The potential of dielectric mirrors as key elements in future non-line-of-sight indoor terahertz communication systems

R. Piesiewicz, K. Baaske, K. Gerlach, M. Koch, T. Kürner

Abstract— **We present results of transfer matrix simulations of the reflectivity of dielectric mirrors in the THz range. The potential of dielectric mirrors as key elements in future non-line-of-sight indoor communication systems is demonstrated with ray-tracing simulations. The channel properties are derived for the case when dielectric mirrors are used as wall paper and for the case without them. Our simulations show that the indirect transmission paths between a transmitter and a receiver will provide a significantly enhanced signal coverage when mirrors are present.**

Index Terms **— submillimeter wave communication, terahertz systems, dielectric mirrors, ray tracing, channel characterization**

I. Introduction

Short range wireless communication systems are expanding at a rapid rate, finding applications in offices, congested urban areas and homes. The development of wireless local area networks is accompanied by an increasing demand for higher data rates. This in turn entails the necessity to develop communication systems which operate at higher frequencies. Currently WLAN work at a few GHz, while systems operating at several ten GHz appear already feasible. It can be expected that wireless short-range communication networks will soon push towards the THz frequency range and that systems which support very large bandwidth communications with gigabit data rates will be developed in a few years time.

Since THz radiation is strongly absorbed by the atmosphere and free-space path losses are high, working distances may be short and individual THz pico-cells may cover only single rooms or one building at the most. Furthermore, these systems will require high directivity antennas and hence will depend on an unobstructed line-of-sight between a transmitter and a receiver. However, a practical indoor THz communication system must be robust against shadowing, as moving people or other objects may block the direct line of sight link. Thus, for reliable operation, such a system should also allow non-line-of-sight (NLOS) transmissions, realized with directed reflections from the walls or other objects. Considering the small wavelengths in the THz range and the roughness of indoor walls, it can be expected that such reflections have significant diffuse contributions. Hence, the power will be inefficiently scattered, the directivity of antennas will be lost and it will be rather difficult to obtain gigabit data rates. Recently, flexible all-plastic mirrors, supporting specular reflections in the THz range have been demonstrated [1]. They are cheap and easy to produce and can be used as frequency selective wall-paper to enhance the reflectivity of walls and hence facilitate NLOS communication in a THz cell.

This paper is organized as follows. In Section II we discuss the fundamentals of dielectric mirrors and the transfer matrix approach to calculate their reflectivity. In Section III the results of transfer matrix simulations of the mirror reflectivity for different angles of incidence, polarization and frequencies are shown. Furthermore, the influence of the variation of the mirror parameters on its reflectivity is investigated. In Section IV the potential of dielectric mirrors is shown with ray-tracing simulations of indoor terahertz channel parameters for the cases with and without them. Section V concludes the paper.

II. Dielectric Mirrors

Dielectric mirrors are well known from optical frequencies. They consist of a stack of pairs of different dielectric materials. In Fig. 1 a structure consisting of 3.5 pairs is displayed [2].

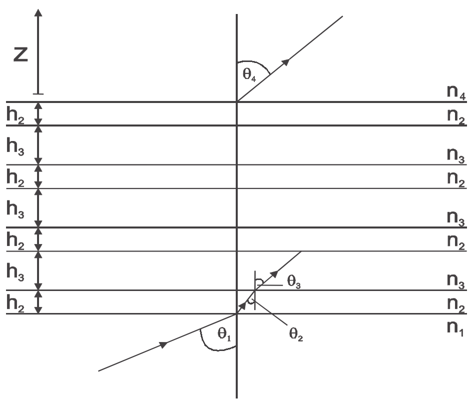

Fig. 1. Schematic of a dielectric mirror consisting of 3.5 pairs [2].

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The layer designated by n_2 and h_2 occurs four times whereas the layer designated by n_3 and h_3 appears three times resulting in 3.5 alternating layers. The two materials involved have refractive indexes of n_2 and n_3 ($n_2 > n_3$) and thickness of h_2 and h_3. In Fig. 1 n_1 is a refractive index of an ambient medium and n_4 that of a substrate medium.

In the following we consider a plane wave incident at an angle θ as depicted in Fig. 1. At each transition from one refractive index to another the wave is partially transmitted and partially reflected. If the condition

$$n_2 h_2 = n_3 h_3 = \frac{\lambda_0}{4} \tag{1}$$

holds, the optical thickness of the two materials matches. It means that all reflected components including those originating from internal reflections interfere constructively at the given free-space wavelength of λ_0 and odd order multiples (1,3,5, …) of λ_0. This condition potentially results in a very high reflectivity of a mirror.

The reflectivity and transmission of a mirror can be calculated by determining the propagation of a plane wave through the stratified medium with the help of a transfer matrix, the so called characteristic matrix.
The characteristic matrix of a single layer is given by

$$M_j = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \begin{bmatrix} \cos\delta_j & \dfrac{-i\sin\delta_j}{p_j} \\ -ip_j \sin\delta_j & \cos\delta_j \end{bmatrix} \tag{2}$$

where $\delta_j = \frac{2\pi}{\lambda_j} n_j h_j \cos\theta_j$ is the optical thickness of each layer, λ_j denotes wavelength in the given medium and θ_j is the angle of refraction in the j_{th} layer [3]. Depending on the layer referred to, j takes on the values of 2 or 3, whereas i is the square root of –1. In (1) p_j is given by

$$p_j = n_j \cos\theta_j \tag{3}$$

for TE polarized waves and by

$$p_j = \frac{\cos\theta_j}{n_j} \tag{4}$$

for TM polarized waves. The characteristic matrix M_{23} of one double layer with n_2, n_3, h_2, h_3 can be expressed by $M_{23}=M_2M_3$. Thus, the characteristic matrix of the dielectric mirror consisting of a stack of N double layers has the following form

$$M_{N(23)} = \underbrace{M_{23} \cdot M_{23} \cdots M_{23}}_{Ntimes} \tag{5}$$

The reflection coefficient of a mirror can be obtained from (5) and is given by

$$r = \frac{(M_{11} + M_{12}p_4)p_0 - (M_{21} + M_{22}p_4)}{(M_{11} + M_{12}p_4)p_0 + (M_{21} + M_{22}p_4)} \tag{6}$$

where p_0, p_4 are the values for ambient and substrate media corresponding to (3) and (4) for TE and TM polarization respectively. The elements of M in (6) refer to the characteristic matrix of the multilayer structure in total.

A transmission measurement for a structure which contains 4.5 pairs of materials with the following parameters: $n_2=2.6$, $h_2=200\mu m$, $n_3=1.33$, $h_3=130\mu m$ [2] is shown in Fig. 2.

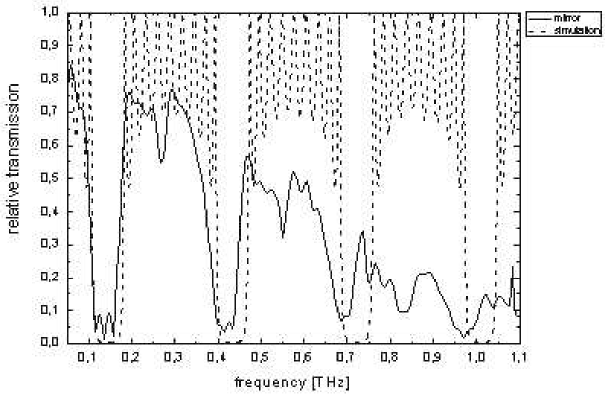

Fig. 2. Results of transmission measurement and simulation of a dielectric mirror with $n_2=2.6$, $h_2=200\mu m$, $n_3=1.33$, $h_3=130\mu m$ [2].

The solid line in Fig.2 shows results of mirror measurements. The transmission of the measured mirror decreases with the increase in frequency which can be attributed to the scattering. However, the foils were arbitrarily taken from commercially available ones. No emphasis was put on the quality of the material. The dashed line in Fig. 2 shows the simulation of the mirror transmission. The discrepancy between the measurement and the simulation of the mirror can be attributed to the measurement error of the mirror parameters on one hand and to the fact that constant values of the refractive indexes were taken for the foils and no account was made for their frequency dependence.

III. Results of Mirror Reflectivity Simulations

For applications in directed NLOS communication scenarios a dielectric mirror should have good reflective properties in a broad range of angles of incidence. Such a mirror is called omni-directional and can be obtained by a proper choice of its parameters, i.e. refractive indexes and thickness of layers [4].

In the following, a mirror designed for a center frequency of 300 GHz is investigated for its reflective properties. The chosen frequency corresponds to a relatively low atmospheric attenuation and hence would be a good candidate for a carrier frequency for the potential THz communication system. The mirror is composed of 8.5 pairs of foils with refractive indexes of $n_2=2.5$, $n_3=1.5$ and thickness $h_2=107\mu m$, $h_3=178\mu m$.

A. *Frequency and angular dependence of the mirror reflectivity*

The results of simulations of the mirror reflectivity are presented in Fig. 3 and 4 for TE and TM polarization respectively. The reflectivity is shown as a function of frequency for different angles of incidence.

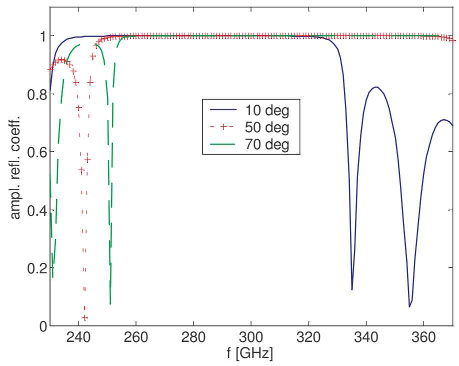

Fig. 3. Mirror reflectivity for TE polarization as a function of frequency for angles of incidence of 10, 50 and 70 degrees.

As can be seen from Fig. 3 and 4 the mirror has an excellent reflectivity over a wide frequency band for all angles. In the case of TE polarization the reflectivity band is centered around 300 GHz with a width exceeding 60 GHz. In the case of TM polarized waves the bandwidth, for which the mirror has very good reflective properties is smaller and amounts to 40 GHz.

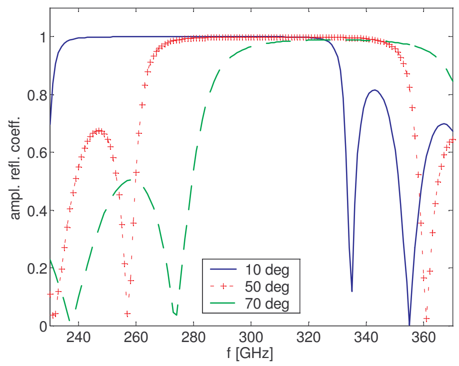

Fig. 4. Mirror reflectivity for TM polarization as a function of frequency for the angle of incidence of 10, 50 and 70 degrees.

The simulation results of the mirror reflectivity as a function of angle of incidence are shown in Fig. 5 and 6 for different frequencies and for TE and TM polarization, respectively.

Fig. 5 and 6 show the omni-directional character of the presented mirror. In the case of TE polarized waves the mirror shows excellent reflective properties in the whole range of angles of incidence and over bandwidth of 60 GHz. In the case of TM polarization the mirror is highly reflecting for the angles of incidence up to 50 degrees if the same bandwidth is considered. Yet, for a smaller bandwidth the mirror is a good reflector up to angles of 90 degrees.

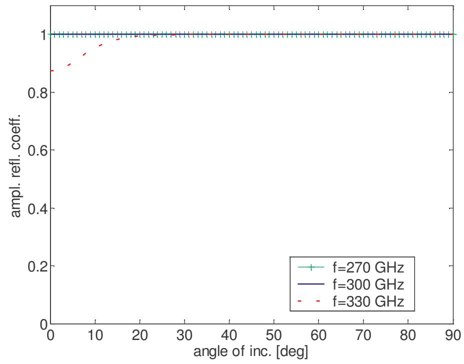

Fig. 5. Mirror reflectivity for TE polarization as a function of angle of incidence for the frequencies of 270, 300 and 330 GHz.

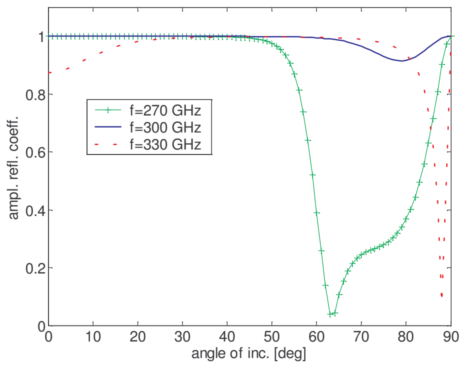

Fig. 6. Mirror reflectivity for TM polarization as a function of angle of incidence for the frequencies of 270, 300 and 330 GHz.

B. *Thickness variation of the dielectric layers*

The thickness of the dielectric layers can deviate from the nominal values. In the following we investigate the influence of a variation of h_2 and h_3. Fig. 7 and 8 show the reflectivity of the mirror at 300 GHz as a function of the angle of incidence and the variation of the thickness of h_2 for TE and TM polarization, respectively. The thickness variations are in the range of ±25% around the nominal value of 107µm.

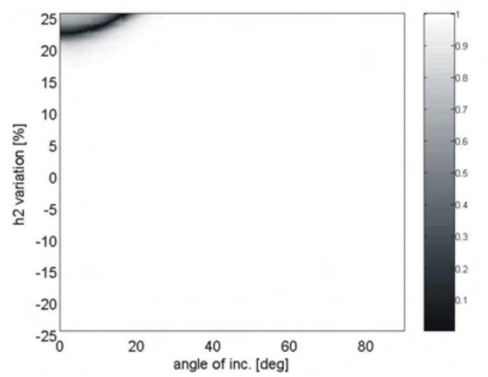

Fig. 7. Mirror reflectivity for TE polarization as a function of the angle of incidence and the variation of the thickness of layer 2.

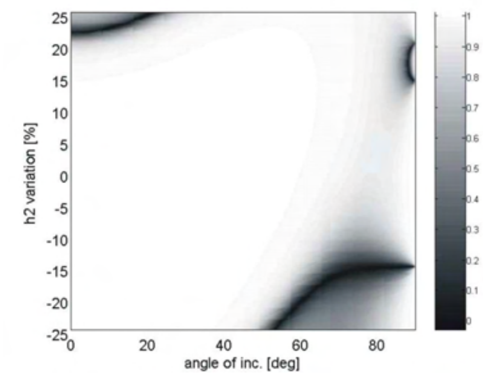

Fig. 8. Mirror reflectivity for TM polarization as a function of the angle of incidence and the variation of the thickness of layer 2.

In the case of TE polarization the mirror reflectivity is less than one only for large positive thickness variations of layer 2 and small angles of incidence. In the case of TM polarization considerable negative thickness variations of layer 2 result in a reflectivity reduction for large incidence angles.

In Fig. 9 and 10 the reflectivity of the mirror at 300 GHz is shown as a function of the angle of incidence and a variation of the thickness h_3 for TE and TM polarization, respectively. The thickness variations are again in the range of ±25% around the nominal value. A comparison with Fig. 7 and 8 shows that thickness variations of layer 3 have similar effect as variation of layer 2.

C. Variation of the refractive index of the mirror layers

In analogy to the thickness variations also the refractive index of mirror layers can deviate from the nominal values. In the following, we investigate the influence of a variation of n_2 and n_3 on the mirror performance. Fig. 11 and 12 show the reflectivity of the mirror at 300 GHz as a function of the angle of incidence and the variation of n_2 for TE and TM polarization, respectively. The n_2 variations are in the range of ±25% around the nominal value of 2.5. In the case of TM polarization negative variations of n_2 greater than 5 % result in a reflectivity reduction. Large angles are more heavily affected. In contrast, reflections under TE polarization are much more immune to variations of the refractive index of layer 2.

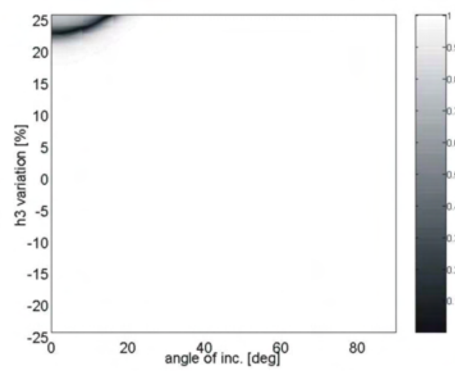

Fig. 9. Mirror reflectivity for TE polarization as a function of the angle of incidence and the variation of the thickness of layer 3.

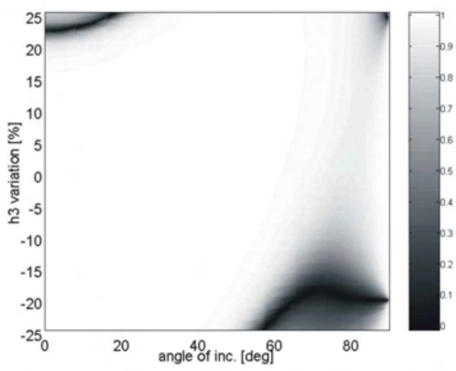

Fig. 10. Mirror reflectivity for TM polarization as a function of the angle of incidence and the variation of the thickness of layer 3.

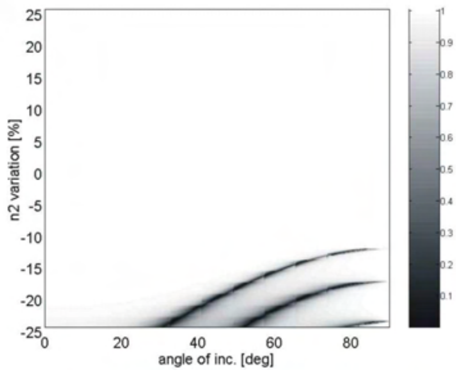

Fig. 11. Mirror reflectivity for TE polarization as a function of angle of incidence and variation of refractive index of layer 2.

In Fig. 13 and 14 the reflectivity of the mirror at 300 GHz is shown as a function of the angle of incidence and the variation of n_3 for TE and TM polarization, respectively. The n_3 variations are in the range of ±25% around the nominal value of 1.5. Here, in the case of TE polarization positive variations of n_3 greater than 15 % result in reflectivity reduction, especially at small angles. In the case of TM polarization both negative and positive variations of n_3 lead to a reduced reflectivity. Large angles are more affected for negative variations, whereas small angles are more for positive ones.

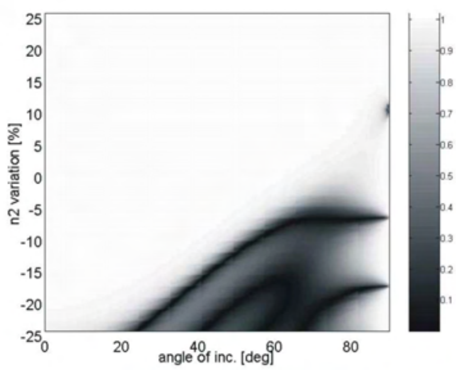

Fig. 12. Mirror reflectivity for TM polarization as a function of the angle of incidence and the variation of refractive index of layer 2.

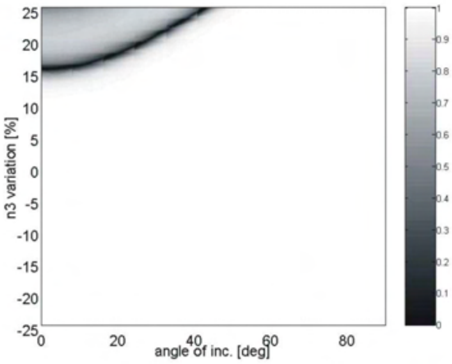

Fig.13 Mirror reflectivity for TE polarization as a function of the angle of incidence and the variation of the refractive index of layer 3.

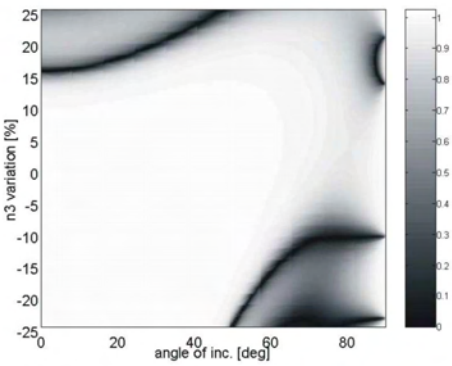

Fig. 14. Mirror reflectivity for TM polarization as a function of the angle of incidence and the variation of the refractive index of layer 3.

IV. RAY-TRACING SIMULATIONS

In the following we present ray-tracing simulations which are preformed to demonstrate the potential of dielectric mirrors as key elements in future non-line-of-sight indoor communication systems at terahertz frequencies. A possible THz communication scenario is shown in Fig. 15. The simulated room is without furniture and there are windows on one of the walls. The walls are covered with plaster. The transmitter, with an output power 0 dBm is centered on the ceiling in the middle of the room with dimensions 6m x 5m x 2.5m. The receiver is about one meter above the ground in the plane z=0.95m. Ray-tracing simulations are performed for the frequency of 300 GHz to derive the properties of the THz propagation channel [5]. The channel characteristics are simulated for the case when dielectric mirrors are used as wall paper and for the case that the walls are made of plaster.

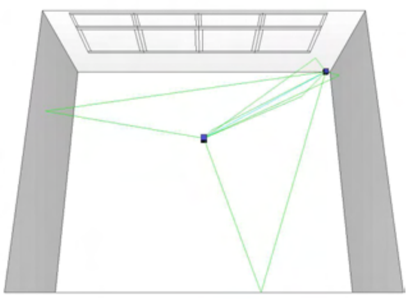

Fig. 15. Three dimensional view of the simulated THz cell scenario.

Fig. 16 and 17 show the power distribution in the plane of the receiver which arise from electromagnetic waves with TM polarization that are reflected once. Fig 16 shows the power level for the case that that walls are covered with dielectric mirrors and Fig. 17 shows the same for the case that no mirrors are present and the walls are covered with plaster. The reflectivity of plaster was measured in a THz-TDS (terahertz time-domain spectrometry) reflection set-up in the 70 – 400 GHz frequency range for different angles of incidence. The measurement results were incorporated as interpolated reflectivity functions into the ray-tracing simulations.

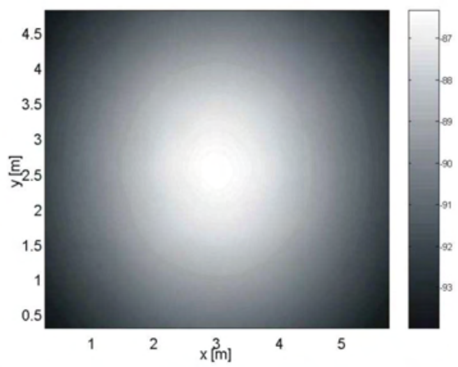

Fig. 16. Power distribution in dBm in the plane z=0.95m of the receiver arising from once-reflected paths. It is assumed that the electromagnetic waves have TM polarization and that the walls are covered by mirrors.

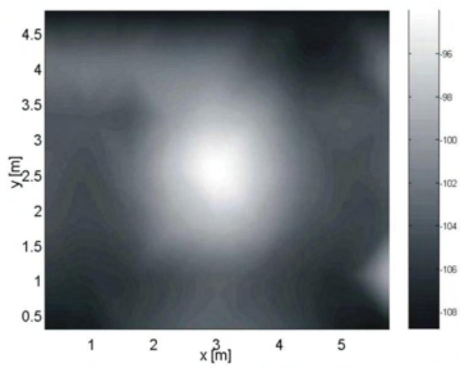

Fig. 17. Power distribution in dBm in the plane z=0.95m of the receiver arising from once-reflected paths. It is assumed that the electromagnetic waves have TM polarization and that the walls are made from plaster.

When the walls are covered with mirrors the received once-reflected power varies between –87 and –94 dBm. If the walls are covered with plaster the received power is considerably lower and varies between –95 and –108 dBm.

If mirrors are present we obtain essentially the same results for TE polarization. Yet, if the walls are covered by plaster the results are different. Fig. 18 shows that case. Note, that the signal level varies between –96 and –98 dBm and is much higher than that displayed in Fig. 17. This difference results from the fact that the reflectivity of TE waves is always higher than that of TM waves. Also the variation of the received power is not as pronounced as for the case of TM polarization. This can be attributed to the non existence of a Brewster angle for TE waves. Nonetheless, the received power level for once-reflected TE waves is considerably smaller if the walls are covered with plaster than if they are covered with mirrors.

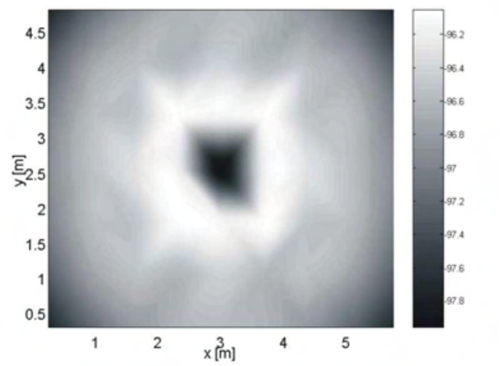

Fig. 18. Power distribution in dBm in the plane z=0.95m of the receiver arising from once-reflected paths. It is assumed that the electromagnetic waves have TE polarization and that the walls are made from plaster.

V. Conclusion

We have presented the results of transfer matrix simulations of the reflectivity of dielectric mirrors in the THz range. A proper choice of the layer thickness and the index of refraction allows us to construct a quasi omni-directional mirror that shows excellent reflective properties for a broad range of incidence angles for both TE and TM polarization. The presented mirror was simulated for a center frequency of 300 GHz. The bandwidth, over which it shows good reflective properties is around 40 GHz. Such mirrors are cheap, easy to produce and could be used as wall paper to enhance the reflectivity of walls in order to facilitate non-line-of-sight propagation in future gigabit data rate THz communication cells.

Furthermore, ray-tracing simulations were performed to derive propagation channel characteristics for the case when walls are covered with dielectric mirrors and for the case without them. Our simulations show that indirect transmission paths between a transmitter and receiver, supported by dielectric mirrors will provide better signal coverage in future THz cells and will make the THz communication channel much more robust against shadowing.

Acknowledgment

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