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Measurement of Refractive Index for High Reflectance Materials with Terahertz Time Domain Reflection Spectroscopy *

SUN Wen-Feng(孙文峰)^{1**}, WANG Xin-Ke(王新柯)², ZHANG Yan(张岩)^{1***}

¹Beijing Key Lab for Terahertz Spectroscopy and Imaging, Key Laboratory of Terahertz Optoelectronics (Ministry of Education), Department of Physics, Capital Normal University, Beijing 100048

²Department of Physics, Harbin Institute of Technology, Harbin 150001

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A method to measure the refractive index for high reflectance materials in the terahertz range with terahertz time domain reflection spectroscopy is proposed. In this method, the THz waveforms reflected by a silicon wafer and high reflectance sample are measured respectively. The refractive index of the silicon wafer, measured with the THz time domain transmission spectroscopy, is used as a reference in the THz time domain reflective spectroscopy. Therefore, the complex refractive index of the sample can be obtained by resorting to the known reflective index of the silicon and the Fresnel law. To improve the accuracy of the phase shift, the Kramers-Kronig transform is adopted. This method is also verified by the index of the silicon in THz reflection spectroscopy. The bulk metal plates have been taken as the sample, and the experimentally obtained metallic refractive indexes are compared with the simple Drude model.

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Terahertz time domain spectroscopy (TDS) systems including time domain transmission spectroscopy (TDTS) and time domain reflection spectroscopy (TDRS) have been used widely for obtaining optics constants of materials in the region of terahertz, because they are highly accurate, simple, and stable.^[1–5] Both TDTS and TDRS systems have great dependence on the reference waves obtained by scanning the time delay without sample.^[6,7] In addition, in TDTS systems, neither the high absorption nor the high reflectance of the sample is required, so that the terahertz wave can go through properly to reach the accurate results. In the TDRS system where the reference terahertz wave was reflected by a metallic mirror, if the reflectance of the sample is close to that of the metallic mirror, the reference wave is inappropriate, and the TDTS system is invalid for this high reflectance sample. Similarly, these terahertz wave measurements can be performed with the existing commercial Fourier transform infrared spectrometry (FTIR), unfortunately the FTIR needs special detectors in the region of terahertz, and only works under the liquid helium cooled condition.^[8]

In this Letter, a method to measure the refractive index of high reflectance with THz time domain spectroscopy under ambient conditions is proposed. The bulk copper and aluminum, which have high reflectance, have been taken as samples, and their refractive indexes have been measured without phase error.

The essence of this method is that the refractive index of the high reflectance sample can be obtained with a low reflectance reference, which is the antithesis of the traditional ones. Yet this low reflective index reference can be measured easily and accurately in the experiment. Furthermore, the Kramers-Kronig transformation is adopted to improve the accuracy of the phase shift existing in the reflective measurement of the traditional TDS systems.

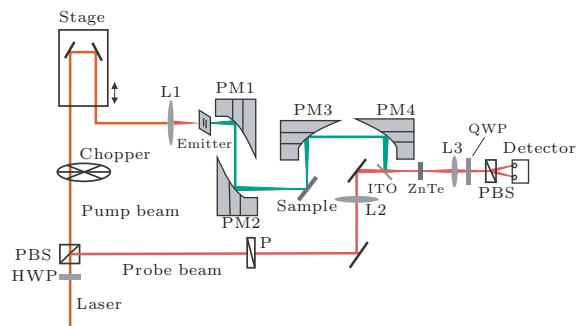


Fig. 1. Experimental setup. HWP: half wave plate; PBS: polarization beam splitter; L1, L2, L3: convex lens; ITO: Indium Tin Oxides; PM1, PM2, PM3, PM4: parabolic mirrors; PP: polythene plate; M1, M2: metallic reflecting mirrors; P: polarizer; ZnTe: Zinc Telluride Crystal; QWP: quarter wave plate.

A THz time domain reflection spectroscopy (THz-TDRS) system is used for measurements. The schematic configuration of the experimental setup is

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**Email: wfsun@mail.cnu.edu.cn

***Email: yzhang@mail.cnu.edu.cn

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shown in Fig. 1. The optical pulses generated by a Ti:sapphire oscillator has a duration of 120 fs and a central wavelength of 800 nm with a repetition rate of 80 MHz. Then, the optical pulses are separated into pump beam and probe beam. The pump beam is focused on a photoconductive antenna to emit THz radiation. After that, the THz beam is collimated by parabolic mirrors, and focused onto the aluminum mirror or sample at 45° incident angle. The reflected THz pulses are recollimated by the parabolic mirrors and detected by a conventional electric-optic crystal of ZnTe. The signal noise ration of the system is better than 600. The sample is placed close to the aluminum mirror.

As a conventional THz TDRS, the THz waveforms are obtained by scanning the delay line. Two waveforms with and without sample, $E_{\text{sample}}(t)$ and $E_{\text{mirror}}(t)$, are measured and Fourier-transformed into complex electric fields $\tilde{E}_{\text{sample}}(\omega)$ and $\tilde{E}_{\text{mirror}}(\omega)$. Consequently, the optical constant can be obtained by putting these two measured complex electric fields into the Fresnel formula

$$r_p = \frac{\tilde{E}_{\text{sample}}}{\tilde{E}_{\text{mirror}}} = \frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}, \quad (1)$$

where θ_1 and θ_2 are the angles of incidence and refraction, respectively, and they suffice the Snell law

$$\sin \theta_1 = \frac{1}{n} \sin \theta_2, \quad (2)$$

where n is the refractive index of the sample. The refractive index of the sample can be obtained by solving Eqs. (1) and (2), simultaneously

However, the method mentioned above is valid only on the assumption that the reflective index of the sample is far less than 1. If the reflective index of the sample is close to 1, the complex electric field reflected by the mirror $\tilde{E}_{\text{mirror}}$ can not be considered as an ideal reference anymore. In our method, the refractive index of the high reflectance sample can be obtained by the refractive index of the low reflectance sample as reference, which is quite contrary to the traditional ones. Si is widely used in the THz region due to its lower dispersion. Its reflectance was far less than 1 when it was used as the sample in THz-TSRS, so it may be a good reference to measure the sample with reflectance near to 1. For Si wafer and the metal to be measured, the Fresnel and Snell formulas are

$$r_{p1} = \frac{\tilde{E}_{\text{Si}}(\omega)}{\tilde{E}_{\text{per-ref}}(\omega)} = \frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}, \quad (3)$$

$$r_{p2} = \frac{\tilde{E}_{\text{metal}}(\omega)}{\tilde{E}_{\text{per-ref}}(\omega)} = \frac{\tan(\theta_1 - \theta'_2)}{\tan(\theta_1 + \theta'_2)}, \quad (4)$$

$$\sin \theta_2 = \frac{1}{\tilde{n}_{\text{metal}}} \sin \theta_1, \quad (5)$$

$$\sin \theta'_2 = \frac{1}{\tilde{n}_{\text{metal}}} \sin \theta_1, \quad (6)$$

where $\tilde{E}_{\text{Si}}(\omega)$ and $\tilde{E}_{\text{metal}}(\omega)$ are electric field of the Si wafer and metal, respectively. $\tilde{E}_{\text{per-ref}}(\omega)$ is a perfect reference electric field, which cannot be measured directly, but exists objectively; \tilde{n}_{metal} is the complex refractive index of metallic sample. From Eqs. (3)–(6), we have

$$\frac{\tilde{E}_{\text{Si}}}{\tilde{E}_{\text{metal}}} = \frac{\tan(\theta_1 - \arcsin(\frac{\sin \theta_1}{\tilde{n}_{\text{Si}}}))}{\tan(\theta_1 + \arcsin(\frac{\sin \theta_1}{\tilde{n}_{\text{Si}}}))} \cdot \left[\frac{\tan(\theta_1 - \arcsin(\frac{\sin \theta_1}{\tilde{n}_{\text{metal}}}))}{\tan(\theta_1 + \arcsin(\frac{\sin \theta_1}{\tilde{n}_{\text{metal}}}))} \right]^{-1}. \quad (7)$$

In Eq. (7), there is only an unknown parameter \tilde{n}_{metal} , therefore the complex refractive index of the metallic sample can be obtained by solving Eq. (7). It is known that the phase shift is quite important for getting an accurate result \tilde{n}_{metal} , and many researchers have described the methods to deduce the effects of phase shift on experimental results.^[9] As a result of sole dependence on the experimentally measured reflectance of sample, the Kramers–Kronig transformation with which we can obtain the phase shift accurately is adopted in this study.

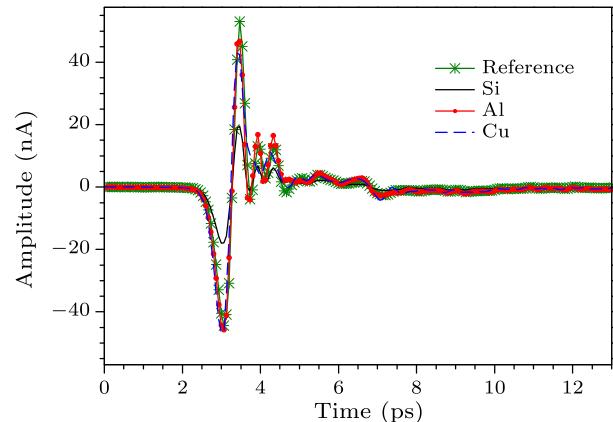


Fig. 2. THz waveforms of different samples obtained by THz-TDRS.

A Si wafer, copper and aluminum plate are used as the samples, respectively, and all of the measurements are performed in the ambient nitrogen to exclude the effect of vapor. The thickness of the Si wafer is 0.5 mm, while the thicknesses of copper and aluminum plates are 200 μm and 500 μm, respectively, much exceed their theoretical penetrate depths in the THz frequency range, and should be considered as bulk metals. The measured THz waveforms of silicon wafer, copper plate, aluminum plate, and aluminum mirror are shown in Fig. 2. It can clearly be seen that the reflected THz amplitudes of copper plate, aluminum plate, and aluminum mirror are nearly the same, which results in the fact that the THz wave reflected by aluminum mirror should not be considered

as a perfect reference wave, so the complex refractive indexes of these two metal plates cannot be obtained directly by Eqs. (1) and (2).

In order to measure the refractive index of bulk metal, the silicon wafer is chosen as the reference sample for its low dispersive characteristic in the terahertz range, and its reflective index is measured by the THz TDTs previously. Using the procedures described in the literature,[10,11] the complex refractive index \tilde{n} of the silicon wafer has been obtained. The real part of the refractive index for silicon wafer is shown by line in Fig. 3. It can be found that it has a little float of the value 3.4 over the entire measured frequency range. To verify the validity of this method, another measurement of the same Si wafer is obtained using our method. The real part of the reflective index is shown by the circle line in Fig. 3. It is found that the two lines are closer to the value of 3.4 and float synchronously. Consequently, it is proved that this method works well.

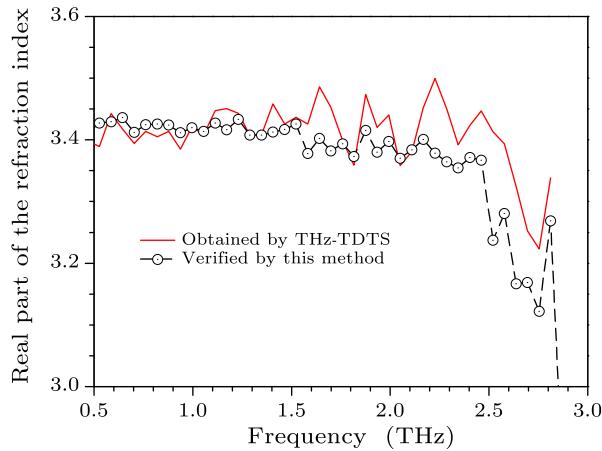


Fig. 3. Real parts of the refraction index for Si wafer obtained by THz-TDTS and this method.

Using our method, the real parts of the refractive index for different metals have been obtained and shown in Fig. 4. The solid circle expresses the real part of the refractive index for aluminum plate and solid triangle for copper plate. At 1.5 THz, the real parts of the refractive index for copper and aluminum are 38 and 20.38, respectively. It is obviously shown that, after 0.8 THz, the refractive index of the aluminum plate is higher than that of the copper plate in the measured frequency range. Furthermore, the characteristics of the refractive indexes in Fig. 4 show that the values of them decrease with the increasing frequency, similar to those in the optical frequency range.

In addition, the Drude model is also used to confirm the validity of the obtained values. According to the polarizability formula, there is no natural frequency for free electrons in the metal because of its absence of strained force for the atomic nucleus, thus

the Drude model reads

$$\tilde{n} = \sqrt{\varepsilon_r + \varepsilon_i} = \sqrt{1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} + i \frac{\omega_p^2 \gamma}{\omega_p^3 + \gamma^2 \omega}}, \quad (8)$$

where ω_p is the plasmon frequency of metal, depending on the volume density of free electrons in the metal, electron charge, electron mass, and dielectric constant in vacuum; $\omega_p = 2.123 \times 10^{16}$ rad/s, 1.971×10^{16} rad/s for the aluminum and copper respectively; ω is the angular frequency of the incidence wave; γ is the damping coefficient of the aluminum. $\gamma = 1.975 \times 10^{11}$ /s, 3.798×10^{11} /s for the aluminum and copper respectively. Thus the real parts of the refractive index for aluminum and copper are obtained and shown with open circles and triangles in Fig. 4. Similarly, the imaginary parts and their simulation for copper and aluminum can be obtained and we do not show them here. It is illustrated that the tendencies of experimental and theoretical results agree with each other well. The values decrease with the increasing frequency in the THz region. The figure also displays that the simulated values agree more with the experimental ones in the high frequency, because the low frequency of the incident wave ω is nearer to γ . That is, in the high frequency region, the metal reveals much more of its reflection characteristic than that of low frequency. At the time, the real parts of the refractive indexes for copper, directly obtained by Eq. (1) are shown in Fig. 4 with solid squares. It is obvious that, for the high reflectance materials, great deviation results from abusing the ideal reference in Eq. (1), and the traditional method is invalid. It is noted that the refractive index obtained experimentally depends greatly on the smoothness and oxygen of the surface, which is the key factor affecting the accuracy of results. Therefore, different results may be obtained by this method with the same sample in different surface states.

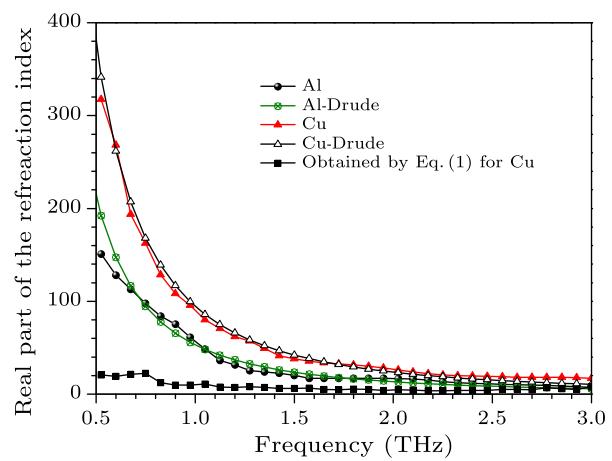


Fig. 4. Real parts of refractive indices for copper, aluminum, and Drude simulations.

In summary, we have proposed a method to measure the refractive index of bulk metal with THz

TDRS. The refractive index of the un-penetrated sample can be obtained accurately. Moreover, this method can be used for measuring other optical constants, such as dielectric constant ε and conductivity σ .

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