Broadband Characterisation of Interior Materials and Surface Scattering using Terahertz Time-Domain Spectroscopy

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***Abstract*—Indoor wireless communications need to move towards Terahertz (THz) frequencies in order to keep up with society's demand for data transmission, but this change is currently hindered by limited knowledge of material properties and propagation and scattering models at these frequencies. The dielectric properties of common household materials are investigated here with a twofold objective: (1) to extend the library of material properties at THz, and (2) to estimate and disentangle losses in scattering measurements in order to facilitate propagation, scattering and, ultimately, channel models.**

***Index Terms*—terahertz time-domain spectroscopy, retrieval method, scattering.**

I. Introduction

Terahertz (THz) technology [1] has applications in multiple instances of state-of-the-art research, including radar for driverless vehicles [2], and security screening [3]. Additionally, THz waves are being considered as future communication channels in indoor environments to supplement the GHz frequencies currently used; however, this presents a complex set of challenges.

Firstly, the properties of materials are not well documented at THz frequencies. This currently makes it difficult to predict dielectric losses upon reflection from an interface, or how a wave would propagate through a given dielectric. Secondly, scattering from a rough interface causes problems for the propagation of communication channels due to the potential for diffuse scattering components to interfere with the desired wave packets.

In the context of indoor wireless communications, it is challenging to have propagation, scattering, and channel models that overcome the problems stated above without a thorough investigation of material properties at THz frequencies.

II. Experimental Setup

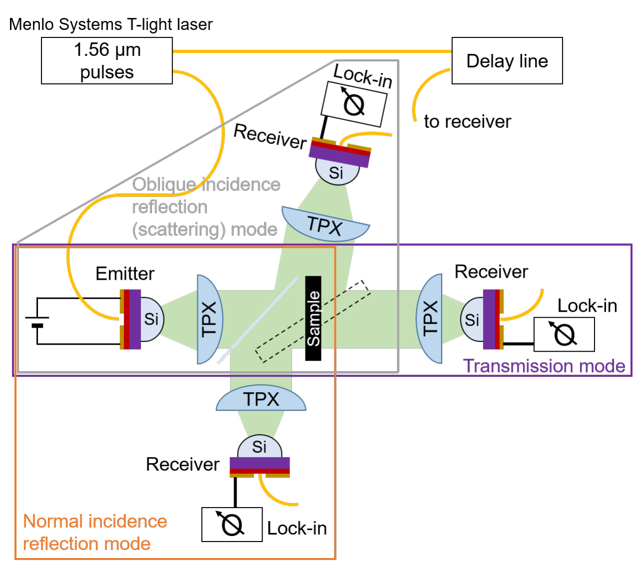

Fig. 1. Schematic diagrams of the THz-TDS system used for the material property retrieval (purple and orange boxes), and scattering measurements (grey box).

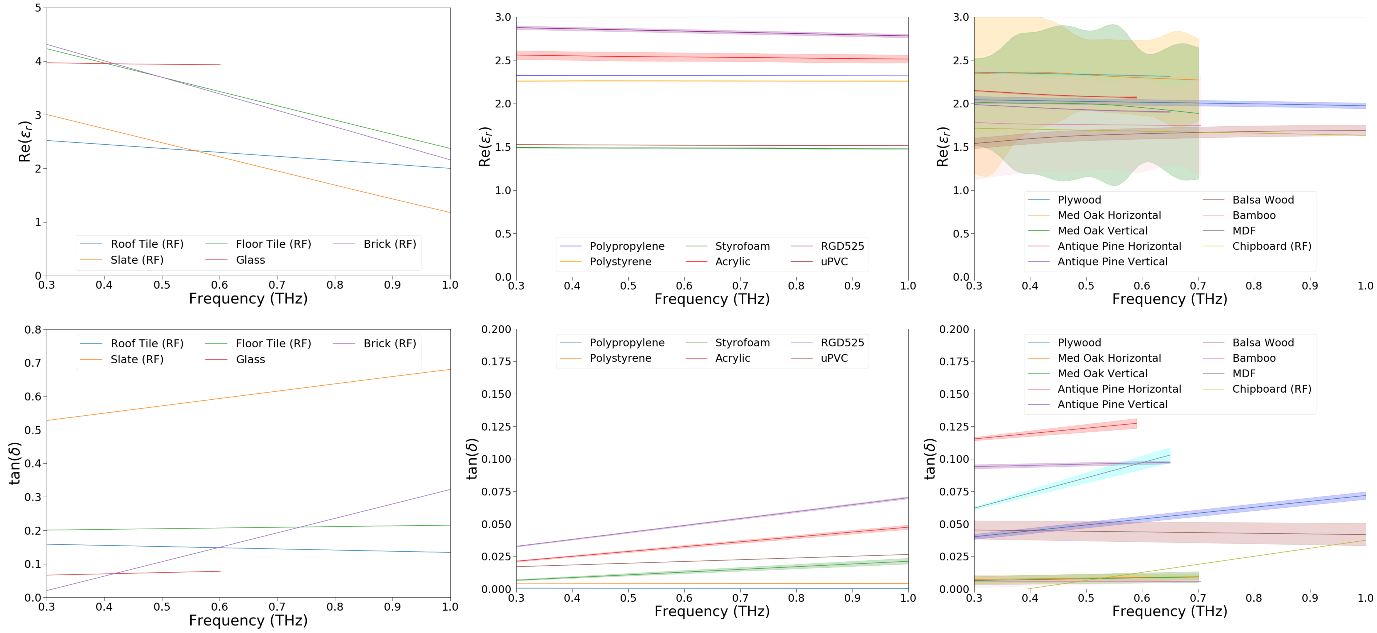

Fig. 2. Relative real part of the electric permittivity and loss tangent as a function of frequency for building materials (left), plastics (centre), and wood (right). The shaded regions indicate the error for each material. Samples whose material properties were retrieved in reflection shows (RF) in the legends.

A Menlo Systems TERA K15 THz time-domain spectrometer (THz-TDS), was used for the retrieval of material properties and for the scattering measurements. Figure 1 shows a schematic of the experimental setup with the three different configurations used in this work: transmission [4] and normal incidence reflection mode [5] for material properties extraction and oblique incidence reflection mode for scattering measurements [6].

III. Results and Discussion

A. Dielectric Properties

For those samples with good transmission, the software Teramat or TeraLyzer was used for material properties extraction. The former was used for etalon (i.e. Fabry–Pérot) free samples, whereas the latter was used for samples displaying etalon effects. Further details about the methodology can be found in [7]. Meanwhile, for thick lossy samples unsuitable for transmission measurements, an in-house Kramers-Kronig retrieval reflection algorithm was used. Details of the extraction algorithm can be found in [5]. In addition, the averaged results (to decrease systematic errors, each sample was measured 4 times) were smoothed using the `signal.savgol_filter` function from the Python SciPy package.

The building materials group in Fig. 2 had the largest values of Re(ε) and tan(δ), suggesting that transmission of signals through different rooms and floors would be the most weakened in the context of transmission through dielectrics. Useful data for glass could only be extracted between 0.3 - 0.6 THz, as beyond this the data was too noisy.

For plastics, Re(ε) ranges from 1.5 to 2.85 with very low dispersion, and tan(δ) is < 0.075 for all cases. The acrylic and RGD525 polymers, which are common materials used for 3D printing, have the highest values of Re(ε) of the plastics investigated. This is good for device miniaturisation, but they also show the highest tan(δ).

In the case of wood, the values of Re(ε) are similar to those of the plastics, but tan(δ) generally tends to be larger. Some wood samples were visually anisotropic (i.e grains visible in the wood), but this does not result in a significant anisotropy for THz frequencies.

Similar trends for all type of materials (e.g. building materials, plastics and wood) have been reported in the literature [8].

B. Scattering

The dielectric properties found in Section III-A were then used to inform analytical scattering simulations based on the Beckmann-Spizzichino model, which was implemented in Python. The reader is referred to [9] for a general outline of this model, and to [10] for the correction which allows this model to account for dielectric properties.

An example of these results is shown in Fig. 3. These results can be used to separate dielectric and scattering losses as follows.

The infinite conductor peak represents the loss due to roughness only, as a perfect electric conductor has neither ohmic nor dielectric losses. The difference between the peaks of the materials and the infinite conductor gives the dielectric losses of each material. The different materials all have very similar peak values, and this was true for all material groups investigated. Since the materials form ”bands”, this is evidence that only a material type needs to be known to make a well informed estimate of total losses.

When waves scatter from a rough surface, only a fraction is reflected back in the specular direction. This fraction, Γ_{rough},

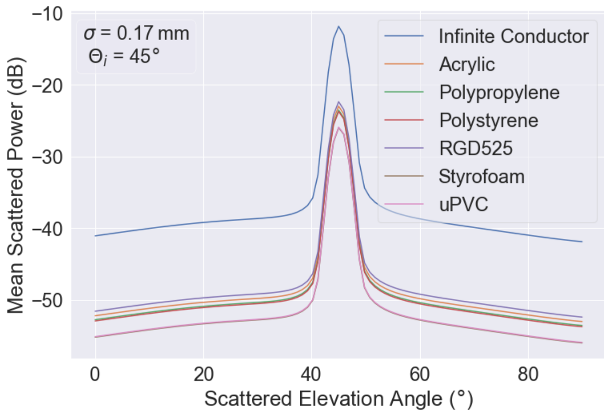

Fig. 3. Mean scattered power from each plastic surface at 300 GHz as calculated using the Beckmann-Spizzichino model. The root mean square height is denoted by σ, and the angle of incidence, θ_{i} = 45°.

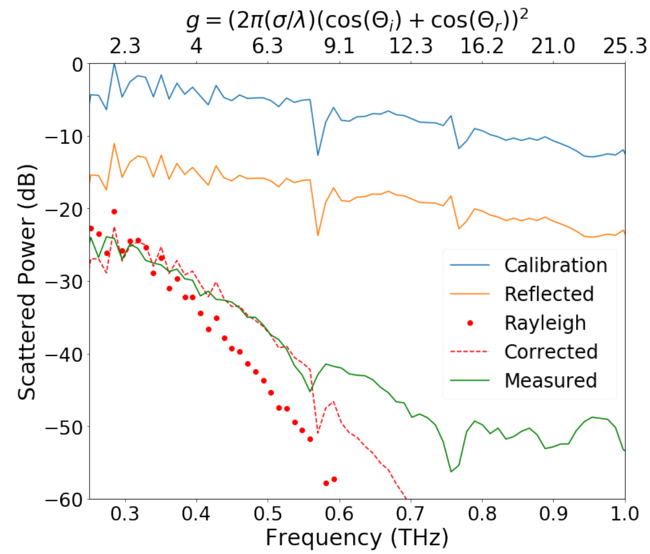

Fig. 4. Disentangled losses for a slab made of RGD525 with σ = 0.17 mm at θ_{i} = 45°. The corrected loss scattering factor matches up better to the measured scattering data than using the typical Rayleigh factor.

can be estimated by multiplying the Fresnel coefficient of a smooth surface, Γ_{smooth}, with a roughness factor, ρ_{s}.

In the classical literature such ρ_{s} is the Rayleigh roughness factor [11] and is defined as

$$\rho_{\text{s}} = e^{\frac{-f}{2}}, \quad \frac{f}{2} = \frac{8\pi^2\sigma^2 cos^2(\theta_{\text{i}})}{\lambda^2}, \tag{1}$$

where σ is the root mean square height of the surface. This correction shows good fitting when the roughness parameter $g < 4$, as demonstrated by our experiments ($\theta_{\text{i}} = \theta_{\text{r}}$ = 45°) with a rough 80 mm × 80 mm RGD525 sample for frequencies up to 0.4 THz (see red dots in Fig. 4). However, for larger g (i.e. above 0.4 THz for our choice of surface roughness σ = 0.17 mm) the model breaks down. Motivated by this limitation, we empirically found a new roughness factor

$$\rho_{\text{s}} = 2.42 \cdot \frac{f}{2} e^{\frac{-f}{2}}, \tag{2}$$

that fits better up to g = 9 (i.e. up to 0.6 THz) as shown by the dashed red line in Fig. 4.

IV. Conclusion

The dielectric properties of different indoor materials were found to inform the Python simulations of the Beckmann-Spizzichino model. It was found that the power loss after scattering is very similar between materials in the same group, so informed estimates of scattering loss from a dielectric can be made using this approach. A new correction to the Rayleigh scattering factor was found empirically from experimental scattering data from a 3D printed sample of RGD525 with σ = 0.17 mm. This work represents a stepping stone to pave the way for future THz communication and sensing services.

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