LETTER

Modeling and evaluation of millimeter wave scattering from minimally rough surfaces on stones

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Abstract In recent years, millimeter and terahertz waves have attracted significant attention owing to their potential applications in high-speed wireless communication. However, such waves are susceptible to being scattered from surfaces of surrounding objects because their wavelengths are short and sensitive to even minimal roughness. Therefore, using an electromagnetic wave scattering theory based on the stochastic integral, millimeter-wave scattering distributions from minimally rough surfaces such as stones were investigated in simulations and experiments. Finally, millimeter-wave scattering measurements were compared to experimental and simulation results.

key words: Millimeter-wave, Scattering, Stochastic function, Rough surface

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

The scattering phenomena have been researched for many years [1]. In general, we could neglect scattered component because the power of scattered wave is lower than direct or reflected wave. However, we should consider scattering component for millimeter and terahertz bands, which will be used for transmission in systems beyond the 5th and 6th generations. For such bands, the surfaces of macroscopically flat objects would not be flat because their wavelengths are below or of the order of a few millimeters. For example, if one-tenth of a wavelength causes scattering at 300 GHz, scattering can be caused by a small surface roughness of 100 µm. An example of such a surface is that of polished oak wood that has a surface roughness of approximately 80 µm [2]. Thus, minimally rough surfaces would scatter millimeter and terahertz waves, thereby degrading spectrum transmission of wireless communication. Moreover, specific scattering phenomena such as Brewster’s scattering angle [3, 4, 5], Yoneda peak [6, 7, 8, 9], and quasi-anomalous scattering [3, 10] have been reported theoretically and experimentally in light propagation.

To investigate the characteristics of millimeter and terahertz wave reflection and scattering from common objects (e.g., furniture, stones), we numerically calculated scattering distributions using a stochastic functional method. We also measured the scattering distribution of W-band (75–110 GHz) millimeter waves to verify the numerical calculation.

2. Theoretical formulation

Various studies on wave scattering from random surfaces of varying roughness have been investigated [11, 12]. The Kirchhoff approximation is a common method used to analyze wave scattering from a random surface [13]. However, it is intended for random surfaces with large roughness. Considering small surface roughness, we introduce a method using a stochastic function that describes the distributions of scattered waves using roughness parameters [14, 15]. Using this approach, random electromagnetic (EM) fields can be represented as a functional of Gaussian random surfaces [16]. In addition, we adopt theorems such as the probabilistic Floquet theorem, Hermite polynomial, and Wiener–Ito expansion. With these introductions, the distribution of EM wave scattering can be represented by Wiener kernels that describe a stochastic functional. In other words, EM wave scattering distributions can be obtained by finding the Wiener kernels instead of solving the complicated Maxwell equations.

Under the stochastic functional approach, we consider the scattering configuration as shown in Fig.1. A plane wave, the incident angle of which is θ₀, illuminates a random rough surface on a dielectric substrate. Owing to the roughness of the surface, a scattered wave as well as reflected wave is generated, where scattering distributions are described as functions of the azimuth angle (ϕ) and elevation angle (θ).

Although the detailed derivation is omitted, the scattered wave can be expressed by Eqs. (1)–(6), where n, σ, and l denote the refractive index, surface roughness, and correlation length, respectively [17]. Eq. (1) and Eq. (2) represent transverse-electric (TE)-polarized scattering, and Eq. (3) and Eq. (4) represent transverse-magnetic (TM)-polarized scattering. For simplicity, we only consider the

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first order scattering that dominates the EM wave scattering induced by incidence on a random dielectric surface.

![Diagram of EM wave scattering](image)

$$p^H_1 = \frac{\Lambda_1 \cos^2 \varphi}{(\sqrt{n^2 - \sin^2 \theta} + \cos \theta)^2 (\sqrt{n^2 - \sin^2 \theta_0} + \cos \theta_0)^2}$$  \hspace{1cm} (1)

$$p^{HV}_1 = \frac{\Lambda_1 (n^2 - \sin^2 \theta_0) \varphi}{(\sqrt{n^2 - \sin^2 \theta} + \cos \theta)^2 (\sqrt{n^2 - \sin^2 \theta_0} + \cos \theta_0)^2}$$  \hspace{1cm} (2)

$$p^{VH}_1 = \frac{\Lambda_1 (n^2 - \sin^2 \theta) \varphi}{(n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta})^2 (\sqrt{n^2 - \sin^2 \theta_0} + \cos \theta_0)^2}$$  \hspace{1cm} (3)

$$p^{VV}_1 = \frac{\Lambda_1 (n^2 \sin \theta_0 \sin \theta - \sqrt{n^2 - \sin^2 \theta} \sqrt{n^2 - \sin^2 \theta_0} \cos \varphi}{(n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta})^2 (n^2 \cos \theta_0 + \sqrt{n^2 - \sin^2 \theta_0})^2}$$  \hspace{1cm} (4)

$$\Lambda = a^2 l^2 \pi \int \psi_{12} \left[ (\sin \theta \cos \varphi - \sin \theta_0)^2 + (\sin \theta \sin \varphi)^2 \right]$$  \hspace{1cm} (5)

$$\tau = 4(n^2 - 1)^2 \cos^2 \theta \cos^2 \theta_0$$  \hspace{1cm} (6)

In this study, we obtained the surface roughness, correlation length, and refractive index for stone (granite) sample shown in Fig. 2. Surface roughness was measured using a digital microscope, KEYENCE VHX-8000. In addition, correlation length, which represents the horizontal distance in the direction in which the autocorrelation function decays fastest to 0.2 or less, was calculated and charted, as illustrated in Fig.3. MATLAB was used for this purpose after acquiring the surface height data using the KEYENCE microscope. Finally, refractive index was reported in the relevant literature [18, 19]. The resulting values are listed in Table. I, with surface roughness and correlation length being normalized by wavelength.

| Table I. Constants for stone sample shown in Fig.2. |
|-----------------------------------------------|
| Refractive index, $n$ | 2.4 [18, 19] |
| Surface roughness, $h$ | 0.047 |
| Correlation length, $l$ | 0.67 |

Another method to analyze scattering from random surfaces with small roughness is the surface perturbation approach. It solves a scattered wave field using a power series expansion with roughness parameters [20, 21, 22, 23]. However, the solution obtained by this approach diverges when the rough surfaces hold EM wave propagation models; several methods have been proposed to overcome this limitation, such as the renormalization theory in quantum physics [24, 25, 26]. In contrast, the solution obtained by the adopted stochastic function approach does not diverge [27, 28]. Thus, the stochastic functional approach is applicable to a variety of cases.

3. Simulations results

Figures 4-9 show the simulation results for $\varphi = 0$, 30, and 75°, where the incident wave angle, $\theta$, was set to 60°, and all physical quantities were normalized to have an incident power of 1.

Dips in the power range near $\theta = 78°$ in Fig. 5, $\theta = 60°$ in Fig. 7, and $\theta = 16°$ in Fig. 9 correspond to Brewster’s scattering angles, at which the scattering component becomes zero. When the incident angle matches the ordinary Brewster’s angle, Brewster’s scattering angle is equal to the ordinary Brewster’s angle. This is the reason the dip angles...
are named Brewster’s scattering angles. However, the characteristic of Brewster’s scattering angle is dependent on not only the refractive index but also incident angle, which is different from that of the ordinary Brewster’s angle [17]. The simulation results show that the scattering distribution of TM polarization incidence has a Brewster’s scattering angle, but that of TE polarization incidence does not. Furthermore, it must be noted that the power of the scattered wave ranges from −40 to −60 dB in the simulation results shown in Fig. 8 and 9.

4. Experiment results

We conducted scattering experiments for the stone sample shown in Fig. 2. Subsequently, the same experiment was conducted using the aluminum plate shown in Fig. 10. The second experiment was conducted to verify the scattering from the stone sample by contrasting it with the absence of scattering from flat surfaces such as the aluminum plate. Measurements from the aluminum plate experiment revealed the noise floor of the experimental system in addition to the reflection component as reference. The
 experimental setup (Fig. 11) maximized the use of wood and Styrofoam to prevent undesired reflection from the metal plate.

Table. II lists the parameters of our experiment. The wave frequencies were step-swept from 75 to 110 GHz, and 100 measurements were obtained per frequency. For the analysis, we averaged the power of the scattered wave for different frequencies at each elevation angle. This approach was adopted to compensate for the “speckle effect” caused by short wavelengths [29, 30].

Table II. Parameters of experiment

| Incident angle θ₀ (°) | 60 |
|-----------------------|----|
| Azimuth ϕ (°)         | 0, 30, and 75 |
| Elevation θ (°)       | 0, 20, 40, 50, 60, 70, and 90 |
| Frequency (GHz)       | 75, 80, 85, 90, 95, 100, 105, and 110 |
| Polarization          | TE→TE, TE→TM, TM→TE, and TM→TM |

The results of the scattering experiment are shown in Figs. 14-19. For the experiment, the incident wave power was −33.5 dBm and the result of scattered wave power was normalized by this value. Furthermore, to compare the result of the experiments using the stone sample and aluminum plate, the result of aluminum plate experiment is connected with a line, as a reference.

Figures. 14–17 show that the power level of the stone sample is lower than that of the aluminum plate for cross-polarized and co-polarized scattering at ϕ = 0° and 30°. This can be attributed to the fact that the scattered wave was drowned out by the higher-powered reflected wave that could not be set to zero in this experiment. Consequently, the presence of a scattering component could not be confirmed.

Figures 18 and 19 show that the power level of the stone sample is higher than that of the aluminum plate for cross-polarized and co-polarized scattering at ϕ = 75°. As scattering phenomena does not occur in the case of the aluminum plate, scattering from the stone sample can be confirmed at ϕ = 75°, where the reflected wave component is small.

As shown in Figs. 18 and 19, the power level of the scattered...
wave ranges from $-35$ to $-55$ dB, which is close to the range obtained from the simulations. The error in the range can be attributed to the fact that a plane wave perfectly incident on the sample was considered in the simulations. As incident waves are not perfect plane waves in experiments owing to the beam width of the transmitting and receiving antennas, the power range of the scattered wave in the experiment is different to that in the simulation.

5. Conclusion

We structured an experimental setup with FWG, which is flexible and has robust transmission loss that do not vary significantly, and conducted scattering simulations and experiments for millimeter waves. We confirmed the presence of a scattering component at $\varphi = 75^\circ$ both theoretically and experimentally and found the power levels of the scattered waves in the simulations and experiments to
be similar. In the simulations, Brewster’s scattering angles, which have been reported in light scattering, were confirmed in case of millimeter waves. In future work, simulations and experiments for terahertz waves will be conducted.

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