Terahertz characterisation of building materials

R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch and T. Kürner

To obtain realistic models for propagation channels in future pico-cellular indoor terahertz communication systems it is necessary to know the reflective properties of building materials found in a typical office environment. The angular dependent reflection coefficients of different building materials were determined using terahertz time-domain spectroscopy in transmission geometry and Fresnel's equations. This approach is more efficient than a set of measurements in reflection geometry for different angles. Verification of the method with a set of such reflection measurements shows an excellent agreement.

Introduction: Short range wireless communication systems are expanding at a rapid rate, finding applications in offices, congested urban areas and homes. From the increasing demand for higher data rates it is expected that data transfers at speeds of several tens of Gbit/s will soon be requested [1]. The lack of unoccupied frequency bands for large bandwidths is expected soon to push carrier frequencies in wireless pico-cellular short-range communication networks above 100 GHz. A successful design of communication systems requires the knowledge of propagation channel characteristics. To estimate the spatial and temporal channel properties and to calculate the required antenna gains for signal transmission, ray-tracing simulations coupled with link budget analysis can be performed [2]. However, the reliability of ray-tracing simulations depends on the accuracy of the estimated signal reflection properties in the modelled cells. In a prospective terahertz (THz) cell, reflections from the walls, the ceiling and from areas covered with flexible dielectric plastic mirrors could contribute to an enhanced signal coverage in a non-line-of-sight (NLOS) scenario and make a THz communication link robust against shadowing [3]. Realistic predictions of the channel properties require the measurement of angle dependent reflection coefficients for common building materials over a wide frequency range. Such measurements can be performed with THz time-domain spectroscopy in reflection geometry. However, in order to account for transverse-electric (TE) and transverse-magnetic (TM) incidence at multiple angles, they require considerable effort. In this Letter, we determine the absorption coefficient and refractive index [4] for three typical materials, i.e. window glass, plaster and pine wood in transmission geometry and calculate the reflection coefficients from Fresnel's equations. This takes into account that losses due to scattering are not a significant factor in our case. To verify our method we compare our calculations with reflection measurements.

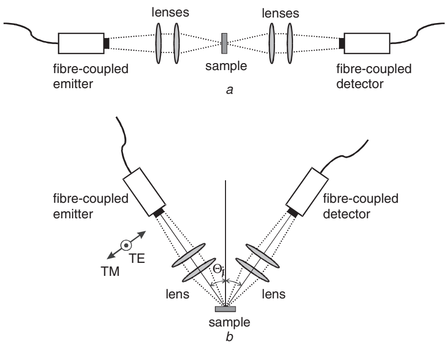

Fig. 1 *Fibre-coupled THz TDS measurement setup*

a Transmission geometry
b Reflection geometry

Experimental setup and measurements: Both, transmission and reflection measurements are performed using a commercially available THz time-domain spectrometer (Picometrix T-Ray 2000^{TM}) [5] with fibre-coupled emitter and detector, as shown in Fig. 1. We examine three planar samples of window glass ($d = 2.84$ mm), plaster ($d = 2.74$ mm) and wood ($d = 3.68$ mm). In transmission geometry we determine absorption coefficient and refractive index in the frequency range 70–350 GHz from the Fourier transformed time traces of consecutive reference and sample measurements. To directly obtain reflection properties we measure all three samples for seven different angles, i.e. 20°, 30°, 40°, 50°, 60°, 70° and 75° with TE and TM polarised waves. The frequency dependent reflection coefficients are then determined as the ratio of the Fourier transforms of consecutive reference and sample measurements. The reference measurements have been obtained by placing a polished copper mirror in place of the sample so that the reflection coincides with the surface reflection of the sample.

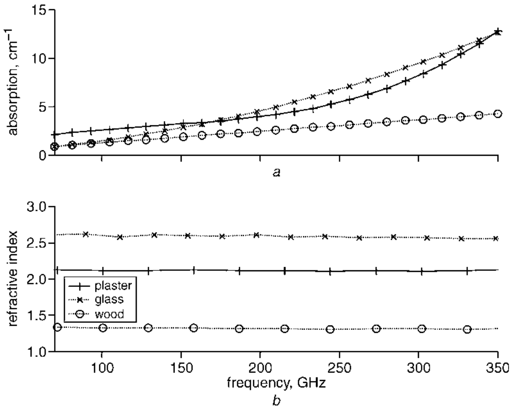

Fig. 2 *Results of measurements of absorption coefficient (fitted to the polynomials: third degree for plaster, second degree for glass, first degree for wood) and refractive index of building materials in a transmission geometry*

a Absorption coefficient
b Refractive index

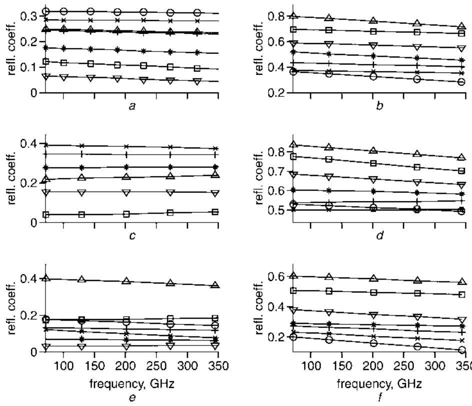

Fig. 3 *Results of measurements of reflection coefficient (fitted to the first degree polynomials) of building materials for TM and TE polarisation and different angles of incidence in reflection setup*

a Plaster TM
b Plaster TE
c Glass TM
d Glass TE
e Wood TM
f Wood TE
○ 20 deg; × 30 deg; + 40 deg; ∗ 50 deg; ▽ 60 deg; □ 70 deg; △ 75 deg

Results and discussion: The refractive index and absorption coefficient for glass, plaster and wood as obtained from the transmission measurements are shown in Fig. 2. For all three samples the absorption coefficients increase considerably with frequency, whereas the refractive indices remain rather frequency independent.

The directly measured reflection coefficients for glass, plaster and wood are shown in Fig. 3 for the seven different angles of TE and TM incidence. The reflection coefficients are an increasing function of the incidence angle for TE polarisation. In the case of TM polarisation the reflection coefficient is a decreasing function of the incidence angle for the angles smaller than the Brewster angle and an increasing function for angles larger than the Brewster angle. As expected, the materials feature a greater reflectivity for TE polarisation than for TM polarisation. Out of the three measured materials, glass is the best reflecting material, whereas wood is least reflective.

We calculate the reflection coefficients r_{TE} and r_{TM} from our measurements of absorption coefficient α and refractive index n using Fresnel's equations [6]:

$$r_{TE} = \frac{Z\cos\theta_i - Z_0\cos\theta_t}{Z\cos\theta_i + Z_0\cos\theta_t}$$

and

$$r_{TM} = \frac{Z\cos\theta_t - Z_0\cos\theta_i}{Z\cos\theta_t + Z_0\cos\theta_i} \quad (1)$$

Here θ_i is the angle of incidence and reflection, $\theta_t = \arcsin(\sin(\theta_i)*Z/Z_0)$ the angle of refraction, $Z_0 = 377\,\Omega$ the free space wave impedance and Z is the wave impedance of the reflecting material, which is calculated using the expression

$$Z = \sqrt{\frac{\mu_0}{\varepsilon_0(n^2 - (\alpha c/4\pi f)^2 - j(2n\alpha c/4\pi f))}} \quad (2)$$

where μ_0 and ε_0 are free space permeability and permittivity, c is the velocity and f is the frequency of the incident wave.

The calculated reflection coefficients for the investigated materials are shown as lines in Fig. 4 for incidence angles in the range of 0–90° for TE and TM polarised waves at the frequencies of 150 and 300 GHz. The directly measured reflection coefficients are shown as symbols for comparison. A good agreement between simulated and measured reflection coefficients can be found for all materials, incidence angles, polarisation types and frequencies.

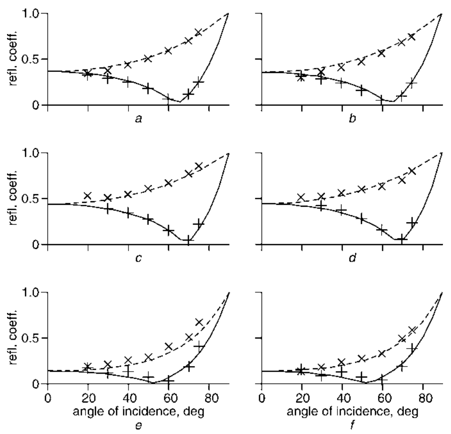

Fig. 4 *Calculated reflection coefficients for TM and TE polarised waves at frequencies of 150 and 300 GHz and direct reflection measurements*

a Plaster at 150 GHz *b* Plaster at 300 GHz *c* Glass at 150 GHz
d Glass at 300 GHz *e* Wood at 150 GHz *f* Wood at 300 GHz
------ TE simulated × TE measured —— TM simulated + TM measured

Conclusions: We have presented measurements of the absorption coefficient and refractive index of typical building materials and have used Fresnel's equations to calculate the reflection coefficients. Knowledge of the material reflectivities is required for accurate modelling of the propagation channel for future indoor THz communication systems including NLOS scenarios. The calculated values are in good agreement with direct measurements of the reflection properties. This implies that losses due to scattering (e.g. diffuse reflectance of the surface) can be neglected.

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