Propagation measurements and modeling for future indoor communication systems at THz frequencies

R. Piesiewicz, *Student Member, IEEE,* J. Schoebel, *Member, IEEE,* M. Koch and T. Kürner, *Senior Member, IEEE*

Abstract— **This paper provides an overview of propagation studies beyond 100 GHz in the Terahertz Communications Lab in Braunschweig and the results achieved so far. In particular, rough surface reflections are investigated. The example is concrete plaster. Also the effect of multiple reflections in layered media is studied. The investigated material is wall paint on plaster.**

Index Terms — **THz communication, propagation models, scattering, multiple reflections**

I. Introduction

THE demand for higher data rates in indoor wireless communications is steadily growing. Current communication systems operate at few tens Mbps speeds in the ISM band at 2.4 GHz. Higher data rates require however larger bandwidths and consequently higher carrier frequencies. The unlicensed 60 GHz band, where data rates of the upcoming radio systems will reach up to 3 Gbps is an option. In order to have even greater data rates, higher carrier frequencies must be tapped. In the future, systems operating with data rates of 10 Gbps and beyond at the carrier frequencies above 100 GHz will be envisaged [1]. They might be accommodated in the THz range and could potentially work with directed transmissions supported by omni-directional dielectric mirrors. The first two atmospheric frequency windows, which might be used for such systems are centered at 300 and 350 GHz, respectively.

Before the introduction of such systems, the THz propagation channel must be thoroughly investigated. We use site-specific modeling, implemented with ray-tracing to calculate the spatial channel properties. Its reliability depends on the accuracy of the estimated signal propagation in the modeled environment. In case of future THz communication systems which will rely on directed high gain antennas, accurate prediction of reflection losses in the specular direction will be crucial for determining the channel behavior. Reflection and transmission losses of interior structures have been thoroughly characterized and modeled up to the frequencies of 60 GHz [2]. The lower part of the THz-band, extending from 300 GHz to 1000 GHz, which might be interesting to accommodate ultra-broadband high speed communication systems in the future, is still an almost unexplored land in this respect.

In the recent past, propagation studies in the Terahertz Communications Lab (TCL) at the Braunschweig Technical University focused on modeling reflection and scattering processes in indoor environments based on measurements beyond 100 GHz [3,4,5,6]. This paper provides an overview of these activities and the results achieved so far. In particular, rough surface reflections are investigated. For example, for concrete plaster or ingrain wallpaper (Raufaser), which appear as flat surfaces at microwave bands, the surface roughness gains in importance at mm- or submm-wavelengths. Also the effect of multiple reflections cannot be neglected any more for layered media. Typical examples for multi-layer surfaces are paint on plaster or a single or double glass window.

II. Propagation Models

A. Scattering

In general, the problem of rough surface scattering can be solved with numerical simulation approaches that are based on integral or differential equation methods to solve the underlying Maxwell boundary value problem [7]. However, numerical approaches are rather complex and usually time-intensive. Instead, under certain conditions analytical approximations can be used. Such algorithms are very robust, give physical insight into the problem and can be easily implemented in ray-tracing. Here, we extend the method which we presented in [3] and which accounts for the reflectivity of smooth materials above 100 GHz, in order to model reflective properties of rough materials in the specular direction. The extension utilizes Kirchhoff theory of scattering from rough surfaces [8], which is implemented into the

R. Piesiewicz is with the Institut für Nachrichtentechnik, Technische Universität Braunschweig, and with the Terahertz Communications Lab in Braunschweig (phone: +49-531-3912414; e-mail: r.piesiewicz@ ieee.org).

J. Schoebel is with the Institut für Hochfrequenztechnik, Technische Universität Braunschweig, and with the Terahertz Communications Lab in Braunschweig.

M. Koch is with the Institut für Hochfrequenztechnik, Technische Universität Braunschweig, and with the Terahertz Communications Lab in Braunschweig.

T. Kürner is with the Institut für Nachrichtentechnik, Technische Universität Braunschweig, and with the Terahertz Communications Lab in Braunschweig.

existing model by multiplication of the reflection coefficient derived from Fresnel equations with a Rayleigh roughness factor. This factor can be calculated from measured surface roughness data of the investigated material. The extended model is verified by the measurement of reflection data for rough concrete plaster in the frequency range from 0.1 to 1 THz.

In order to account for scattering losses in the specular direction, the Fresnel reflection coefficients must be multiplied by the Rayleigh roughness factor [8]

$$\rho = e^{-\frac{g}{2}} \quad \text{with} \tag{1a}$$

$$g = \left(\frac{4\pi \cdot \sigma \cdot \cos\Theta_i}{\lambda} \right)^2. \tag{1b}$$

Here Θ_i is the angle of incidence and reflection, σ the standard deviation of the surface roughness and λ the free space wavelength of the incident wave. The modified reflection coefficients r'_{TE} and r'_{TM} that model the reduction of the signal amplitude in the specular direction are then

$$r'_{TE} = \rho \cdot r_{TE} \quad \text{and} \tag{2a}$$

$$r'_{TM} = \rho \cdot r_{TM}, \tag{2b}$$

where r_{TE} and r_{TM} are the Fresnel reflection coefficients for a smooth surface in the case of TE or TM polarized waves, respectively, which can be efficiently and reliably calculated in the THz range from the frequency dependent materials' index of refraction n and absorption coefficient α [3]

$$r_{TE} = \frac{Z\cos\Theta_i - Z_0\cos\Theta_t}{Z\cos\Theta_i + Z_0\cos\Theta_t} \quad \text{and}$$

$$r_{TM} = \frac{Z\cos\Theta_t - Z_0\cos\Theta_i}{Z\cos\Theta_t + Z_0\cos\Theta_i}. \tag{3}$$

Here, $\Theta_t=\arcsin(\sin(\Theta_i)\cdot Z/Z_0)$ is the angle of refraction, Z_0=377 Ω the free space wave impedance and Z the wave impedance of the reflecting material, which is calculated using the expression

$$Z = \sqrt{\frac{\mu_0}{\varepsilon_0\left(n^2 - \left(\frac{\alpha\, c}{4\pi\, f}\right)^2 - j\frac{2n\alpha\, c}{4\pi\, f} \right)}} \tag{4}$$

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

Kirchhoff solution to the scattering problem assumes that there is no multiple scattering, no shadowing and that the surface is locally smooth, i.e. there are no sharp edges or corners. Furthermore, equations (2) will only deliver accurate results if the surface height distribution is Gaussian and the correlation length of the surface exceeds the wavelength [8].

B. Multiple reflections

If the surface reflection dominates the overall reflection coefficient of the investigated structure, classical Fresnel equations [3] sufficiently describe the reflectivity. This is the case if the thickness of the obstacle is large compared to the wavelength and the material is absorbing strong enough, so that internally reflected waves are nearly completely attenuated when they reach the surface. However, in the presence of optically thin materials or stratified stacks, multiple reflections must be included in the calculations. Frequency and angle dependence of the reflection coefficient can differ considerably from the ones of optically thick materials, due to constructive and destructive interference of reflected waves.

The internal reflections phenomenon has been thoroughly studied in literature for propagation modeling at microwave frequencies [9] and in the 60 GHz band [10]. Here, we investigate multiple reflections effect above 100 GHz.

The simulations presented here are based on the transfer matrix method [11]. The model is verified by the measurement of reflection data for white paint on gypsum plaster in the frequency range from 0.1 to 0.5 THz.

The chosen implementation employs two matrix types, the P_m and the I_m matrices which describe the behavior of a propagating wave in a stratified material as

$$\begin{aligned} \begin{pmatrix} E_{inc} \\ E_{ref} \end{pmatrix} &= I_0 \left(\prod_{m=1}^{N} P_m I_m \right) \begin{pmatrix} E_{trans} \\ 0 \end{pmatrix} \\ &= \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} E_{trans} \\ 0 \end{pmatrix} \\ &= \begin{pmatrix} a_{11} \\ a_{21} \end{pmatrix} E_{trans} \end{aligned} \tag{1}$$

when no wave coming from the backside of the stratified material is present. P_m represents the propagation through the layer m while I_m covers the effects at the interface between layer m and layer m+1. The P_m matrix can be written as:

$$P_m = \begin{pmatrix} e^{in_m k_0 \cos(\theta_m) l_m} & 0 \\ 0 & e^{-in_m k_0 \cos(\theta_m) l_m} \end{pmatrix} \tag{2}$$

with n_m as refractive index, θ_m as angle of propagation and l_m as thickness of layer m. k_0 represents the free-space wave number. The I_m matrix can be formulated as

$$I_m = \frac{1}{t_{TE/TM}} \begin{pmatrix} 1 & r_{TE/TM} \\ r_{TE/TM} & 1 \end{pmatrix} \tag{3}$$

using the Fresnel reflection coefficients for bulk materials

$$r_{Fresnel} = \frac{n_{eff,m} - n_{eff,m+1}}{n_{eff,m} + n_{eff,m+1}}$$
$$t_{Fresnel} = \frac{2n_{eff,m}}{n_{eff,m} + n_{eff,m+1}} \quad (4)$$

with

$$n_{eff,m} = n_m \cos(\theta_m) \quad (5)$$

for TE-polarization and

$$n_{eff',m} = \frac{n_m}{\cos(\theta_m)} \quad (6)$$

for TM-polarization.

The amplitude reflection and transmission coefficients of the stratified material can then be written as

$$t_{strat} = \frac{E_{trans}}{E_{inc}} = \frac{1}{a_{11}}$$
$$r_{strat} = \frac{E_{ref}}{E_{inc}} = \frac{a_{21}}{a_{11}} \quad (7)$$

III. Measurements and Simulations

A. Material parameters

The common baseline of investigated propagation models is their dependence on material parameters. For the extraction of refractive index and absorption coefficient we use terahertz time-domain spectroscopy in transmission geometry (THz-TDS) [4].

Measured material parameters of the concrete sample are shown in Fig.1. In Fig.2 we show measured material parameters of white paint and gypsum plaster.

In case of rough surface scattering, statistics of surface roughness are needed. The surface roughness of the concrete sample is measured using commercially available equipment for optical 3D micro- and nanometrology [12]. With a 5x objective, lateral and vertical resolutions of 25 µm and 5 µm are achieved, respectively. The surface height distribution of the sample is obtained by processing the measured surface roughness data which has been offset to a zero mean value. The surface roughness of the sample is approximated by a Gaussian distribution. The calculated standard deviation σ of the surface height of the investigated concrete amounts to 0.15 mm.

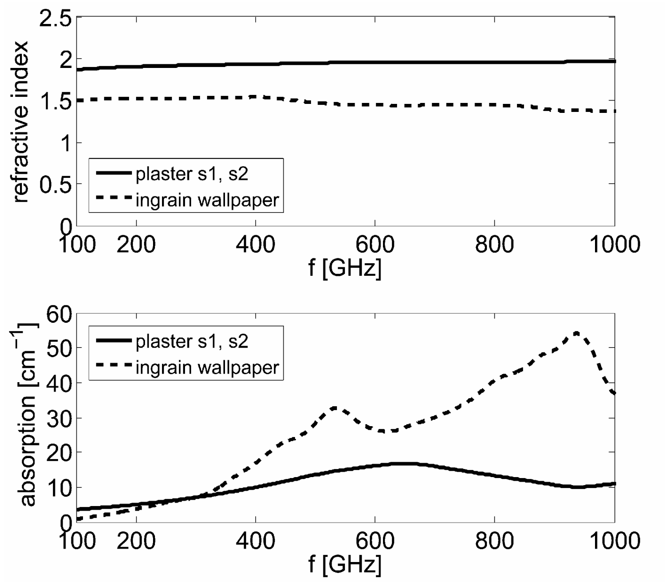

Fig. 1 Measurements of refractive index (top) and absorption coefficient (bottom) of the investigated concrete plaster sample.

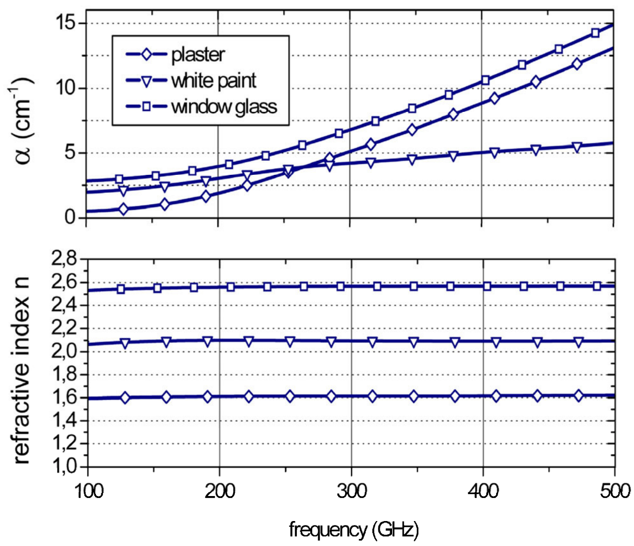

Fig. 2 Frequency dependent absorption coefficient α and refractive index n of gypsum plaster and white paint.

B. Scattering

We measure the reflection from the concrete sample with terahertz time-domain spectroscopy in reflection geometry. Then we calculate the reflection coefficients r_{TE} and r_{TM} of rough concrete plaster from our measurements of absorption coefficient and refractive index using the conventional Fresnel equations, as in [3]. These coefficients are then multiplied by the Rayleigh factor ρ taking into account the measured standard deviation of the surface height in order to get r'_{TE} and r'_{TM}. The calculated magnitude of reflection coefficients r_{TE} and r_{TM} (dashed lines) as well as the calculated magnitude of modified reflection coefficients r'_{TE} and r'_{TM} (solid lines) for the rough concrete plaster are shown for illustration in Fig.3 for TE and TM polarized waves for the frequency range between 100 and 1000 GHz and two different angles of incidence (25 and 60 degrees). The directly measured reflection coefficients (interconnected symbols) are shown for comparison. Additionally, in Fig.4 the calculated magnitude of modified reflection coefficients r'_{TE} and r'_{TM} as well as the directly measured values for the rough concrete plaster sample are shown as a function of angle of incidence for TE and TM polarized waves at the frequency of 350 GHz.

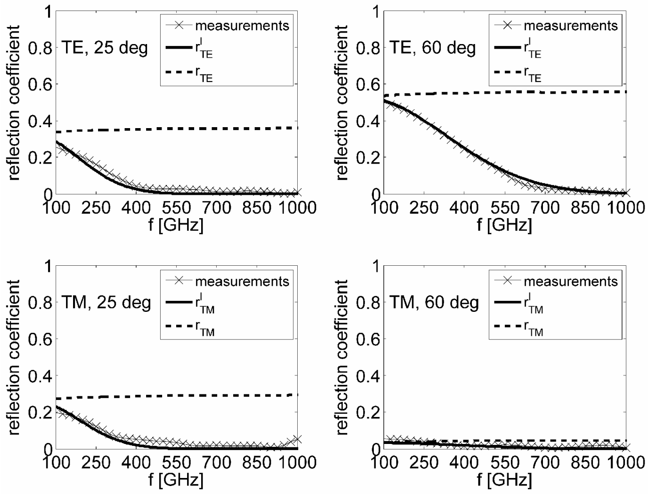

Fig. 3 Calculated magnitude of reflection coefficients r_{TE} and r_{TM} and of modified reflection coefficients r'_{TE} and r'_{TM} and direct reflection measurements of plaster sample in the frequency range from 100 to 1000 GHz for two angles of incidence of TE and TM polarized waves: 25 deg, 60 deg.

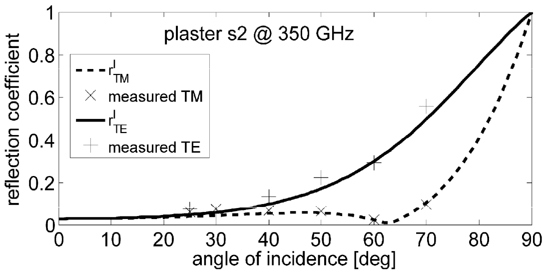

Fig. 4 Calculated magnitude of modified reflection coefficients r'TE and r'TM and direct reflection measurements of plaster sample for angles of incidence between 0 and 90 degrees at a frequency of 350 GHz for TE and TM polarized waves.

A good agreement between the simulated modified reflection coefficients r'_{TE} and r'_{TM} and the measured reflection coefficients can be found for all incident angles, polarization types and frequencies. The simulated conventional reflection coefficients r_{TE} and r_{TM} conform with the measured data only for long wavelengths, depending on the angle of incidence and polarization. Except for these limited cases, the simulated conventional reflection coefficients deviate significantly from the measured ones. The difference becomes more and more significant as the frequency increases and is correlated to the parameter *g*. For frequencies and angles of incidence for which the parameter *g* takes on values greater than 1, the specular reflections are strongly diminished. Also, for a given angle of incidence and polarization the amplitude of the reflection coefficients decreases with increasing frequency. This is expected, since with an increase in frequency, the effective roughness of the material (described by the parameter *g*) grows along with the scattering losses in the specular direction.

C. *Multiple reflections*

We measure the reflection from the paint on gypsum plaster sample with terahertz time-domain spectroscopy in reflection geometry. Then we calculate the reflection coefficients with the model from section II. Figure 5 a) and b) illustrate the amplitude reflection coefficient of the paint on plaster sample for TE- and TM-polarization, both measured (solid lines) and simulated (lines with symbols).

A very good agreement between simulated and measured reflection coefficients can be found for all angles of incidence, polarization types and frequencies. As expected, strong variations in the reflection coefficient result from the multiple reflections in the structure. Peak to peak values in the measured frequency range are as high as 0.23 for the painted plaster. The small discrepancies between the measured and simulated data might be the result of fluctuations of the laser power during the measurements of reference and sample pulse as well as slight thickness deviations from the measured value. For the paint on plaster sample, a slight decrease in the measured reflectivity with increasing frequency compared to the simulations can be observed. Possibly, this can be explained by scattering due to slightly rough surfaces of the single layers. Kirchhoff scattering theory suggests increasing diffusive losses with increasing frequencies in specular direction as shown in [5].

The different behavior for TE- and TM-polarization over the angle of incidence is to some extent comparable to that of a single layer material. While there is no clear Brewster angle with zero average reflection for TM-polarization due to the differing refractive indices, the curves show a minimum located between the Brewster angles of the individual materials. For TE-polarization the average reflectivity increases with increasing angles similar to bulk materials.

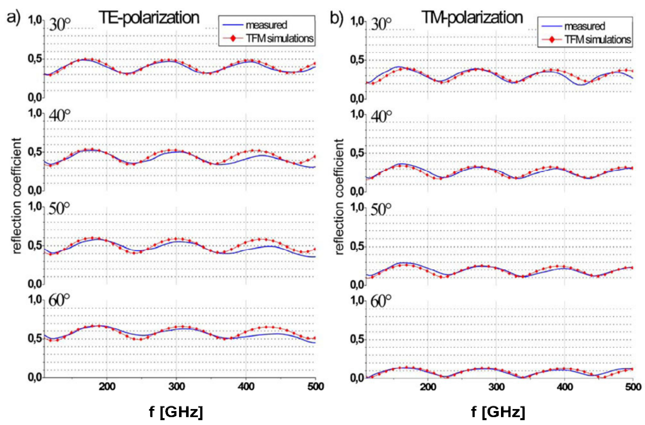

Fig. 5 Measured data (solid lines) and transfer matrix simulations (lines and symbols) of the frequency and angle dependent amplitude reflection coefficient of a white paint on plaster

IV. Conclusion

In this paper we gave an overview of propagation studies beyond 100 GHz in the Terahertz Communications Lab in Braunschweig. It has been demonstrated that at frequencies beyond 100 GHz both rough-surface properties and multi-layer structures play an important role. Future work will also include scattering in non-specular direction as well as modeling of rough surfaces on top of multi-layer structures.

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