The Impact of Reflections From Stratified Building Materials on the Wave Propagation in Future Indoor Terahertz Communication Systems

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***Abstract*—In order to derive reliable propagation models for future terahertz indoor pico-cellular communication systems, accurate reflectivity data of building materials is necessary. Here we present reflection terahertz time domain spectroscopy (THz-TDS) measurements and matching transfer matrix simulations of the frequency dependent reflection coefficient of multi layer building materials in the frequency range from 100 to 500 GHz for a set of angles, both in TE- and TM-polarization. Two prominent stratified structures, a double pane window and white paint on plaster are investigated as they usually account for large areas in indoor environments. Communication systems located above 100 GHz are expected to be strongly affected by the variations of the reflectivity over the frequency and incident angle of such stratified materials as they will rely both on line of sight (LOS) and non line of sight (NLOS) propagation. We discuss this impact on the power distribution in a sample scenario employing the ray-tracing method.**

***Index Terms*—Multilayers, nonhomogeneous media, ray-tracing, stratified materials, submillimeter wave communication, THz channel modeling, THz communication, transfer matrix.**

I. Introduction

FUTURE short range wireless communication systems will require more bandwidth than current ones like WLAN or BLUETOOTH and the emerging ones, like UWB, or 60 GHz systems, can provide. If the current trend continues, an extrapolation shows that data rates of several tens of Gbps will be required in the future [1]. Applications for such high speed data links might include generic data transfer, e.g. as wireless extensions of 10 Gbps Ethernet, or uncompressed HD video transmission [2]. To meet these high bandwidth demands is a challenging task. Moreover, the lack of unoccupied and unregulated frequency bands seems to make a spectral shift towards carrier frequencies above 100 GHz, namely into the terahertz regime, highly interesting. Especially in the lower THz range the overall attenuation, including free-space propagation losses and atmospheric losses, is still at a level where viable signal transmissions with multi-gigabit data rates can be expected. While line-of-sight (LOS) mode of communication is always preferable, robustness against shadowing can be achieved by directed non-line-of-sight (NLOS) transmissions with reflections from walls and other objects in the environment [3].

For a cost-efficient and reliable communication system design a precise propagation model is mandatory, so that the required antenna gain and other system parameters can be predicted in advance without the need of expensive, site specific measurements. The signal coverage in indoor application scenarios can be estimated by ray-tracing [4] simulations in conjunction with the link budget analysis technique [5]. However, accurate simulations require the knowledge of the reflective properties of the propagation environment.

If the surface reflection dominates the overall reflection coefficient of the investigated structure, classical Fresnel equations [6] 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. For frequencies below 100 GHz, [7] and [8] analyze the properties of some common building materials. Measurements and simulations of the reflectivity of such materials at terahertz frequencies can be found in [9]. 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 [10], [11]. Sato *et al.* [12], [13] and Langen *et al.* [14] investigated the reflection coefficients of stratified indoor materials at 57.5, 78.5, 95.9 GHz and 60.2 GHz respectively. However, the reflection modeling is not based on measured material parameters, but on the fitting of model equations to the reflection curves. Furthermore, due to the narrowband character of the measurements, only the angle but not the frequency dependence of the reflection coefficient is discussed. Especially the latter has strong influence on the design of wide band communication systems with NLOS propagation via reflections present. The impact of multiple reflections on wave

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propagation in future ultra broadband communication systems above 100 GHz has not been studied yet.

In this paper we present frequency and angle dependent reflection measurements for both TE- and TM-polarization, along with the corresponding transfer matrix simulations in the frequency range between 100 and 500 GHz taking into account the frequency dependence of the complex refractive index of the single layer materials. A plaster sample, covered with white paint and a double pane glass window are studied as examples for two commonly encountered multilayer structures in indoor scenarios. The investigated materials usually account for a considerable surface area in indoor environments and thus are of special importance for the propagation modeling. Furthermore, ray-tracing simulations in a sample indoor scenario are performed in order to discuss the impact of the internal reflections effect on the frequency dependent spatial power distribution.

The remainder of this paper is organized as follows. In Section II the experimental setup and measurement techniques are introduced. Numeric calculations and THz-TDS reflection measurements of the reflection coefficients of stratified stacks follow in Section III. Afterwards, Section IV discusses the impact of multiple reflections on wave propagation in an indoor communication scenario at 350 GHz and finally, Section V finishes with a conclusion.

II. Experimental Setup and Measurements

Two slightly different experimental configurations, both based on a commercially available fiber coupled terahertz time domain spectrometer [15] are employed. The spectrometer consists of a diode pumped $\mathrm{Ti}:\mathrm{Al_2O_3}$ femtosecond laser which generates 80 fs laser pulses. The pulses are chirp precompensated, splitted and directed to the receiver and transmitter photoconducting antenna via polarization maintaining fibers. The emitter antenna is biased, so that the laser pulse generated photo carriers are separated in the DC field, emitting a terahertz pulse. On the receiver side, the photocurrent which corresponds to the electric terahertz field present when the femtosecond pulse gates the receiver is detected. The receiver path includes a delay rail. By sweeping the time delay of the receiver pulse and detecting the photocurrent at each rail position the complete terahertz time-domain waveform is sampled [16]. The available bandwidth of the system is 1.1 THz with a peak dynamic range of 48 dB.

The first configuration is a transmission THz-TDS setup as shown in Fig. 1(a), which is used to determine the refractive index and the absorption coefficient of white paint, glass and plaster as a function of frequency between 100 and 500 GHz. The optical parameters are needed for the transfer matrix simulations. In order to obtain the angle and frequency dependent measurements of the reflection coefficient, the transmission setup is mounted on movable rails, making it capable of reflection measurements as illustrated in Fig. 1(b).

For the transmission measurements the time domain pulses, once with and once without the sample of the single layer material in the focal spot, are measured. The refractive index $\mathrm{n}(\omega)$ and the absorption coefficient $\alpha(\omega)$ are calculated from the phase and amplitude information of the Fourier spectra

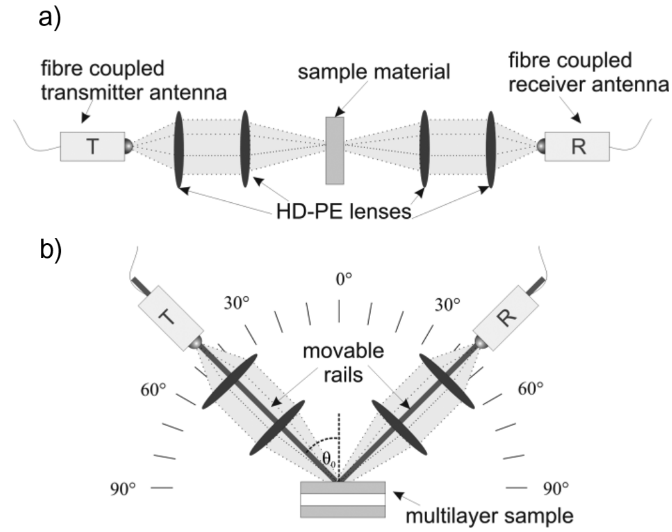

Fig. 1. Fiber coupled THz-TDS setup in (a) transmission and (b) reflection geometry.

together with the thickness of the sample [16]. A Blackman time domain window is used to ensure that multiple reflections are not included in determining $\mathrm{n}(\omega)$ and $\alpha(\omega)$ [17].

The reflection setup is now employed to analyze the reflectance behavior of the material stack. The first sample consists of 2.92 mm glass, 1.96 mm air and then again 2.92 mm glass, which represents a double pane window. The second sample is made of a thick piece of plaster and a 695 $\mu\mathrm{m}$ layer of white paint on top, which represents a wall. The reflections from the backside of a typical wall will not noticeably affect the reflection coefficient in the frequency range studied due to the high attenuation in the material, so that only the thickness of the paint on top is relevant. All thicknesses are measured with an accuracy of $\pm 10\ \mu\mathrm{m}$. Reflection data are obtained for 25°, 30°, 45° and 60° for the double pane window structure and for 30°, 40°, 50° and 60° for the white paint on plaster sample, both in TE- and TM-polarization. A sample and a reference pulse are measured, where a polished copper plate serves as THz mirror which replaces the sample for the detection of the reference pulse. Again, a window is applied to the time domain data, but this time large enough to include multiple reflections. An FFT is used to find the Fourier spectra from which the reflection coefficients are calculated by taking the ratio of the sample and the reference pulse.

III. Transfer Matrix Simulations and Reflection Measurements

The simulations presented here are based on the transfer matrix method [18]. The chosen implementation employs two matrix types, the $\mathrm{P_m}$ and the $\mathrm{I_m}$ matrices which describe the behavior of a propagating wave in a stratified material as

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

when no wave coming from the backside of the stratified material is present. $\mathrm{P_m}$ represents the propagation through the layer m while $\mathrm{I_m}$ covers the effects at the interface between layer m and layer $\mathrm{m}+1$.

The $\mathrm{P_m}$ matrix can be written as

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

with $\mathrm{n_m}$ as refractive index, θ_m as angle of propagation and $\mathrm{l_m}$ as thickness of layer m. $\mathrm{k_0}$ represents the free-space wave number.

The $\mathrm{I_m}$ matrix can be formulated as

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

using the Fresnel reflection and transmission coefficients for bulk materials

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

with $n_{\mathrm{eff},m} = n_m \cos(\theta_m)$ for TE-polarization and $n_{\mathrm{eff}},_m = n_m/(\cos(\theta_m))$ for TM-polarization.

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

$$t_{\mathrm{strat}} = \frac{E_{\mathrm{trans}}}{E_{\mathrm{inc}}} = \frac{1}{a_{11}}$$
$$r_{\mathrm{strat}} = \frac{E_{\mathrm{ref}}}{E_{\mathrm{inc}}} = \frac{a_{21}}{a_{11}}. \quad (5)$$

The simulations use the frequency dependent refractive index and absorption coefficient obtained from the transmission experiment. With the knowledge of the frequency dependent optical parameters of the single materials any multi-layer structure consisting of a combination of these components can be precisely modeled for its transmission and reflection behavior.

Fig. 2 depicts the refractive index n and the absorption coefficient α of glass, plaster and white paint obtained by the transmission measurements. Please note, that white paint is analyzed here for the first time, while the results for glass and plaster are reproduced from [19]. Between 100 and 500 GHz, the white paint has a rather high average refractive index n_{paint} of 2.09 which can be attributed to titania particles, used as white color pigment. The average refractive index of plaster is $n_{\mathrm{plaster}} = 1.61$, yielding $\Delta n_{\mathrm{plaster/paint}} = 0.52$. The glass has an average refractive index n_{glass} of 2.56 so that together with $n_{air} = 1.0$ for air $\Delta n_{\mathrm{glass/air}} = 1.56$ results.

Fig. 3 and 4 illustrate the amplitude reflection coefficient of the double pane window structure and paint on plaster, respectively. Part (a) of the figures corresponds to TE-polarization and part (b) to TM-polarization, both measured (solid lines) and simulated (lines with symbols).

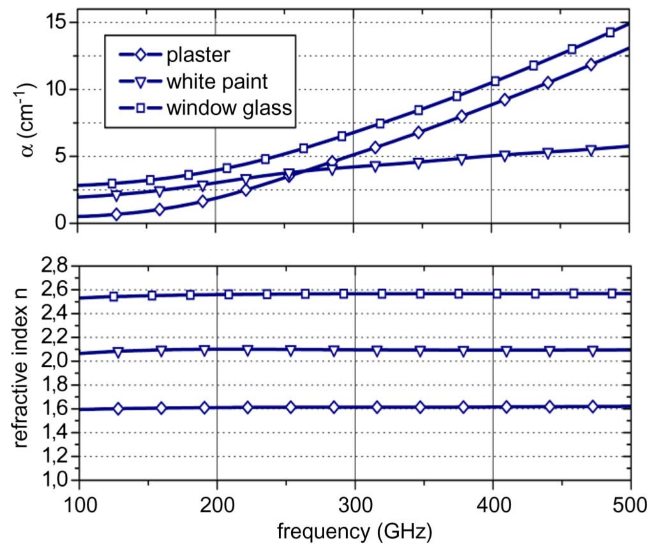

Fig. 2. Frequency dependent absorption coefficient a and refractive index n of plaster, white paint and window glass.

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 0.54 for the double pane window and 0.23 for the painted plaster. The stronger variations in the double pane sample can be explained by the bigger Δn in that structure. For high frequencies the oscillations decrease, as the corresponding wavelengths are now considerably smaller than the thickness of one single layer of the structure. 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's scattering theory suggests increasing diffusive losses with increasing frequencies in specular direction as shown in [20].

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.

IV. Ray Tracing Simulations in a Sample Indoor Scenario

In order to discuss the relevance of multiple reflections on wave propagation modeling for future terahertz communication systems, we present ray tracing simulations of the received signal power in an empty $6\ \mathrm{m} \times 5\ \mathrm{m} \times 2.5\ \mathrm{m}$ room at the level of 0.95 m above the floor. The transmitter with an output power of

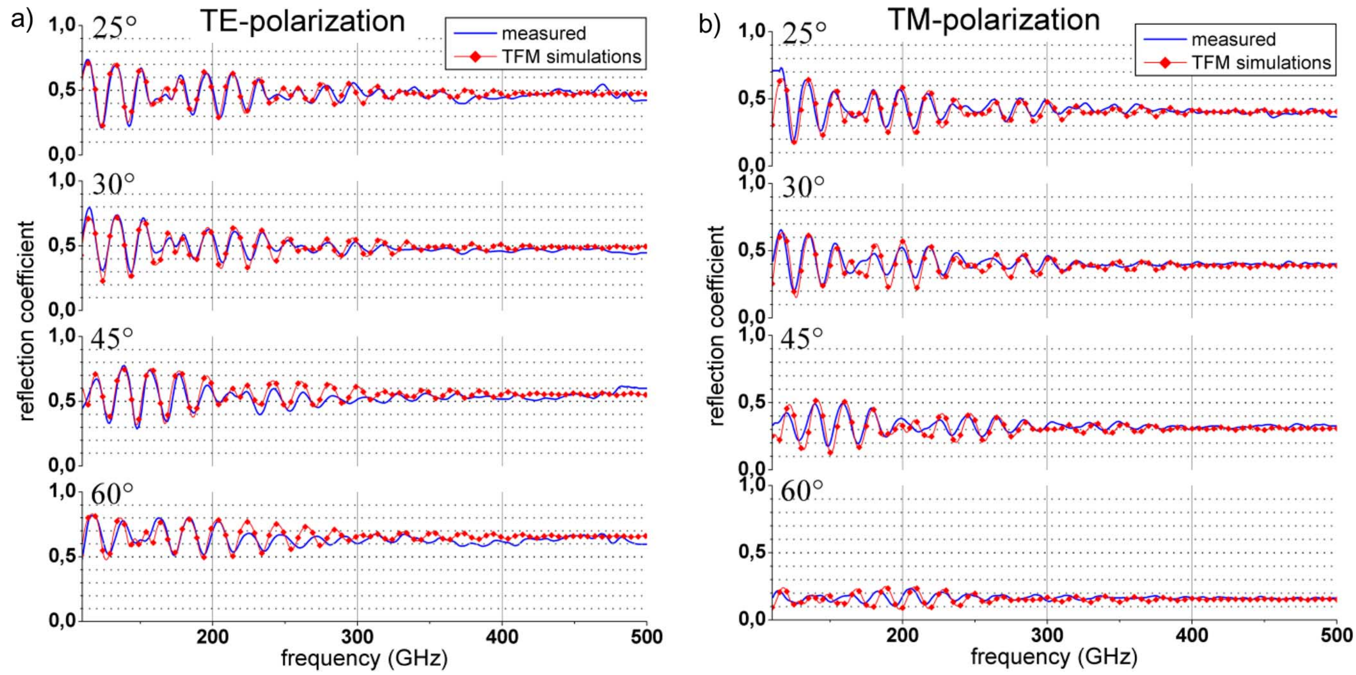

Fig. 3. Measured data (solid lines) and transfer matrix simulations (lines and symbols) of the frequency and angle dependent amplitude reflection coefficient of a double pane window.

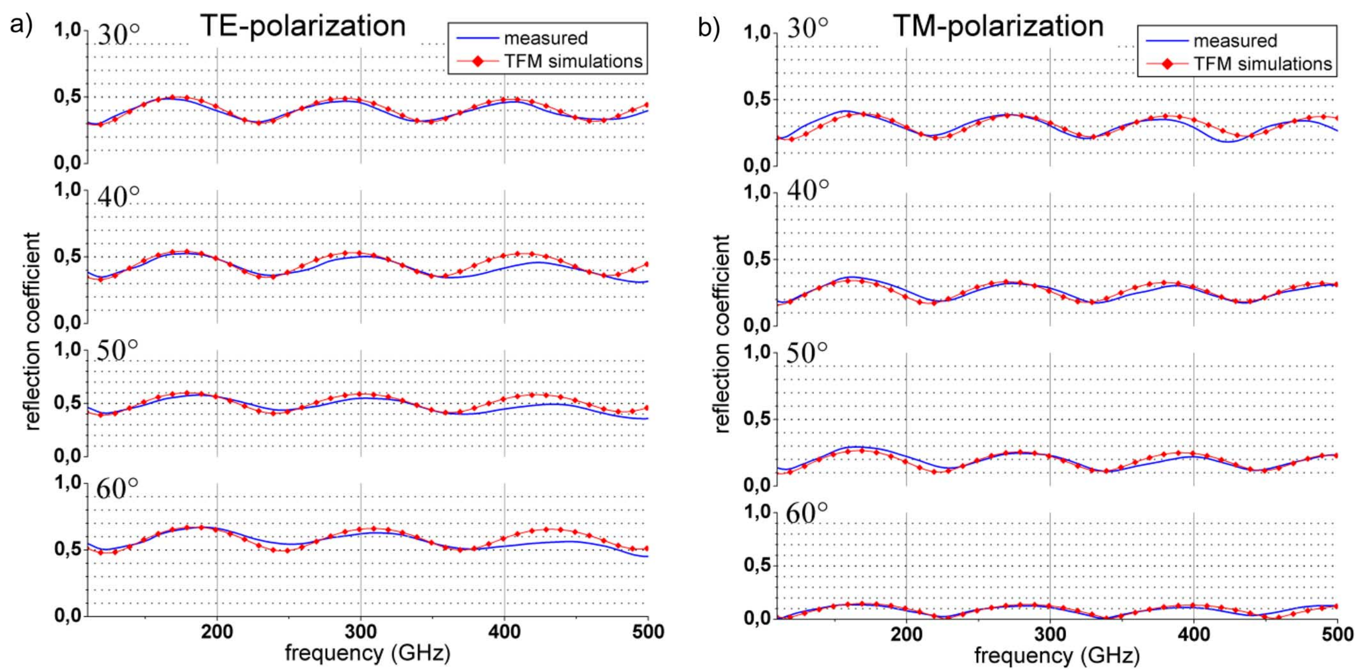

Fig. 4. Measured data (solid lines) and transfer matrix simulations (lines and symbols) of the frequency and angle dependent amplitude reflection coefficient of a white paint on plaster.

0 dBm is centered in the room 0.2 m below the ceiling. We analyze two scenarios. Scenario 1 models the room with 0.2 m thick concrete plaster as floor material, two double pane windows (without frames) on the front wall and white paint on plaster as ceiling and wall material. Each window has dimensions of 2.3 m $\times$ 1.1 m, is positioned 1.1 m above the floor and 0.6 m to the left, respectively to the right of the side wall. Scenario 2 neglects multiple reflections by substituting the double pane windows with massive glass blocks and the white paint on plaster with simple plaster walls. We perform two types of simulations, spatial signal coverage at a single frequency and frequency dependent received power at a chosen receiver position.

First, the spatially received power is analyzed in order to investigate the influence of multiple reflections on the signal coverage in future indoor THz communication systems. Received NLOS signal power at 350 GHz, including reflection and free-space propagation losses is simulated for once reflected propagation paths for receiver positions in the plane parallel to

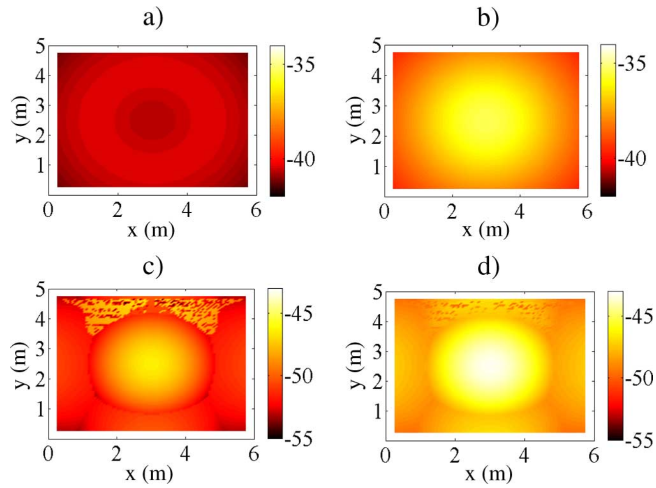

Fig. 5. Simulated spatial signal coverage resulting from single reflection paths for TE- and TM-polarization calculated once with the Fresnel and once with the multiple reflections approach. (a) TE with Fresnel reflections; (b) TE with multiple refections; (c) TM with Fresnel reflections; (d) TM with multiple reflections.

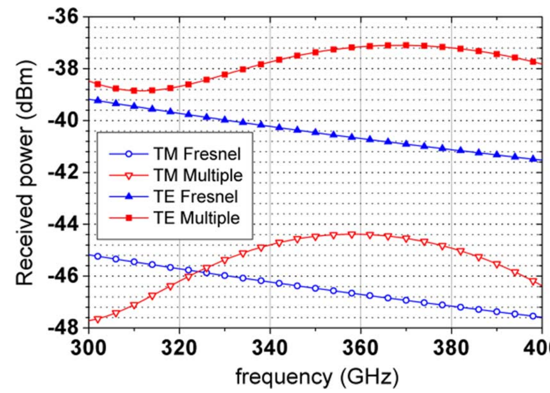

Fig. 6. Simulated received power over the frequency resulting from once reflected waves at a fixed position in the room.

the floor at the height of 0.95 m. The chosen frequency corresponds to the center of an atmospheric frequency window, where future THz communication systems could be accommodated. It is assumed that both the transmitter and the receiver are equipped with directive antennas with 30 dB gain each. Furthermore, it is assumed that for each transmitter receiver pair the antennas are aligned so that always the single reflection propagation path with minimum transmission losses is chosen at a time. Due to the high directivity of the antennas, other possible paths with one reflection are effectively cancelled out by the radiation patterns and it is not necessary to take them into account when calculating the received power [21]. Moreover, our simulations show that twice reflected paths lie approximately 10–15 dB below the level of once reflected ones. This fact, in addition to the small beam widths of the antennas makes their potential contribution to the received signal level negligible.

The simulated spatial signal coverage for TE- and TM- polarization, resulting from once reflected waves is shown in Fig. 5. Both, simulations considering and neglecting multiple reflections are shown.

As already observed in [20], in case of once reflected paths for TE-polarization, modeled with simple Fresnel equations, the power maintains almost a steady level in the plane of the receiver, varying only very slightly between -40.5 and -41.2 dBm. This can be explained with decreasing reflection losses due to the increasing incident angle when moving away from the center of the room, which compensates for the growing free-space losses due to the increased propagation distance. In case, multiple reflections are considered, the calculated power diminishes clearly from the center of the room towards the walls, varying between -35.5 and -39.5 dBm. The decreasing reflection losses no longer compensate for the raising propagation losses. Yet, the absolute signal level is predicted to be higher than in the simple Fresnel case, which can be attributed to the higher average reflectivity of paint on plaster than of plaster only.

For TM-polarization, the general trend of the received once reflected power is similar for both modeling cases. Here, the power levels decrease substantially from the center of the room towards the walls. Because the reflection losses in the TM-case are higher than in the TE-case, the increasing free-space propagation losses are not compensated for. In Fig. 5(c) and (d) a circular boundary in the coverage pattern is observed. This can be explained by the sudden switch of the lowest loss propagation path. Inside the circular area, the waves are reflected from the ceiling, whereas outside of it the reflections originate from the walls. The clear edge in the pattern is due to the abrupt change of the incident angle of the lowest loss beam. As for TE-polarization, the predicted power for multiple reflections, varying between -36 and -46 dBm is higher than for the simple Fresnel case, where it takes on the values in the range -42 and -56 dBm. Also, the influence of the windows on the received power patterns can be clearly seen. Near the windows, the power levels are increased, taking on similar values in both modeling cases.

Furthermore, the level of the received signal is analyzed at a chosen spatial position in order to illustrate the influence of multiple reflections on the frequency dependence of the received power. The chosen receiver position is at the coordinates: 4.5 m, 1.25 m, 0.95 m. As in the previous case, the transmitter and the receiver are equipped with 30 dB gain antennas and it is assumed that once reflected NLOS path with minimum transmission losses is chosen. The simulated frequencies cover the range between 300 and 400 GHz, encompassing the atmospheric frequency window. The calculated received power for a single reflection path once for TE- and once for TM-polarization are shown in Fig. 6. Simulations are performed with and without multiple reflection effects, according to the two considered scenarios.

The calculated received power, when reflections are modeled with simple Fresnel equations shows a linear decrease with frequency for both TE- and TM-polarization. Considering that the material parameters, especially the refractive index do not very considerably in the investigated frequency range, it is clear that the power decrease is attributed to the increasing free-space propagation losses, which we calculate according to the Friis free-space formula. In contrast, the calculated power, when multiple reflections are taken into account shows a far more complicated behavior, oscillating around the values predicted by the simple Fresnel approach. This strong frequency dependence will have to be considered in the design and planning of future ultra wide band communication systems working in NLOS mode via reflections.

V. Conclusion

We present measurements and transfer matrix simulations of the angle and frequency dependent reflection coefficient of stratified building materials in the terahertz regime, as well as ray-tracing simulations for a sample indoor communication scenario at 350 GHz. The transfer matrix simulations agree very well with the measured reflection coefficients. The ray tracing simulations emphasize the importance of including multiple reflections from stratified structures in NLOS propagation models, especially when broadband systems are considered.

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He 1988, he joined the research group of Dr. Charles Shank at the University of California, Berkeley. His primary research involved the spectroscopy of semiconductor nanocrystals using laser pulses with durations of less than 20 femtoseconds, at wavelengths from 480 to 670 nm. These experiments were performed in collaboration with the Alivisatos group in the Chemistry Department at Berkeley and were carried out at the Lawrence Berkeley National Laboratory. He then joined the research group of Dr. Richard Freeman, as a Postdoctoral Member of the Technical Staff at AT&T Bell Laboratories. While there, he pursued research into high harmonic generation in noble gases using a 100 femtosecond, 1 terawatt laser system. When he left Bell Labs in early 1995, he began working with Dr. Martin Nuss, who, with his previous post-doc Dr. Binbin Hu, had recently pioneered the use of THz time-domain spectroscopy for imaging. His work in this laboratory included the non-contact characterization of doped semiconductor wafers using the THz Hall effect, the construction of a THz imaging system in a reflection geometry for use in "T-Ray Tomography" measurements, and the THz spectroscopy of inverse micelles of water in heptane. During this time, AT&T split into three companies, and most of Bell Labs became part of one of the three pieces, Lucent Technologies. In September 1996, he joined the ECE Department at Rice University, Houston, TX, where he is affiliated with the Rice Quantum Institute.

Thomas Kürner (SM'01) was born in Tailfingen, Germany, in 1964. He received the Dipl.-Ing. degree in electrical engineering and the Dr.-Ing. degree both from University of Karlsruhe, Germany, in 1990 and 1993, respectively.

From 1990 to 1994, he was with the Institut für Höchstfrequenztechnik und Elektronik (IHE), University of Karlsruhe, working on wave propagation modeling, radio channel characterization and radio network planning. Until 1994, he was also a Lecturer for the Carl Cranz Series for scientific education teaching wave propagation modeling and channel characterization. From 1994 to 2003, he was with the Radio Network Planning Department at the headquarters of the GSM 1800 and UMTS operator E-Plus Mobilfunk GmbH & Co KG, Düsseldorf, where he was Team Manager radio network planning support responsible for radio network planning tools, propagation models, algorithms, processes and parameters. Since 2003, he is a Professor for Mobile Radio Systems at the Institut für Nachrichtentechnik, Technical University of Braunschweig. His working areas are propagation, traffic and mobility models for automatic planning of mobile radio networks, planning of hybrid networks, car-to-X-communication as well as indoor channel characterization for high-speed short-range systems including future terahertz communication systems. He has been engaged in several international bodies like ITU-R SG 3 (radio wave propagation), UMTS Forum Spectrum Aspects Group, COST 231, COST 273, COST 2100, and COST 259, where he chaired the working group "Network Aspects." He was also a Work Package Leader in the European IST-MOMENTUM project working on methods for "Automatic Planning of large-scale Radio Networks."

Prof. Kürner received the "ITG-Förderpreis" Award from the German VDE for his Ph.D. thesis in 1994, and in 1995 he was awarded the IEE/ICAP'93 Best Propagation Paper Award. He was Vice-Chair of the European Conference on Antennas and Propagation 2007.

Martin Koch was born in Marburg, Germany, in 1963. He received the Diploma and Ph.D. degree in physics from the University of Marburg, in 1991 and 1995, respectively.

From 1995 to 1996, he was a post-doc at Bell Labs/Lucent Technologies, Holmdel, NJ. From 1996 to 1998, worked in the Photonics and Optoelectronics Group at the University of Munich. Since 1998, he is an Associate Professor in the Electrical Engineering Department, Technical University of Braunschweig, Braunschweig, Germany. In 2003, he took a three month sabbatical at the University of California in Santa Barbara. In 2006, he founded the Terahertz Communications Lab (TCL) and in 2007 the German Terahertz Center (DTZ) followed, of which he currently is President.

Dr. Koch was awarded the Kaiser-Friedrich Research Price in 2003.