and polyethylene microbeads according to the process described in [7]. For the healthy skin phantom, the same approach as in [7] was followed to mimick the skin properties presented in [8]. Concerning the melanoma tumor phantom, we have tried to obtain the dielectric properties of the sample S6 of [6] but using different materials; indeed the component proportions were adjusted thanks to Bruggeman mixing rule used in [7] in order to reach the aimed real permittivity without controlling the relative permittivity imaginary part.

B. Measurement results :

Measurements of the reflection coefficient (S_{11}) from 1 to 6 GHz, on reference liquids (Water, Ethanol, Dimethyl sulfoxide) and phantom tissues (skin/tumor) were carried out using our sensor (Figure 6) in order to compare the measurements and evaluate the probe discrimination capability of the media. Since the tumor phantom was synthesized using PE powder and water instead of the materials used in [6], only the real part of the permittivity is expected to be close to the aimed one, so that the imaginary part are not presented. The real permittivities of the skin and tumor phantom tissues are extracted and compared to the expected values (Figure 7). The small deviations for the extracted permittivity real parts are due to a manufacturing issue (air gap due to soldering) and imprecision on the extraction method and a small resonance caused by the Teflon box. To validate the probe operation several liquids with known dielectric properties were also tested and their extracted permittivities compared to their theoretical values at 25°C showing the probe and extraction method reliability.

IV. CONCLUSION

These first obtained results make it possible to evaluate the capacity of the probe to analyze tissues over a wide frequency band, from 1 to 6 GHz, while maintaining small dimensions (current detection area of 2.8 mm diameter), with good capability to differentiate a normal skin from a tumor. Thanks to a calibration step, it is then possible to extract the dielectric properties of the synthesized phantom tissue with a good accuracy compared to the dielectric probes available in the industry [9] and seen in the litterature [10] [11] (Table 2). Our next goal will be to find a way to simplify the calibration process without reducing the probe performance and validate the measurement made with the phantom tissues with *in vivo* measurement.

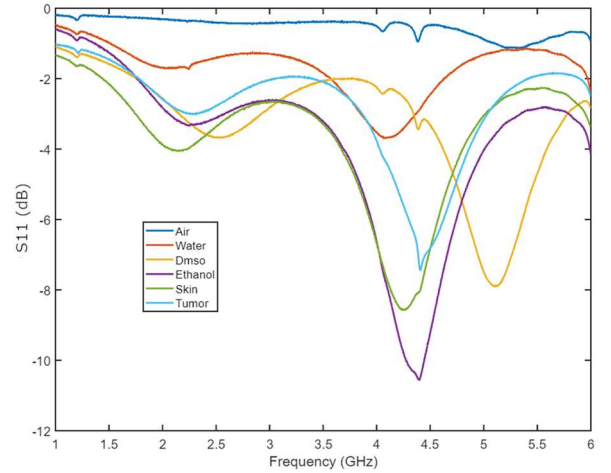


Figure 6: Measured reflection coefficient (Amplitude in dB) for different materials

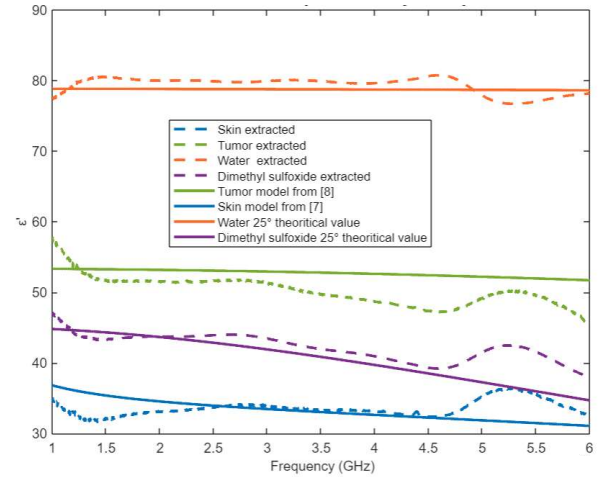


Figure 7: Permittivity real part extracted from measurements for phantom tissues and liquids at 25°C

Reference	Probe size	Frequency	Technology	ϵ' deviation
[4],[5]	/	0.1 MHz to 10 GHz	Planar	Similar to [9]
[9]	46.7x19 mm ²	200 MHz to 20 GHz	Coaxial waveguide	5 %
[10]	150x9.5 mm ²	0.5 MHz to 18 GHz	Coaxial waveguide	0.2% to 2.4 %
[11]	1.8x22 mm ²	10 MHz to 5 GHz	Coaxial waveguide	8% at 1 Ghz
This work	40x13 mm ²	1 GHz to 6 GHz	Planar	1% (simulated) 3% (measured)

Table 2: Comparison to the state of the art

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