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Citation for the original published paper (version of record):
Jayasankar, D., Hernandez-Serrano, A., A. Hand, R. et al (2022). Investigation of Hydrogel Skin Phantoms Using Terahertz Time-domain Spectroscopy. 2022 52nd European Microwave Conference, EuMC 2022: 401-403. http://dx.doi.org/10.23919/EuMC54642.2022.9924308

Investigation of Hydrogel Skin Phantoms Using Terahertz Time-domain Spectroscopy

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***Abstract*— Human skin phantoms are essential to enable fast, label-free, and reliable testing of pharmaceutical and cosmetic products. We report the characterisation of polyvinyl alcohol-based hydrogel phantoms along with *in-vivo* skin measurements of three volunteers from 0.2 to 1 THz. The results indicate that frequency-dependent properties of hydrogel phantoms are similar to human skin and show promising prospects of being utilised as a skin equivalent.**

***Keywords*— Hydrogel, in-vivo, phantom, refractive index, stratum corneum, terahertz, time-domain spectroscopy**

I. INTRODUCTION

Terahertz (THz) region in the electromagnetic spectrum is sandwiched between the microwave and infrared bands. Due to the unprecedented technological advancements over the few decades, THz technology is now widely used in numerous applications in bio-sensing, imaging, communication, and remote sensing [1]. The non-ionising properties due to the low photon energy and strong absorption of water by THz waves have attributed to the development of THz spectroscopic and imaging techniques [2]. Terahertz time-domain spectroscopy (THz-TDS) is a valuable tool for material characterisation due to its broadband frequency coverage [3]. Even though THz-TDS technique has been widely employed as transmission-based systems, reflection geometry as shown in Fig. 1 is ideal for *in-vivo* skin studies [4].

Utilising terahertz waves to measure skin properties has greatly interested many researchers. Due to the strong water absorption, THz waves can only penetrate a few hundreds of μm of superficial tissues revealing many features, including the water content variation in different layers of the skin. In addition to its sensitivity to water content, it also has the potential to distinguish free and bound water states in the tissue, which makes it an excellent diagnostic tool for various skin diseases and also for cancer detection. However, human skin is susceptible to homeostasis and environmental factors, affecting measurement repeatability.

To overcome this problem and enable fast and reliable testing methods of pharmaceutical and cosmetic products, human skin phantoms that mimic the skin properties are essential. Hydrogels are widely used in many biomedical applications, such as contact lenses and drug delivery patches. It is a viscoelastic material with a soft consistency and high porosity. It is similar to mammalian tissues and thus making them a suitable candidate for skin phantoms. Polyvinyl Alcohol (PVA) based hydrogels are super-absorbent cross-linked polymer networks that constitute more than 90% of water. In 2015, Hurtado *et. al* has demonstrated similarities in terms of chemical and mechanical properties of synthesised PVA polymers and human skin data available from literature [5]. In this paper, we have presented the comparison of optical properties of the hydrogel phantoms with *in-vivo* human skin measurements using the THz-TDS technique.

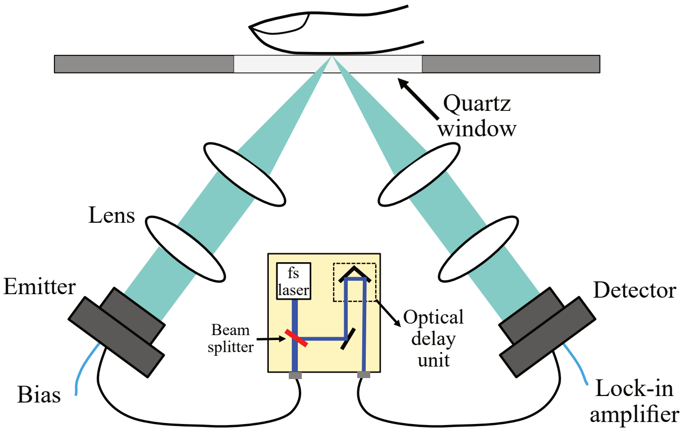


Fig. 1. Schematic of the the terahertz in-vivo time-domain spectroscopy system in reflection geometry based on fiber-coupled photoconductive antennas

This paper is organised as follows: Section II describes the THz-TDS measurement setup and compares reflected THz pulses from different samples, followed by the measurement protocol and a brief description of the refractive index extraction procedure. Section III presents the extracted refractive index and absorption coefficient of the subject's index fingers and different hydrogel samples.

II. METHODOLOGY

Fig.1 shows the schematic of the K15 fibre-coupled THz spectrometer from Menlo Systems GmbH in reflection geometry. It consists of a femtosecond laser source that generates ultra-short optical pulses at a 1560-nm emission wavelength 100-MHz repetition rate. The femtosecond laser pulse is split into two components, using a beam splitter to the emitter and detector. Detailed information on the principle and operation of the TDS system is given here [6], [7].

A series of polymethylpentene (TPX) lenses collimate the THz pulse from the emitter, focus it on the quartz window's top surface, and detect the reflected pulse from the sample. The beam spot of the incident THz signal is $\approx$ 3 mm. The Fourier transform of the detected signal of picosecond length contains broadband THz frequency components typically from 0.1 to 2 THz depending upon the system's dynamic range. By varying the delay line, the THz electric field's amplitude and phase can be recorded as a function of time. Fig. 2 shows the reflected THz pulse as a function of time from the quartz air and sample interface.

The THz pulse is incident on to the top surface of quartz window at 30°. The quartz window aids in pulse alignment and flattens the surface when the volunteer's finger is placed on top of the window. However, this increases the skin's water content due to the accumulation of water in the stratum corneum as the pores are blocked (occlusion effect), and this has a considerable effect on the reflected THz pulse, especially for a longer data acquisition time [8]. The *in-vivo* skin measurements were performed with the informed consent of three volunteers who were later assigned a random code to protect their identity.

When the input THz signal is incident on the quartz window, it results in two reflections from the bottom air-quartz interface and the top quartz-air/sample interface, as shown in Fig.3. To extract the optical properties of the sample, it is essential to subtract the second reflection from the sample and reference measurements [9] by placing another quartz on top of the imaging window as indicated in Fig. 3.

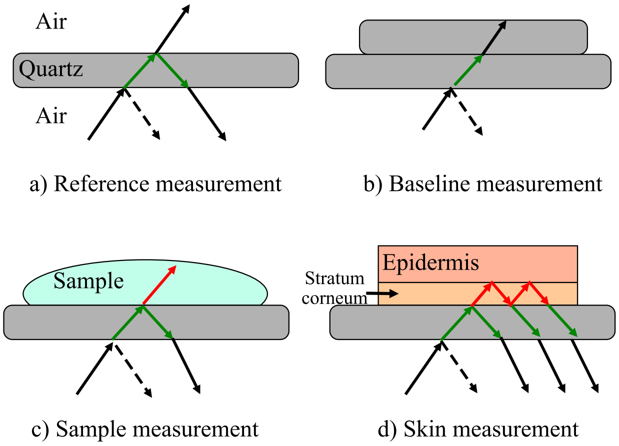


Fig. 3. Illustration of reference, baseline and sample measurements.

The optical properties of the samples and human skin were extracted using Equation 1 where, $E_s(t)$, $E_b(t)$, and $E_r(t)$ are the measured reflected THz signal of the sample, baseline and reference (air) as shown in Fig.3. For validating the extraction algorithm, deionised water was measured and compared with the double-Debye model [10].

$$\text{Impulse function} = \text{iFFT}\left[\text{Filter} * \frac{(E_s(t) - E_b(t))}{(E_r(t) - E_b(t))}\right] \tag{1}$$

III. RESULTS AND DISCUSSIONS

Fig. 4a and b show the extracted refractive index and absorption coefficient versus frequency of the hydrogel

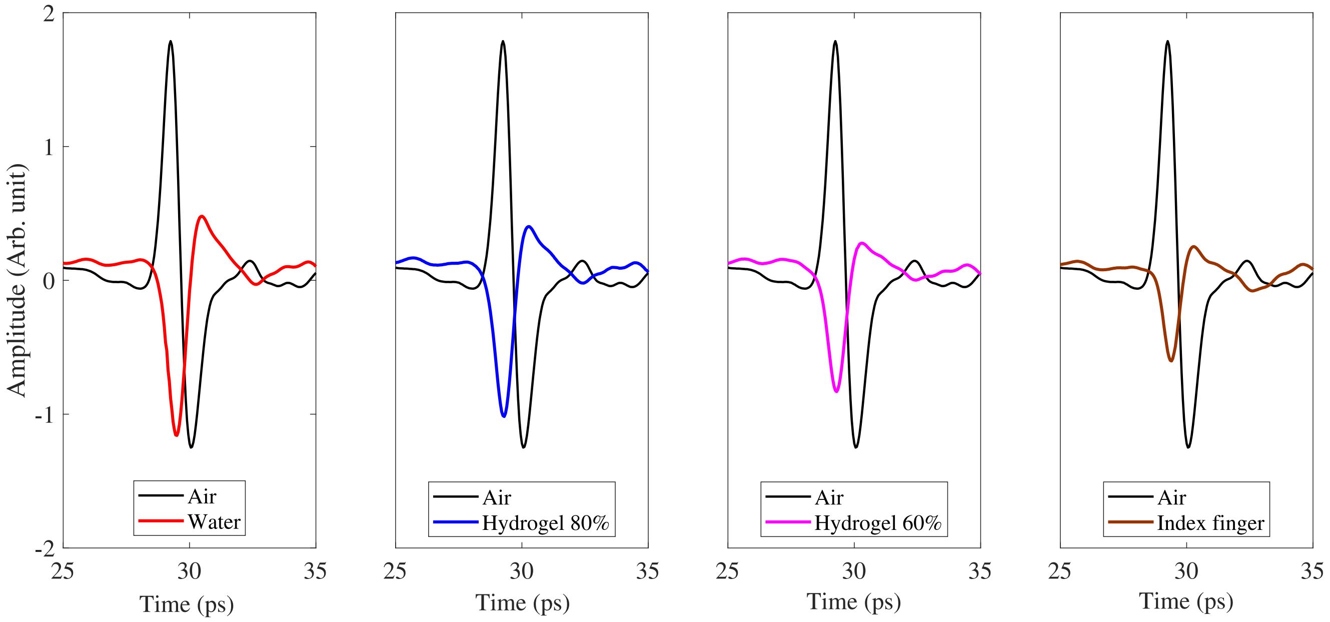
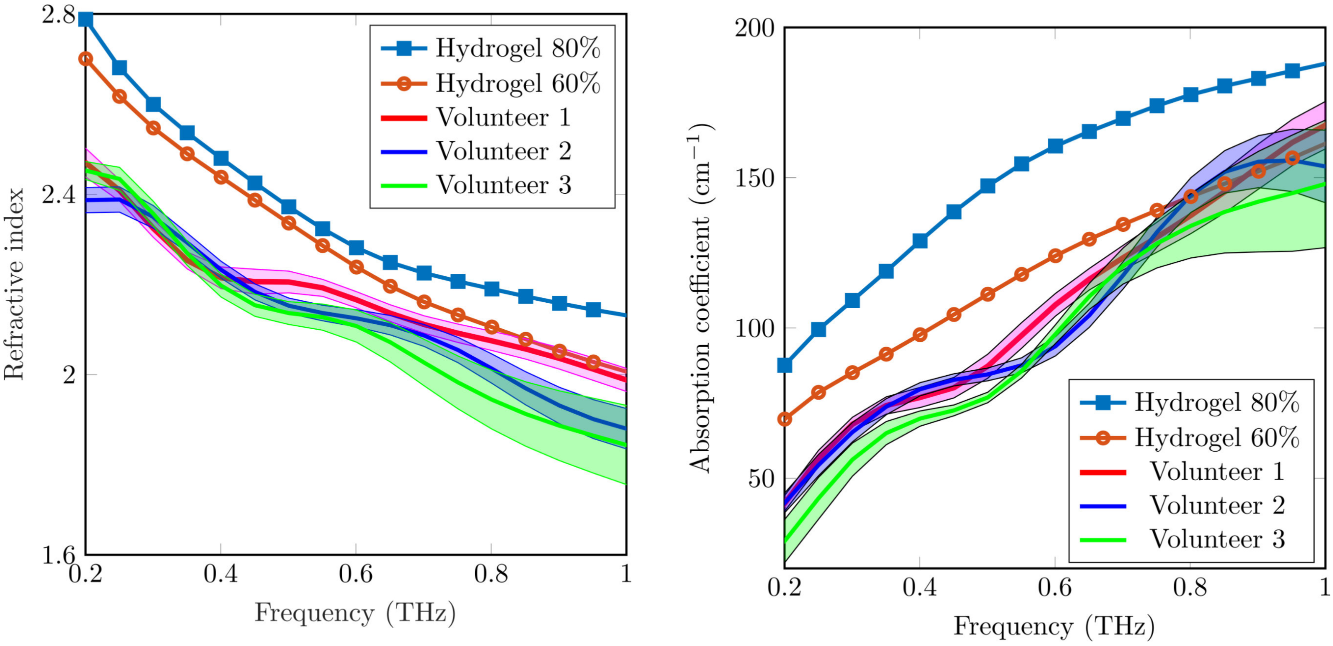


Fig. 2. THz pulses. Picture showing the THz pulses reflected from the quartz-air interface and different samples: distilled water, hydrogel phantom with 80% and 60% water concentration and index finger, respectively.



a)

b)

Fig. 4. Comparison of refractive index and absorption coefficient of hydrogel phantoms of different water concentrations (60% and 80%) along with the *in-vivo* index finger measurements of three volunteers. The lines and shaded area represents the mean and standard deviation with 95% confidence interval of five measurements.

phantoms with different water concentrations compared to in-vivo measurements of human index fingers, respectively. The index finger of each volunteer's dominant hand was measured five times, and the corresponding mean and standard deviation with a 95% confidence interval are shown in Fig. 4. The refractive index of hydrogel phantoms exhibits similar frequency dependence as human skin, and the difference is caused due to the higher water concentration in the samples compared to the skin [11]. The index finger measurements are not identical as each volunteer's skin has a different texture and hydration. In the future, we will carry out an extensive study with more volunteers and understand the correlation between the skin texture and refractive index.

ACKNOWLEDGEMENT

This work was partially funded by the Engineering and Physical Sciences Research Council (EPSRC) project number EP/V047914/1. Miss. Jayasankar's research visit to the University of Warwick was supported by the European Microwave Association's (EuMA) internship award 2021. Her PhD project is supported by the Swedish Foundation for strategic research (SSF) project number FID17-0040.

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