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The influence of surface roughness on conductor at terahertz frequencies

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ABSTRACT

In this paper, a theoretical study of the influence of surface roughness on conductor is proposed at terahertz frequencies. By using the analytic small perturbation method, the effects of a random rough surface on the absorption by a metallic surface at terahertz frequencies are analyzed. And the effect of rough surface on reflectivity and power spectral density are also demonstrated. The numerical results are very useful for the development of terahertz devices and terahertz material.

1. Introduction

Terahertz (THz), locating between the infrared and microwave wave bands in the electromagnetic spectrum is one of the hot research issues because of its great potential applicability in many scientific and technological fields. The interest in THz technology has strongly increased in the last years with diverse applications in the fields of biotechnology, spectroscopy and imaging [1–4]. Efficient guided THz transmission solutions are still under investigation. Many kinds of THz waveguides have been presented, such as metal waveguide [5–10], dielectric waveguide [11–13], and so on. For THz guiding structure, there are three basic types of loss: radiation, dielectric, and conductor loss. Radiation loss, such as excitation of surface wave modes along the dielectric substrate, is only significant at discontinuities in planar circuits. This loss can be lessened by reducing the substrate height, which decreases the amplitudes and number of these modes. Dielectric loss has been analyzed in the past [14–17], and this loss is small compared to the total loss. Thus, the dominant loss mechanism is the conductor loss, which is dependent on the surface roughness parameter of metal. And the effect of rough surface of metal at terahertz frequencies is the emphasis of this paper.

2. Effect of rough surface on reflectivity

A firm understanding of the scattering behavior of terahertz waves from rough surfaces is important to the development of terahertz remote sensing and imaging applications. Electromagnetic waves that are incident on a smooth surface undergo reflection in the specular direction. It is well known, however, that if the surface is even slightly rough, electromagnetic waves are scattered diffusely and result in a loss of intensity in the specular direction [18,19]. The roughness of a surface is primarily characterized by the root mean square (RMS) roughness parameter R. Roughness can be either random or periodic, or a combination of both. The reflectivity of a rough surface R_{rough} in the specular direction is given by the Kirchhoff approximation:

$$R_{\text{rough}} = R_{\text{smooth}} e^{-(4\pi\sigma k \cos\theta)^2} \quad (1)$$

where R_{smooth} is the reflectivity of a perfectly smooth surface ($\sigma = 0$), θ is the angle of incidence, and k is the wavenumber [20–24].

When an electromagnetic wave bounces off the interface of air and metal, the reflectivity of metal with smooth surface at vertical incidence has the form [25]

$$R_{\text{smooth}}(\omega) = \left| \frac{\sqrt{\varepsilon_{\text{r}}(\omega)} - 1}{\sqrt{\varepsilon_{\text{r}}(\omega)} + 1} \right|^2 \quad (2)$$

Where the complex dielectric constant is expressed as

$$\varepsilon_{\text{r}}(\omega) = \varepsilon_{\text{b}} + i\frac{\sigma(\omega)}{\varepsilon_0\omega} \cong i\frac{\sigma_0}{\varepsilon_0\omega} \quad (3)$$

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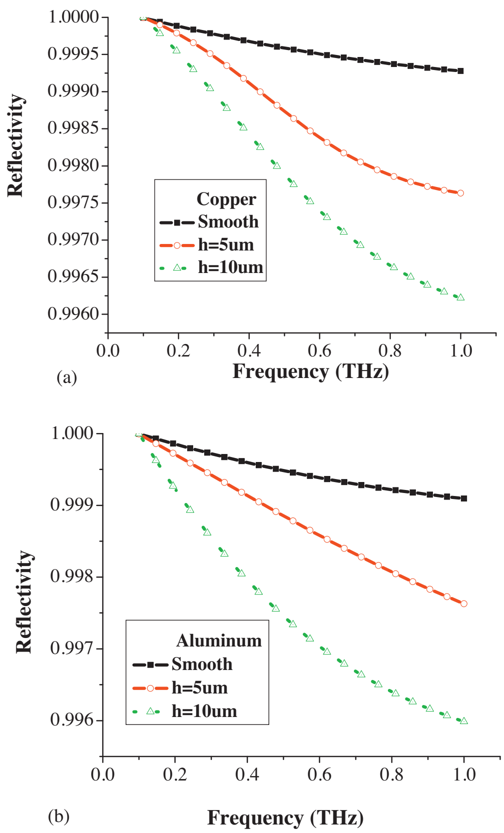

Fig. 1. Reflectivity versus frequency for different rough sample. (a) Copper; (b) aluminum.

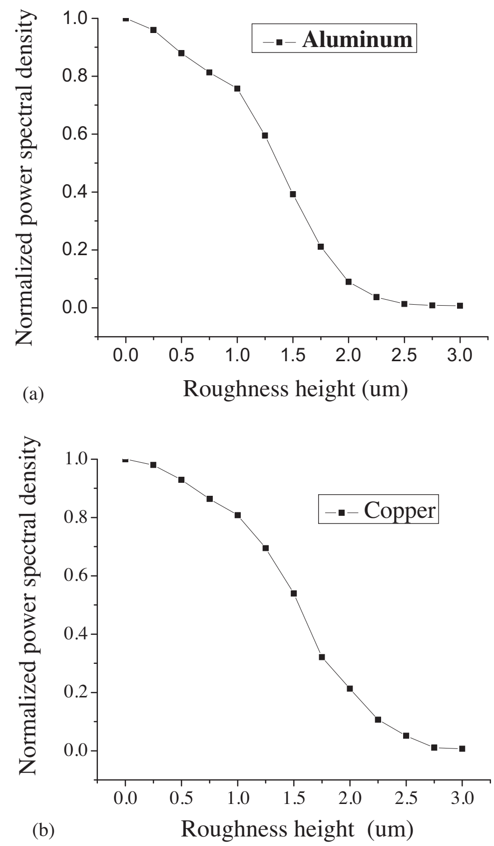

Fig. 2. Normalized power spectral density of aluminum and copper for different rough height. (a) Aluminum; (b) copper.

where ε_b is the contribution from bound electrons and σ_0 is the conductivity of metal. Since $\sigma_0/\varepsilon_0\omega \gg \varepsilon_b$ in the THz region, the equation for the reflectivity is reduced to

$$R_{mooth}(\omega) \cong 1 - \sqrt{\frac{8\varepsilon_0\omega}{\sigma_0}} \tag{4}$$

Fig. 1 shows how the reflectivity at vertical incidence depends on frequency for different rough sample surfaces. As one may expect, low frequencies are not affected the reflectivity. But with the increasing of frequencies, the reflectivity has a stronger decrease than smooth samples. For aluminum and copper, σ_0 is 3.66×10^7 S/m and 5.8×10^7 S/m, respectively. With the different of metal characteristic, the influence of frequency and rough surface on the reflectivity of aluminum is stronger than copper obviously.

3. Effect of rough surface on power spectral density

For a two-dimensional (2-D) problem of random rough surface, the height function $f(x)$ is treated as a stationary random process. The two point ensemble average of the random process is

$$\langle f(x_1)f(x_2)\rangle = h^2 C(|x_1 - x_2|) \tag{5}$$

where h^2C is the correlation function, h is the rough height. Two common correlation functions are the Gaussian correlation function with $C(x) = \exp(-x^2/l^2)$ and exponential correlation function with $C(x) = \exp(-x/l)$, where l is the correlation length. The exponential correlation profile appears significantly rougher than that for the Gaussian correlation function. In generating the roughness profiles [26], we use the spectral density function $W(k_x)$ which is the Fourier transform of the correlation function. The power spectral density of the Gaussian correlation function is given by $W(k_x) = (h^2 l/2\sqrt{\pi})\exp(-k_x^2 l^2/4)$.

In Fig. 2, we show the calculated results of power spectral density of aluminum and copper for different rough height. From the results, a conclusion can be proposed that with the increasing of roughness height of metal surface, electromagnetic waves are scattered diffusely and result in a loss of power spectral density. From Fig. 1, we can obtain that the influence of frequency and rough surface on the reflectivity of aluminum is stronger than copper obviously. Then the power spectral density of copper is stronger than aluminum, as shown in Fig. 2.

4. Effect of rough surface on absorption by conductor

Consider a random rough surface profile $z = f(x)$. Let ψ be the magnetic field that is in the y direction. Then

$$\psi(x, z) = \int_{-\infty}^{\infty} dk_x \exp(-jk_x x) + jk_{1z}z)\tilde{\psi}(k_x) \tag{6}$$

where $k_{1z} = \sqrt{k_1^2 - k_x^2}$ and $k_1 = (1 - j)/\delta$. Here, δ is the skin depth $\delta = \sqrt{2/\omega\mu\sigma}$. We use a second order small perturbation method, setting

$$\tilde{\psi}(k_x) = \tilde{\psi}^{(0)}(k_x) + \tilde{\psi}^{(1)}(k_x) + \tilde{\psi}^{(2)}(k_x) \tag{7}$$

As shown in Ref. [27], we assume that the magnetic field on the surface $z = f(x)$ is a constant H_0, then

$$H_0 = \int_{-\infty}^{\infty} dk_x \exp[-jk_x x + jk_{1z}f(x)]\tilde{\psi}(k_x) \tag{8}$$

Balancing (8) to second order gives

$$\tilde{\psi}^{(0)}(k_x) = H_0\delta(k_x) \tag{9-a}$$