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Measurement and Analysis of Scattering Effects on Rough Surfaces at 300 GHz

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Abstract

Nowadays, terahertz (THz) communication technology is becoming a research hotspot due to its efficient data transmission capability. With short wavelengths, THz waves exhibit unique propagation properties, including significant scattering phenomena on rough surfaces. In this paper, scattering measurements are conducted on ceramic tile surfaces with different roughness at 300 GHz, using incident waves with different polarizations and incidence angles. Then, the influence of surface roughness on the spatial distribution of THz scattering power is investigated by analyzing the cumulative distribution function (CDF) and the root-mean-square scattering angle spread of the scattering power. The measurement and analysis of THz rough surface scattering in this study provide an important experimental basis for the construction of THz channel models.

1 Introduction

With the continuous exploration and development of THz technology, THz communication (frequency bands from 0.1 THz to 10 THz) has received widespread attention, due to its advantageous characteristics such as large bandwidth, ultra-high data transmission rate [1], and strong security. It is regarded as one of the potential key technologies to enable short-range ultra-high-speed data transmission in future mobile communication systems [2][3].

However, although the THz wave shows great potential for communication applications, its short wavelength leads to some propagation characteristics that are quite different from those of electromagnetic waves in lower frequency bands [4]. Especially, THz waves are more susceptible to surface irregularities, and the scattering effect on rough surfaces may become significant [5]. The authors of [6] propose a THz channel modeling method based on the Fresnel equations and use the natural sensing abilities to predict the surface dielectric properties, with modeling results fitting well with measurements. The authors in [7] evaluated the scattering of rough and smooth surfaces at 1.5 THz based on variation of reflected power. The authors in [8] used the Monte Carlo method to model rough surfaces with different roughness, analyzed the effect of roughness on scattering from THz rough surfaces based on the results of full-wave simulations, and concluded that scattering becomes more pronounced as the roughness increases and the depolarization effect becomes more severe. The above studies provide relatively comprehensive research on rough surface scattering, but more measurements and analysis are still needed for THz rough surface scattering in real physical environments with different incidence angles (θ_i) and polarizations.

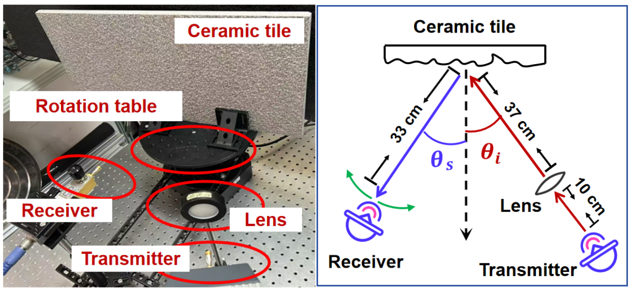
This paper aims to perform a comprehensive measurement and analysis of rough surface scattering at 300 GHz for different incidence angles and polarizations. To further analyze the scattering characteristics, we give the cumulative distribution function (CDF) of the scattering power based on the deviation angle and compare the root-mean-square (RMS) scattering angle spread (SAS), denoted S_{SAS}, to reflect the dispersion effect of the scattering power on the rough surface at different incidence angles. The rest of the paper is structured as follows: A detailed description of the measurement deployment is given in Section II. The results are comprehensively analyzed in Section III. Finally, Section IV summarizes the main conclusions of the full paper.

2 Measurement Campaign

2.1 Measurement Setup

Measurements are an efficient method for obtaining accurate scattering data. As shown in Fig. 1, a measurement scenario for rough surface scattering is deployed. θ_s is the scattering angle. The signal generated by the signal generator is raised to 300 GHz by the frequency multiplier module and fed into the transmitter (Tx). Both the Tx and receiver (Rx) use THz horn antennas, where the Tx is fixed and the Rx is connected to a rotation table via a bracket. Given the significant propagation loss characteristics of THz waves, a lens with a focal length of 10 cm is installed at the front of the Tx to increase the power. The ceramic tile is placed vertically on the rotation table. It is worth noting that the ceramic tile and the Rx can be rotated and controlled independently. The distance between the lens and the ceramic tile is 37 cm, while the distance between the Rx and the ceramic tile is 33 cm. The heights of the Tx, the lens, and the Rx are located at the same height.

The electromagnetic wave radiated by the Tx is linearly polarized. Define the plane formed by the normal vector of the tile and the direction of the incident wave as the incidence plane, then the polarization direction perpendicular to the incidence plane is defined as Transverse Electric (TE) polarization, and the polarization parallel to the incidence plane is Transverse Magnetic (TM) polarization. The antenna polarization can be switched by rotating the transmitter and receiver axially by 90°. In order to study the scattering characteristics of rough surfaces at different incidence angles, three incidence angles of 25°, 45° and 60° are selected for measurement. Rx receives the scattering power in a range of 30° centered in the direction of specular reflection. To ensure the reliability of the data, each measurement is repeated twice and the final result is taken as the average of the two measurements.



(a) (b)

Figure 1. (a) Photograph of the measurement scenario and (b) Schema of measurement scenario.

Because of the addition of a lens at the front of the Tx, to accurately characterize the radiation of the lens-antenna system, we also measure the radiation power of the lens-antenna system. The specific measurement configuration is as follows, Tx and lens are fixed on a rotation table, and Rx is at a distance of 39 cm from Tx. The rotation table is rotated in the horizontal and vertical planes, respectively, and then the received power of the Rx is recorded. Fig. 2 shows the normalized radiated power in the horizontal and vertical planes for the Tx with the lens. The antenna beam is very narrow, ensuring that all the main radiated power of the antenna beam is directed to the tiles.

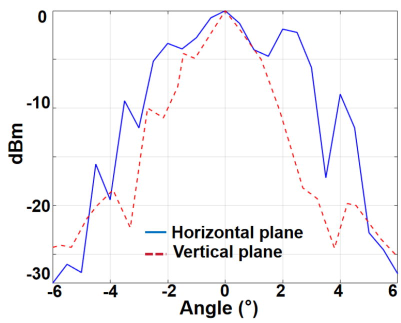


Figure 2. The normalized radiated power of Tx with lens.

2.2 Rough Surfaces

The Ceramic tiles are widely applied in outdoor pavement due to the solidity and aesthetics. However, their electromagnetic and scattering properties in the THz band have been scarcely explored. In this study, four ceramic tiles with different colors and surface roughness are selected for measurement, the size of the tiles is 300 mm × 600 mm. Colors are divided into white and yellow, while roughness is divided into relatively smooth and rough. Therefore, we name these four tiles as White Smooth (WS) tile, White Rough (WR) tile, Yellow Smooth (YS) tile, and Yellow Rough (YR) tile. Fig. 3 illustrates the macroscopic photographs of four tiles that provide rough surface samples for subsequent scattering measurements.

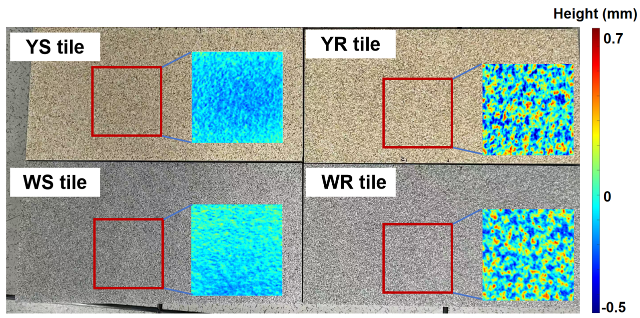


Figure 3. Photographs of the four tiles and heat maps of selected areas.

To accurately obtain the roughness information of the rough surface, a three-dimensional (3D) profiler is used to scan for the height distribution data of the tile surface. We select a area with a size of 100 mm × 100 mm for roughness analysis and show the heat map for the surface height of this area. Two key parameters of surface roughness are calculated: the correlation length (l) and the RMS height (δ) [9]. The l describes the spatial correlation of surface height fluctuations, while the δ indicates the intensity of the height variations. A larger δ and a smaller l implies a rougher surface. Table 1 lists the roughness parameters such as l in the XY direction and δ for the four rough surfaces.

Table 1. Surface roughness of four rough tiles

Roughness	WS	WR	YS	YR
δ [mm]	0.07	0.18	0.06	0.21
X-direction l [mm]	3.28	2.32	1.50	2.05
Y-direction l [mm]	1.64	2.60	2.32	2.46

Notably, at 300 GHz, the δ of both the WR tile and the YR tile is much larger than the Rayleigh criterion [8], predicting a significant scattering effect on rough surfaces.

3 Analysis of Scattering Results

In this section, the measurement results of THz rough surface scattering are shown and the scattering power CDF and the S_{SAS} are compared for various conditions.

The scattering power is measured for the four rough tiles at three incidence angles of 25°, 45°, and 60°. Fig. 4

and Fig. 5 show the scattering measurements for TE polarization and TM polarization, respectively. Compared to relatively smooth surfaces, the peak scattering power on rough surfaces is significantly lower, and the local maximum of the power is more likely to occur farther away from the specular reflection direction, suggesting that an increase in surface roughness leads to a more pronounced diffusion effect of the scattering power. It is worth noting that the results for different polarizations exhibit distinct angle-dependent properties. For TE polarization, the scattering power gradually increases with the incidence angle, whereas for TM polarization, the scattering power decreases as the incidence angle increases. In particular, no significant scattering power is detected on all four rough surfaces when the incidence angle reaches 60° for TM polarization. This may be because the incidence angle is close to the Brewster angle [10] of the material, resulting in an extremely low reflection coefficient. For WS and YS tiles, the amplitude and distribution of the scattering power at the same incidence angle and polarization match well, suggesting that they exhibit similar electromagnetic properties. In contrast, as roughness increases, the scattering power of WR and YR tiles becomes weaker and more random.

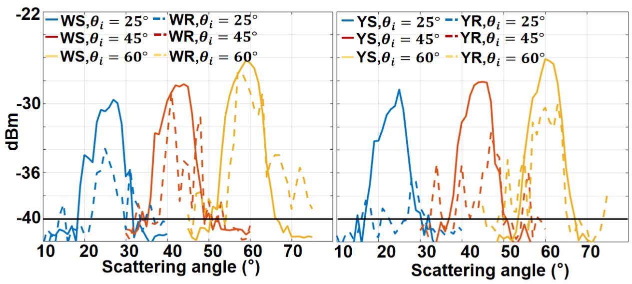


Figure 4. Measurements at different incidence angles for TE polarization, solid lines represent relatively smooth surfaces and dashed lines represent rough surfaces.

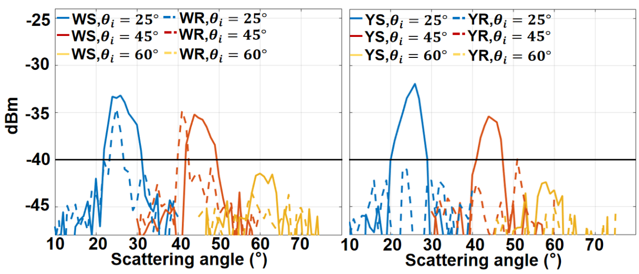


Figure 5. Measurements at different incidence angles for TM polarization, solid lines represent relatively smooth surfaces and dashed lines represent rough surfaces.

Since the power below -40 dBm is close to the noise, we consider signals with power above -40 dBm as valid. The deviation angle is defined as the angle between the scattering direction and the specular reflection direction. The values of the scattering power with the same deviation angle are summed. Fig. 6 and Fig. 7 show the CDF of the scattering power at TE and TM polarization, respectively. It can be observed from Fig. 6 that for TE polarization, the CDF curves are steeper for the relatively smooth surface at all three incidence angles, which indicates that the scattering power is mainly concentrated around the specular reflection direction. In contrast, the CDF curves for rough surfaces show a much flatter distribution, which confirms that the surface roughness leads to a more dispersed scattering power. As shown in Fig. 7, due to the low scattering power at TM polarization, only a few scattering angles have the signal power exceeding the threshold. Therefore, the dispersion effect of the scattering power at TM polarization is not significant compared to TE polarization. Particularly, the scattering power from all four rough surfaces is weaker than the threshold at the incidence angle of 60°, so the CDF is not demonstrated.

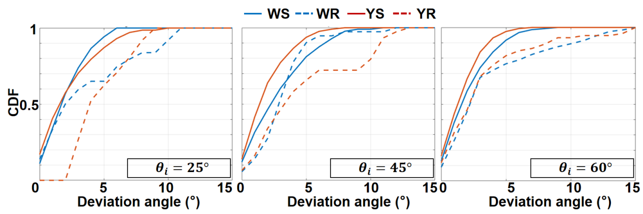


Figure 6. Scattering power CDF for TE polarization.

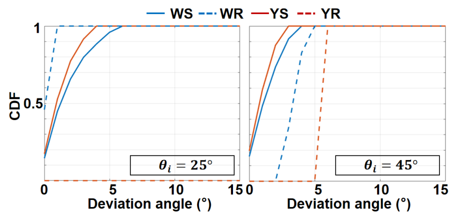


Figure 7. Scattering power CDF for TM polarization.

To quantitatively characterize the THz scattering on rough surfaces, the S_{SAS} is introduced in this paper to effectively quantify dispersion of the scattering power distribution in the angular domain, which is calculated by

$$S_{\mathrm{SAS}} = \sqrt{\frac{\sum_{n=1}^{N}(\theta_{s,n} - \bar{\theta}_s)^2 P(\theta_{s,n})}{\sum_{n=1}^{N} P(\theta_{s,n})}} \tag{1}$$

where $\theta_{s,n}$ is the n-th scattering angle, P is the scattering power at the corresponding scattering angle, and N is the total number of scattering angles. $\bar{\theta}_s$ is the average scattering angle, which is expressed as:

$$\bar{\theta}_s = \frac{\sum_{n=1}^{N} P(\theta_{s,n})\theta_{s,n}}{\sum_{n=1}^{N} P(\theta_{s,n})} \tag{2}$$

Table 2 demonstrates the S_{SAS} for TE polarization at different incidence angles and different rough surfaces. For the relatively smooth WS tile and YS tile, the maximum difference in S_{SAS} (Δ_{S}) for different incidence angles is 0.25° and 0.6°, while for the rough WR tile and YR tile, the maximun Δ_{S} for different incidence angles is 1.62° and 1.45°. This indicates that the randomness of the scattering power distribution on rough surfaces is enhanced by the increase of roughness, and the variation of the S_{SAS} differences for different incidence angles is more significant. For the same incidence angle, the S_{SAS} for rough surfaces is larger, increasing by $0.78°$-$3.86°$ compared to the S_{SAS} for relatively smooth surfaces. It is indicated that the roughness has a large effect on THz rough surface scattering, and the larger the roughness, the stronger the dispersion effect of surface scattering. For TM polarization, the scattering power from the rough surface is so weak that the S_{SAS} cannot characterize the rough surface scattering properly.

Table 2. S_{SAS} at different incidence angles for TE polarization

θ_i [°]	WS	WR	Δ_S	YR	YS	Δ_S
25	2.90	5.17	2.27	3.09	5.48	2.39
45	3.09	3.87	0.78	2.65	6.51	3.86
60	2.84	5.49	2.65	2.49	5.06	2.57
Maximun Δ_S	0.25	1.62		0.60	1.45	

4 Conclusion

In this paper, the scattering power of four ceramic tiles with different roughness is measured at 300 GHz, and the effect of roughness on the dispersion of the scattering power is analyzed with various conditions. The scattering power CDF curves from rough surfaces are smoother compared to relatively smooth surfaces. The maximum difference in S_{SAS} between rough and relatively smooth surfaces at the same incidence angle reaches $3.86°$, implying that the dispersion effect of the scattering power is more obvious on rough surfaces. Due to the increase of roughness, the scattering power distribution is more random, and the variation of S_{SAS} at different incidence angles may become larger. Additionally, influenced by the electromagnetic parameters of the material, the scattering power from rough surfaces in TE polarization may be stronger than that in TM polarization. The study in this paper will provide crucial measurement data to support the modeling of rough surface scattering in the THz band in the future.

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