Study on Random Errors in THz Signal and Optical Constants Observed with THz Time-Domain Spectroscopy

Norihisa Hiromoto, Saroj R. Tripathi, Masanori Takeda, and Makoto Aoki
Shizuoka University, Hamamatsu, 432-8011, Japan

***Abstract*— We have observed that random errors in THz intensity spectra which are much larger than the noise floor. The standard deviation in intensity and phase spectra measured with THz-TDS are almost proportional to THz intensity and phase respectively and common for reference and sample. We discuss on the characteristics related to the origin of the random errors.**

I. Introduction

TERAHERTZ time-domain spectroscopy (THz-TDS) has large dynamic range (10^6 to 10^8) which is ratio of the maximum to the noise floor in intensity spectrum and the noise floor determines the detectable limit [1]. Signal-to-noise ratio (SNR), however, is different from the dynamic range and much smaller than it [2][3].

We have examined characteristics of random errors in both intensity and phase spectra by measuring reference, which is without a sample, and sample many times and by statistically calculating the mean and standard deviation of reference and sample respectively.

II. Measurement and Analysis

A THz-TDS system used in this research is a transmission type and uses a compact femto-second (fs) fiber laser and low temperature-grown GaAs photoconductive antennas (LT-GaAs PCA) as THz emitter and detector. Another system uses a ZnTe crystal as THz detector. In the measurement, ZnTe crystals with three different thicknesses (Nippon Mining and Metals Co. Ltd) were used as samples too.

Time-domain waveforms of THz electric field are sampled 1024 data points by 12μm (40 fs) spacing of optical delay line for reference (R), which is without a sample, and sample (S). The data was measured in a sequence like R_1, S_1, S_2, R_2, R_3, S_3, …, S_m, R_m , where m is 12 or 16, to take a pair of reference and sample data close in time (Fig. 1). It takes ten minutes to measure one waveform and about 300 min to 400 min to carry out the course of measurement for a sample.

Measured electric-field waveforms in time domain are Fourier-transformed to intensity and phase spectra in frequency domain, in which the frequency resolution is 24.4 GHz. Long-term variation of height and drift of time-position of peak-pulse have been corrected in the analysis. Standard deviations are statistically calculated from numbers of intensity and phase spectra of reference and sample respectively. They are displayed in Figs. 2 and 3, for which a sample is 1.496-mm thick ZnTe.

III. Results

We have observed that the random errors in THz intensity spectra are much larger than the noise-floor level and they are

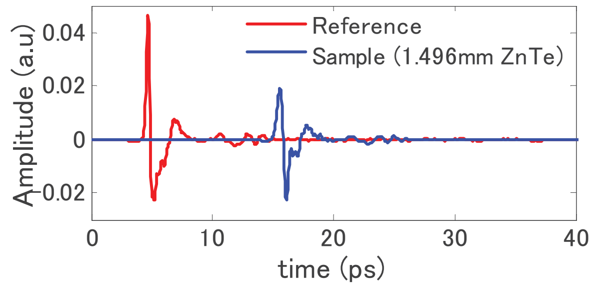

Fig. 1 THz electric-field pulse waveforms of reference and

almost proportional to the THz intensity itself in the high SNR

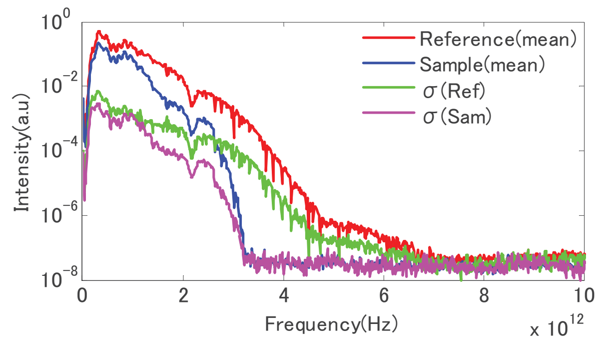

Fig. 2 THz intensity spectra of reference and sample and their standard deviations.

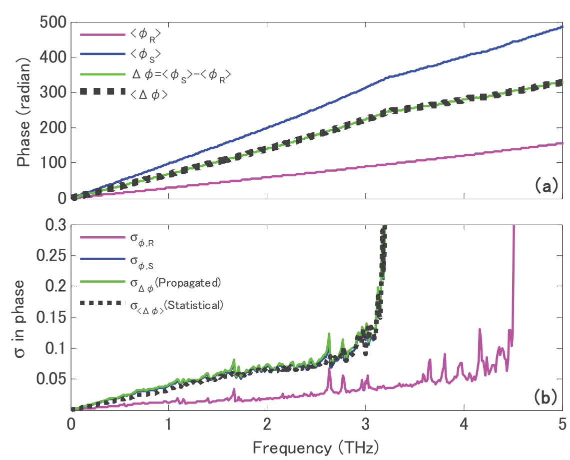

Fig. 3 THz phase spectra of reference and sample and the difference between them as well as their standard deviations.

region as shown in Fig. 2. The relation between the intensity and its standard deviation is expressed by

$$\sigma_I(\omega) = C_I\big(I(\omega) - h\big) + h \ , \tag{1}$$

where $\sigma_I(\omega)$ is the standard deviation of the intensity, $I(\omega)$ is the mean intensity spectrum, h is the noise floor, ω is angular frequency and C_I is a proportional constant [3]. C_I is almost a constant around 0.01 and common for both reference and sample in the high SNR region of 0.3 THz to 2.5 THz.

The random errors in phase spectra are also almost proportional to the observed phase itself in the high SNR region (Fig. 3) and the relation between the phase and its standard deviation is written by

$$\sigma_\phi(\omega) = C_\phi \cdot \phi(\omega)\,, \qquad (2)$$

where $\sigma_\phi(\omega)$ is the standard deviation of the phase, $\phi(\omega)$ is the mean phase spectrum, and C_ϕ is also almost a constant of about 3×10^{-4} and common for both reference and sample [4]. Therefore the standard deviations in intensity and phase spectra of a sample can be estimated from the standard deviations of reference spectra even if the measurement of sample is only once.

IV. Discussion

The observed random error in intensity spectra are much larger than the noise floor, meaning the SNR is very small compared to the dynamic range at around the maximum intensity. We are investigating the origin of such random error in the intensity spectra [5]. We have concluded so far that fluctuation in power of the fs laser, a stagger of the optical delay line and the THz detectors of LT-GaAs PCA and ZnTe EO- crystal as well as change in atmospheric absorption cannot cause this random error in intensity spectra. The origin is still unclear in the present.

If the THz power transmitted from the emitter, I_{THz}, fluctuates in time by δI_{THz}, the SNR in observed THz signal become $I_{THz}/\delta I_{THz}$, which will be common to reference and sample even if the THz power is attenuated by a sample.

The fact that SNR in intensity ($= C_I^{-1} \fallingdotseq 100$) is much smaller than the SN in phase ($= C_\phi^{-1} \fallingdotseq 3300$) suggests the standard deviation in phase spectra is hardly derived by the error propagation from standard deviation of the waveforms in the time-domain [6].

If the variation of pulse position in time domain, δt_p, is present, it is Fourier-transformed to the random error in phase of $\delta\phi = \omega\delta t_p$. $\delta\phi$ is proportional to the phase spectrum which is also in proportion to ω.

We examine the interrelation between peak pulse-height and time-position of peak pulse in time domain (Fig. 4) as well as the correlation of random error in intensity with random error in phase in frequency domain (Fig. 5). The results show the intensity error and phase error are independent from each other.

V. Conclusions

There exist characteristic random errors in intensity and phase spectra measured with THz-TDS. The standard deviations are proportional to the corresponding intensity and phase spectra respectively. The random errors in intensity and phase spectra are independent from each other.

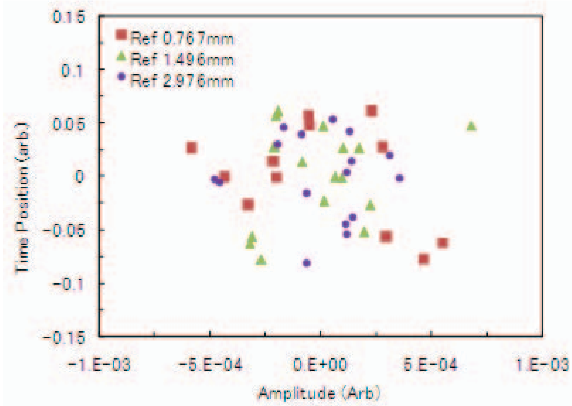

Fig. 4 Correlation of random errors between time-position and amplitude of peak pulse in time domain.

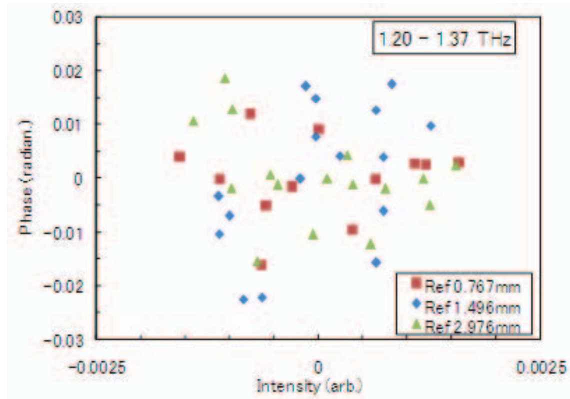

Fig. 5 Correlation of random errors between phase and intensity at 1.20 – 1.37 THz in frequency domain.

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