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THz Frequency Quantification of Water Gradients in Drying Paper

Irina Nefedova[1], Qiushuo Sun[2], Anis Moradikouchi[3], Mariangela Baggio[1], Aleksi Tamminen[1], Juha Ala-Laurinaho[1], Emma MacPherson[4], Helena Rodilla[3], Jan Stake[3], Zachary Taylor[1]
[1]Aalto University, MilliLab, Espoo, Finland, [2]University of Birmingham, Birmingham, UK, [3]Chalmers University of Technology, Gothenburg, Sweden, [4]University of Warwick, Coventry, UK

Abstract— **THz-reflection spectroscopy was used to extract time-varying water gradients in drying paper targets mounted on electrically thick dielectric substrates. The data showed a pronounced and prolonged drop below dry reflectivity when the water content that peaks at low weight (~ 10%). A binomial distribution fitted to the acquired data confirms the existence of the time-varying water content gradient and suggests aqueous thin film hydration can be quantified even when the contrast between the film and backing material is low.**

I. INTRODUCTION

QUANTIFICATION of hydration in targets comprised of water diffused in a low-loss, homogenous, dielectric matrix is a promising application for THz spectroscopic imaging. Free-space wavelengths ranging from ~ 0.3 mm to 3 mm (100 GHz – 1 THz) result in an inherent insensitivity to typical surface scattering and geometry that confound systems operating in the UV/VIS/NIR bands. Further, the large THz permittivity of water provides high intrinsic sensitivity to perturbations in target hydration. Potential applications for water gradient quantification include medicine, industrial sensing, art and conservation [1, 2].

One method for characterizing sensitivity is to hydrate a cleanroom paper samples and acquire concomitant measurements of sample weight and THz reflectivity during drying. These data can be acquired using vector network analyzer (VNA) by measuring reflection coefficient (S_{11}) with sample placed on the scale, Fig. 1. In proposed setup, the extender is mounted in a downward facing orientation allowing to set the working distance between the system and the test object. Calibration plane was at the rectangular waveguide, just before the antenna. Distance between the antenna and the sample was around 6 mm. Spot size of the radiated beam was measured to be 2.5 and 2.5 mm, in *XY* plane, respectively. The hydrated paper required to be backed with a rigid material to maintain the planar geometry while drying. The combination of the backing material and the time varying hydrated paper create a stratified media with complex reflectivity spectra depending on their material parameters i.e. thickness and refractive index [3, 4]. For example, when the target backing is a low-loss dielectric, there exists a significant period where the reflectivity of the drying sample drops well below the dry reflectivity value. When modeling the drying paper sample as a volumetrically homogeneous, effective medium produces poor fits to the observed data, in particular, the dip below dry reflectivity.

Fig. 1 Experimental setup: millimeter-wave module and sample placed on the scale.

In this work, a binomial, water distribution model [5] was applied to the reflectivity data of aqueous towel targets lying on polypropylene (PP) substrates in the WR-2.2 (325-500 GHz) band. Time varying gradients were analyzed and compared to hydrodynamic theory. Water diffusivity was used to model water content profile in the drying sample and estimate the associated THz permittivity gradient and reflectivity. Water diffusivity can be described with a diffusion Equation (1), formulated in [5]:

$$D(t)\frac{\partial^2 W(z,t)}{\partial z^2} - u(t)\frac{\partial W(z,t)}{\partial z} = \frac{\partial W(z,t)}{\partial t}, \qquad (1)$$

where $W(z,t)$ is the water content as a function of depth z and time t, $u(t)$ is the water convection velocity.

II. RESULTS

Fig. 2 shows acquired reflectivity $|S_{11}|$ in the WR-2.2 band, as a function of time. The polypropylene towel was soaked in 225 mg of tap water and measurements were taken every 15 seconds for 2 hours; 1 THz reflectivity and weight measurement pair per time point. The left-vertical-axis of the Fig. 2 intercept values indicate the starting "wet" reflectivity while the steady state values spanning the ~ 120 min – 140 min range indicate the dry reflectivity. The dip below the "wet" reflectivity is > 15 dB from dry and suggests a stratified media composed of depth dependent permittivity with a good wave impedance matching to free space and increasing loss as the wave travels into the bulk (water gradient). The gray shaded area indicates weight in mg corresponding to the right axis scale.

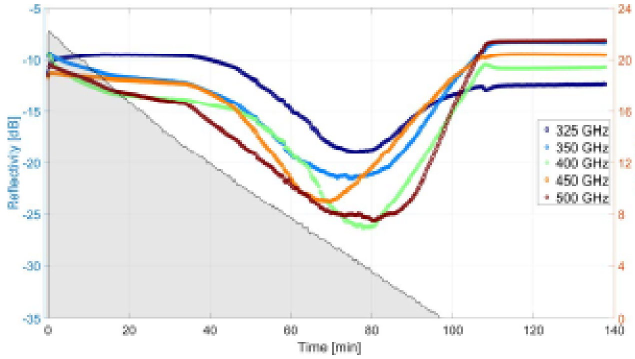

Fig. 2 Reflectivity magnitude in the WR2.2 band of a drying paper target. The gray area indicates the weight as a function of time.

This Observed effect is further elucidated in the Fig. 3, which shows the normalized reflectivity at 620 GHz as a function of normalized weight.

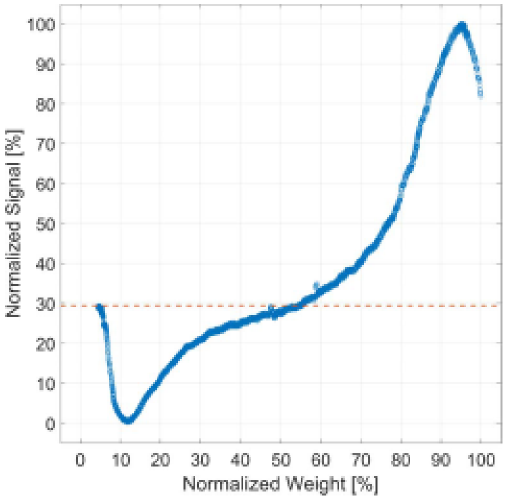

Fig. 3 Reflectivity at 620 GHz (arb scale).

Binomial fits to the 620-GHz data are displayed on Fig. 4 and parameterized by time point. Both PP substrate and dry paper fibers refractive indexes were 1.49-0.001i. The paper was treated as a multilayer structure and three variables were determined: air-paper interface hydration, paper-PP interface hydration and hydrated sample thickness. Initial air-paper interface hydration was higher than the paper-PP interface hydration consistent with dropping water on top of the paper. The gradient transitioned from negative to positive around the 10-minute mark while the paper-PP interface hydration showed little change until the last ~ 15 minutes. Finally, the paper thickness gradually decreased.

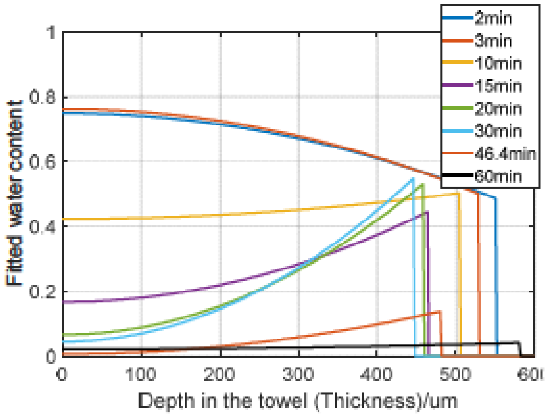

Fig. 4 Binomial fits of the water gradients extracted from the 620 GHz reflectivity data

III. SUMMARY

THz reflection spectroscopy can be successfully used to quantify aqueous thin film hydration, even when the contrast between film and backing material is low. The gradient in free water due to drying significantly contributes to the observed THz reflectivity dynamics.

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