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LETTER

300GHz Terahertz Wave Scattering Experiment and Simulation from Slightly Rough Surfaces on Dielectrics

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Abstract Millimeter and terahertz waves have been investigated to provide high-speed and large-capacity wireless communication. However, the short wavelength of such high-frequency bands would result in communication performance degradation due to wave blocking by obstacles and scattering by surrounding objects. In this paper, we focus on terahertz wave scattering from slightly rough surfaces. Scattering from dielectric surfaces was measured at 300GHz by using a simple experimental setup for stable and precise measurement. The measured results are compared with a numerical simulation based on our theory of stochastic functional approach.

Keywords: Wave scattering, 300GHz-terahertz wave, Stochastic functional approach, Dielectric

Classification: Antennas and propagation

1. Introduction

Beyond 5G and 6G systems, millimeter and terahertz waves are expected to be adapted as commercial frequency bands, for high-speed wireless data transmission which requires large bandwidth. However, the transmission performance would be degraded by wave blocking from obstacles as well as by wave scattering from surrounding objects. Wave blocking and reflection can be evaluated by raytracing method which is commonly used in conventional radio communications. However, scattering from everyday items such as desks are normally neglected, because the wavelength of microwave is much larger than roughness of the surfaces of the items. As the wavelength of millimeter and terahertz wave is approximately 1mm, the radio-wave scattering from slightly rough surfaces on structures, which appear flat to humans, would be an important factor for future wireless systems. We had previously conducted a scattering experiment and confirmed the 100GHz radio-wave scattering component from a slightly rough surface on a stone sample [1].

In this paper, we report a 300GHz radio-wave scattering measurement system and results from a scattering experiment on wooden surfaces. The reported roughness of a polished wooden surface is 80μm [2]; scattering from slightly rough surface on woods would occur in the order of roughness 1/10–1/20 of the wavelength at 300GHz. In addition, our mathematical simulations based on stochastic functional approach which describes electro-magnetic wave scattering from slightly rough surface are compared with the experimental results, where we consider the application scope for our theory in terahertz bands to construct high-precision propagation model for future terahertz wave communication.

2. Theory based on stochastic functional approach

The common scattering analysis involves solving Maxwell's equation with appropriate boundary conditions. However, the calculations related to this method are usually complicated. In general, shorter calculation time is preferred such as raytracing method. Moreover, we focused on the scattering from slightly rough surfaces on structures to investigate the effects on the wireless communication quality by such scattering; to this end, we introduced stochastic functional approach which explicit expressions for statistics of scattered waves. This method can express the distribution of polarized scattering waves and prevent the solution divergence associated with surface modes [3].

In this paper, we consider electro-magnetic wave scattering from slightly rough surfaces as shown in Fig.1, where the scattered wave can be expressed by azimuth angle (φ) and elevation angle (θ), where perfect plane wave, the incident angle θ_0 , illuminates the surface.

In this method, we assume that the slightly rough surface has Gaussian distribution, wherein Wiener's nonlinear functional analysis can be adopted. The scattered wave from the dielectric surface is expressed by

$$P_1^{HH} = \frac{4\Lambda(n^2-1)^2\cos^2\theta\cos^2\theta_0\cos^2\varphi}{\left(\sqrt{n^2-\sin^2\theta}+cos\theta\right)^2\left(\sqrt{n^2-\sin^2\theta_0}+cos\theta_0\right)^2} \quad (1)$$

$$P_1^{HV} = \frac{4\Lambda(n^2-1)^2\cos^2\theta\cos^2\theta_0\ (n^2-\sin^2\theta_0)\sin^2\varphi}{\left(\sqrt{n^2-\sin^2\theta}+cos\theta\right)^2\left(n^2cos\theta_0+\sqrt{n^2-\sin^2\theta_0}\right)^2} \quad (2)$$

$$\Lambda = \sigma^2\frac{l^2}{\pi}e^{-l^2\{(sin\theta cos\varphi - sin\theta_0)^2+(sin\theta sin\varphi)^2\}} \quad (3)$$

where Eq. (1) and Eq. (2) represents primary transverse-electric (TE) and transverse-magnetic (TM) polarization component of the TE polarization incidence, respectively [4]. Eq. (3) is the spectrum of the rough surface shape. In these equations, n, σ, and l respectively denote refractive index, surface roughness, and correlation length which are

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normalized by the free space wavenumber (k) at 300GHz.

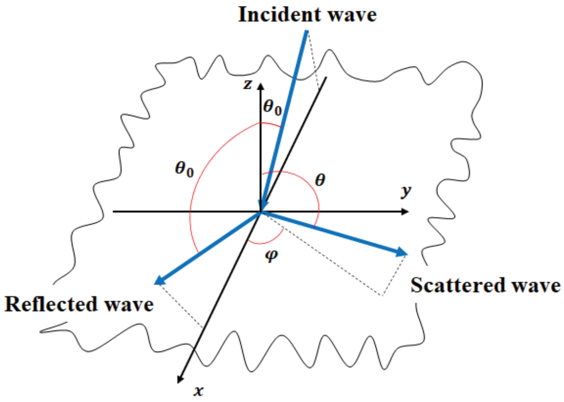

Fig.1 Configuration of wave scattering from a slightly rough surface.

Fig.2 Wooden sample(400×1200mm).

Fig.3 Aluminum plate(400×1200mm).

Figs.2 and 3 show the wooden sample and the aluminum plate which we used in the experiment. Refractive index was measured by THz time domain spectroscopy (ADVANTEST TAS 7500SP). Surface roughness and correlation length were measured using a digital microscope (KEYENCE VHX-8000) and calculated by MATLAB. The measurement results for the samples are shown in Table I.

We conducted the scattering experiment not only on the wooden sample, but also on the aluminum plate with the same dimensions as the wooden sample. Surface roughness of the aluminum plate was much smaller than that of the wooden sample, so that scattering from the aluminum plate could be negligible small. In our experimental setup, received power would include noise from detection devices, and scattered stray beam. Therefore, received power from the aluminum plate would be used as a reference to define the level of background noise in our setup. We can deduce that scattering wave components were successfully measured if the received power level is larger than the background noise level.

Table I Constant parameters of wooden sample and aluminum plate.

	Refractive Index n	Surface roughness $k\sigma$	Correlation length kl
Wooden sample	1.50	0.241(38.14μm)	0.357
Aluminum plate	-	0.0213(3.37μm)	num

3. Experimental Setup

Figs. 4 shows the schematic diagram of our experimental setup, where incident and reflection angles were set to 50 degrees, as shown in Fig. 5. The sample was rotated using a motorized rotation stage between -30 to 30 degrees with 1-degree steps. Consequently, we measured the scattering distribution on the incidence plane, where the azimuth angle (φ) was 0 degree, by changing the “sample angle” which describes how many degrees the sample was rotated, as shown in Fig. 6. In this setup, the antennas, the signal generator and the spectrum analyzer are fixed and alighned firmly, while the samples ware rotated stably and precisely by a computer-controlled rotary stage.

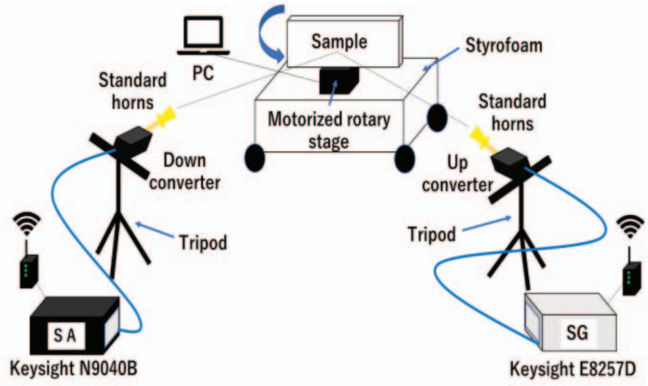

Fig.4 Schematic diagram of experimental setup (SG, signal generator; SA, spectrum analyzer).

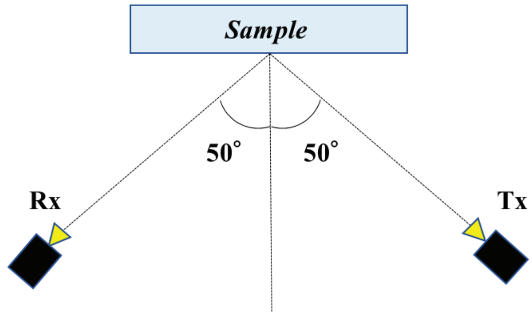

Fig.5 Projection diagram of experimental setup when the sample angle was 0 degrees.

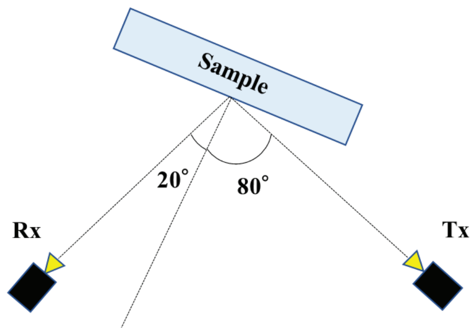

Fig.6 Projection diagram of experimental setup when the sample angle was 30 degrees.

4. Results of the Experiment and Simulation

Figs.7–10 show the results of the experiment and simulation for the wooden sample with four polarizations, where the received power of the aluminum plate and wood were normalized by the power of specular reflected wave on the aluminum plate to compare the simulation results with that of the experiment. In the simulation based on our theory, we focused on wave scattering induced by roughness, while specular reflected wave is not negligible in our experiment. We added the specular component to the calculated scattered wave power distribution by following steps. First, as we changed the incident angle and the detection angle by motorized rotation stage, we multiplied the experiment result of aluminum plate by the reflectance according to the incident angle based on Fresnel equations. Next, we added the power of reflected wave to the simulation result. We conducted this experiment by changing frequencies from 220 to 330GHz with 10 GHz- frequency steps and averaged the received power to suppress the speckle effect.

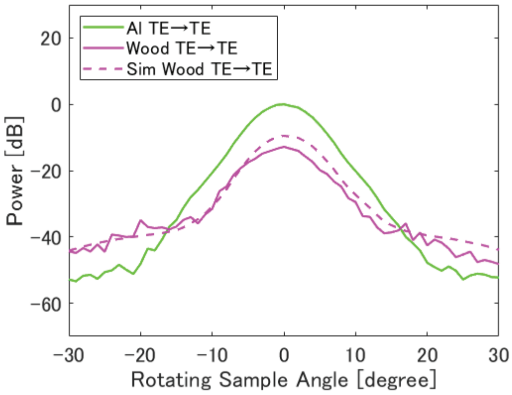

Fig.7 Scattering distribution from wood for TE polarized scattered wave on TE polarization incidence.

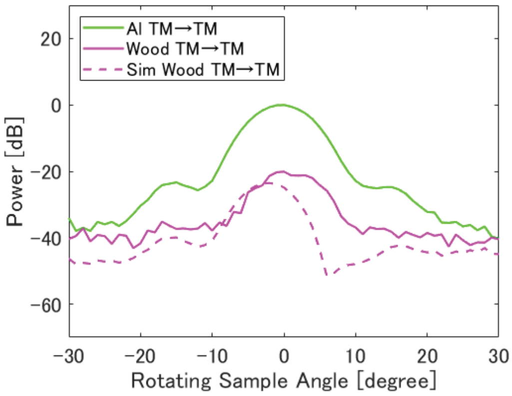

Fig.8 Scattering distribution from wood for TM polarized scattered wave on TM polarization incidence.

Fig. 7 shows that the power level of wood is higher than that of the aluminum plate at ±15 to ±30 degrees of the sample angle, where we deduce that the scattering component for the wooden sample can be found experimentally at 300GHz [5]. In addition, the power level of simulation was close to that of the experiment.

In contrast, Fig.8 shows that the power level of wood is lower than that of the aluminum plate even in the range ±15 to ±30 degrees of the sample angle because of the effect of side lobe of the antenna. As we changed antenna polarization with inserting straight waveguide or twist waveguide (Fig.11), the side lobe of the antenna appeared for H cross-section (Figs.12) [6] and the noise level at ±15 to ±30 degrees of the sample angle was raised, making scattering component disappear. Moreover, the dip point due to Brewster angle is showed in the simulation, beside not in the experiment. We deduce that this reason is the finite beamwidth of the antenna.

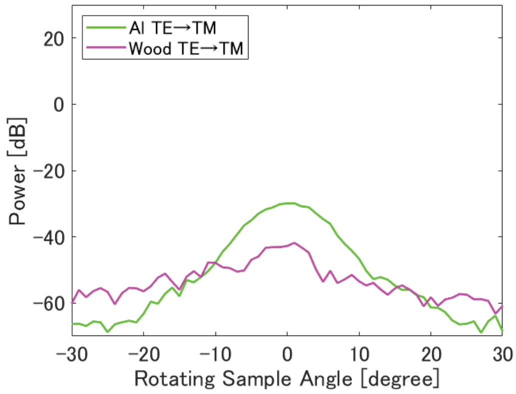

Fig.9 Scattering distribution from wood for TM polarized scattered wave on TE polarization incidence.

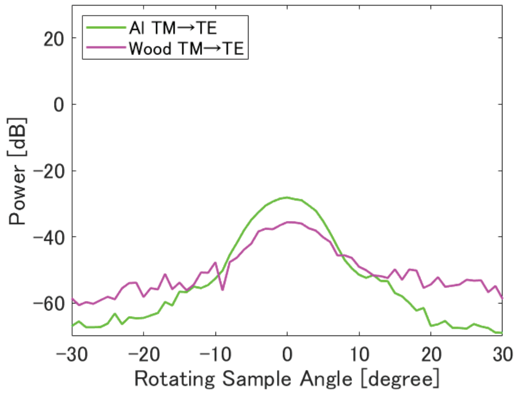

Fig.10 Scattering distribution from wood for TE polarized scattered wave on TM polarization incidence.

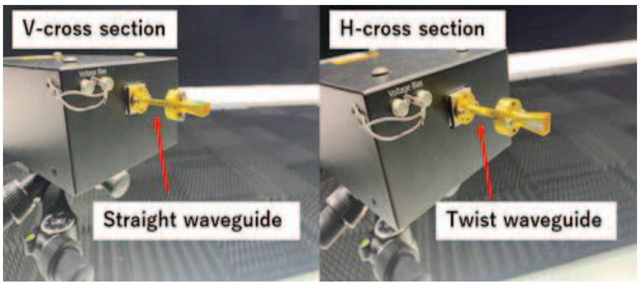

Fig.11 Antenna polarization of standard gain horn antenna used in the experiment.

Figs.9 and 10 show the cross-polarized scattering. The cross-polarized scattering wave power should be zero in the simulation where the second and higher order scattering processes are neglected. The measured receiving power of wood and aluminum plate is approximately -100dBm at ±15 to ±30 degrees of the sample angle, which is close to the noise level of the measurement devices. We deduce the cross-polarized components are due to higher order scattering processes or stray waves in the experimental setup.

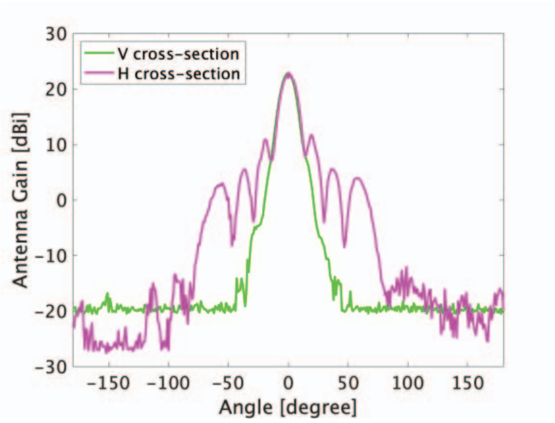

Fig.12 Antenna pattern of standard gain horn antenna used in the experiment [6].

Fig.13 Concrete sample(400×750mm).

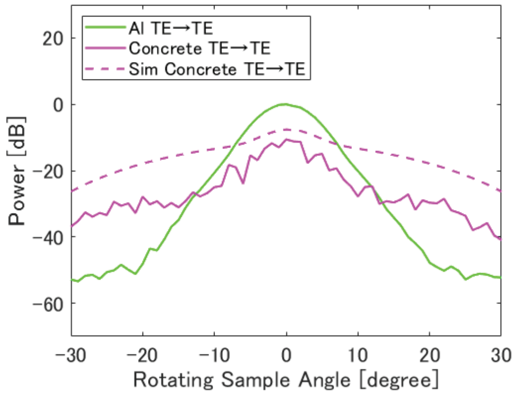

Fig.14 Scattering distribution from concrete for TE polarized scattered wave on TE polarization incidence.

We conducted the same scattering experiment for a concrete sample (Fig. 13). The size of the concrete sample was different from the wooden sample and the aluminum plate because of the load capacity of the experiment system. The surface properties for concrete sample are shown in Table II. Fig. 14 shows that the power level of concrete is higher than that of the aluminum plate at ±15 to ±30 degrees of sample angle, where the scattering component for the concrete sample can be found experimentally at 300GHz. On the other hand, the results of the simulation and experiment were not consistent. In the numerical calculation, we assume that the surface roughness follows a Gaussian shape spectrum as shown in Eq. (3). However, the surface of concrete has regular pattern of horizontal stripes as shown in Fig. 13. We deduce that discrepancy between the simulation and experiment results is due to the non-Gaussian spectrum. Another reason is error in the refractive index for the concrete. The refractive index for the concrete is referred by ITU-R, where this applicable frequency range is 1~100GHz [7]. Moreover, the refractive index depends on the moisture inside the material [8]. Therefore, refractive index for the concrete contains the error and the measurement of refractive index at 300GHz is complicated because of the sample size.

Table II Constant parameters of the concrete sample.

Refractive Index n	Surface roughness $k\sigma$	Correlation length kl
2.29 [7]	0.50(101.12μm)	1.96

5. Conclusion

We conducted scattering experiment and simulation at 300GHz and confirmed the scattering component of wooden and concrete samples. In previous research at 100GHz [1], we constructed a simple experiment setup, where the power level of the simulation was close to that of the experiment within 10dB. At 300GHz, as the detection for scattering component is difficult due to short wavelength, we firmly fixed the transmitter and receiver, where the samples were rotated by the computer-controlled rotary stage. Therefore, we can archive accurate measurement compared to the experiment at 100GHz. The power level of the simulation was close to that of the experiment within 3dB as shown in Fig.7. In addition, surface roughness of the samples is approximately 1/35 and 1/25 of the wavelength at 100GHz and 300GHz, respectively, where the power of scattered wave is same level in both frequencies. As a result, we deduce that our theory can apply to the scattering analysis on slightly rough surfaces at 100GHz and 300GHz, where the scattering distribution at 300GHz could be estimated by the result of that at 100GHz depending on the measurement target and environment.

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