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# Error analysis of polyamide plate thickness detection based on Terahertz Time Domain System

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**Abstract:** The analysis on the thickness of polyamide plate using Terahertz Time Domain System (THz-TDS) in reflection mode is carried out. The refractive index, one of the optical parameters in terahertz band, is solved through the mathematics model, and its value is 1.88. A kind of polyamide plate sample with four kinds of thickness is designed and the ability of THz-based method to detect defects or foreign bodies in fiber glass is verified by attaching metal plates to the back of fiberglass. By the comparison of traditional method and THz method, the terahertz method has a measurement error between 2.5% and 10%. As the thickness increases, the error tends to increase. The reason about the deviations is analyzed, as well as the systematic factors affecting the thickness measurement accuracy, in order to improve the accuracy of THz thickness measurement system and provide theoretical basis for designing terahertz thickness measurement system in the future.

**Keywords:** time-domain spectroscopy; thickness testing; terahertz imaging

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Terahertz wave bears the characteristics of good penetration, high security and strong spectral resolution, which can be used in the fields of anti-terrorism, medical diagnosis and drug detection and so on. Terahertz wave can penetrate most of non-polar, non-metallic objects and it has a very high spatial resolution, so it can measure very thin coatings, paint films, etc.<sup>[1]</sup>. In the thickness measurement field, terahertz wave has the advantages of non-contact and simultaneous measurement of internal defects compared with traditional thickness measuring instruments. Currently, the paint with a thickness of dozens of microns has been measured by terahertz technology, and the results are in good consistency with ultrasonic technology. Terahertz instrument with thickness measuring function has also been designed, proving that terahertz wave has a broad prospect in the field of thickness measurement<sup>[2]</sup>.

In this paper, the thickness measurement samples of polyamide plate and the samples used for imaging are designed. The principle of terahertz thickness measurement and the ability of terahertz to detect defects through imaging are proved through experiments. It provides a reference for the design of terahertz thickness measuring instrument.

## 1 Thickness Extraction Model

When terahertz pulse wave reflection model is utilized to get the thickness, THz wave travels between different media, due to the change of the refractive index of the media interface, THz wave generates reflection and refraction. The principle is shown in Fig.1, assuming that air refractive index is  $n_0$ , measured refractive index is  $n$ , sample thickness is  $d$ , ignoring the effect of sample itself on terahertz wave absorption and refractive index dispersion. When the THz wave is incident to the sample surface at the angle of theta, refraction and reflection are

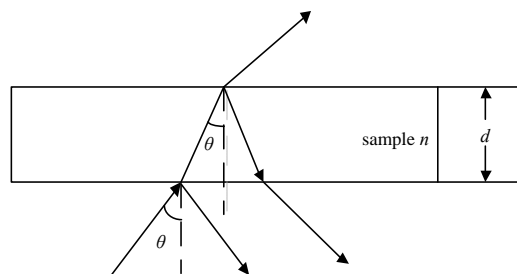


Fig.1 The thickness measurement model of a terahertz pulse

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generated on the surface of air/sample and the sample-air interface, the optical path difference between echo  $R_1$  and  $R_2$  is denoted as  $\Delta s$ , the corresponding delay time is denoted as  $\Delta t$  [3-5].

According to the propagation theory of terahertz pulse in multi-layer media, a simple reflective single-point thickness extraction model is established, as shown in equation(1).

$$d = \frac{\Delta s}{2\sqrt{n^2 - n_0^2 \sin^2 \theta_1}} = \frac{\Delta t c}{2\sqrt{n^2 - n_0^2 \sin^2 \theta_1}} \quad (1)$$

When the terahertz pulse is incident vertically, the model can be simplified into equation(2).

$$d = \frac{\Delta t c}{2n} \quad (2)$$

Where,  $c$  is the propagation speed of light in vacuum. When the refractive index is known, the thickness of the sample can be calculated by the time-of-flight difference of terahertz pulse echo.

$$d_i = \frac{\Delta t_i c}{2n_i} \quad (3)$$

Where,  $d_i$  represents the thickness of the  $i$ th layer medium,  $t_i$  is the time difference of flight through the  $i$ th layer medium, and  $n_i$  is the refractive index of the  $i$ th layer medium.

## 2 The Experiment

### 2.1 Experimental device

The THz-TDS adopted in this paper has a bandwidth up to 2 THz, a dynamic range of 70 dB, a frequency resolution of 11 GHz, the time delay amplitude of 100 ps, and a terahertz pulse width of 400 fs. The sample is so thick that it is measured by reflection model, as shown in the Fig.2. Fiber femtosecond laser with center wavelength of 1 560 nm generates femtosecond pulse divided into pump pulse and probe pulse after a beam splitter, the former is incident to the photoconductive antenna to generate terahertz pulse, the latter is incident to the terahertz detection device and drives the terahertz detection device with THz wave to measure. By controlling the time delay system to adjust the time delay between pump pulse and probe pulse, terahertz pulse of the time domain waveform is obtained eventually [6-8]. In order to reduce the influence of temperature and humidity on the test results of the terahertz time domain system, the ambient temperature is controlled at 25 °C and the humidity at 40%.

### 2.2 Sample preparation

Thickness gauge is adopted to measure the thickness of the polyamide plate, and then the refractive index of a spectrometer measuring function by terahertz time domain can directly measures the refractive index of polyamide plate with 0.1-1 THz [9], multiple measurement to calculate the mean and standard deviation is shown in Fig.3, the refractive index values can be found in the frequency range with small fluctuation, and 1.883 is taken as the refractive index value for subsequent calculation.

The side view and top view of the sample are respectively shown in Fig.4(a) and Fig.4(b), and the whole glass plate is cut according to the thickness requirements.

In Fig.5, metal sheets with different shapes are attached to the back of fiberglass board of three thicknesses, it simulates the presence of foreign bodies or defects inside the fiberglass board, so as to analyze the ability of terahertz

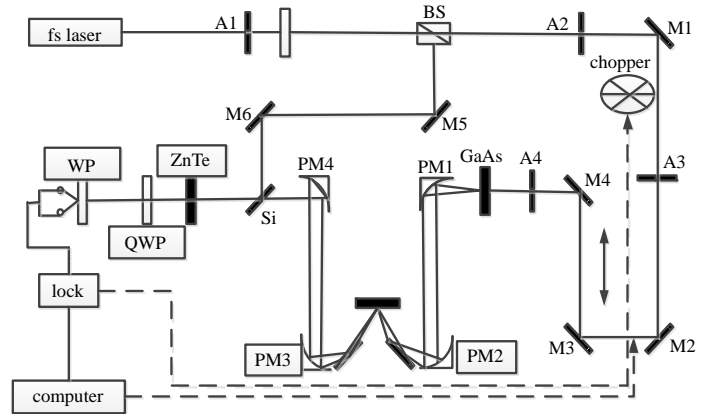


Fig.2 Diagram of reflection THz-TDS

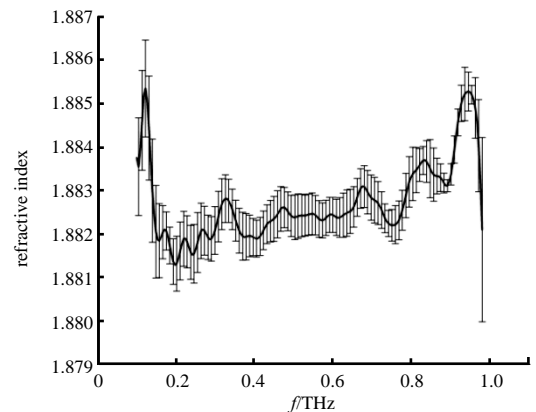


Fig.3 Refractive index curve of polyamide plate

wave to detect defects and foreign bodies at different thicknesses. The thickness of 15 mm is affixed to the triangle, 20 mm to the square, and 25 mm to the trapezoid. The change of thickness is determined by terahertz imaging.

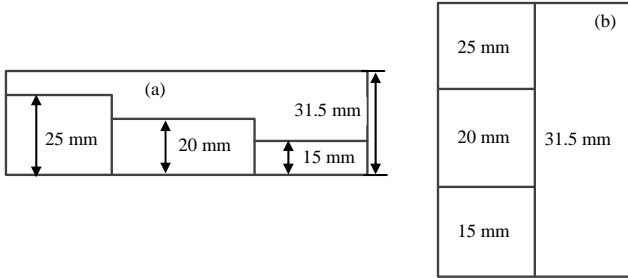


Fig.4 (a) side view of sample; (b) top view of sample

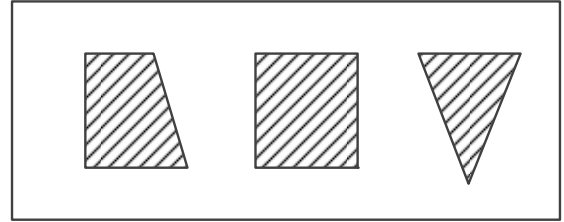


Fig.5 Metal layout attached to the back of the sample

2.3 Experimental results and analysis

2.3.1 Thickness measurement results

The detection results of pulse terahertz are shown in Fig.6. The top surface and under surface can be identified by the reflection peak from the pulse signal, but with the increase of the thickness, the surface of the reflection peak decreases obviously, which is caused by increase of the signal attenuation with the increase of the thickness. Getting the time corresponding to the reflection peaks of the upper and lower surfaces, sample thickness can be obtained by the formula(2). The relative errors between the calculation results and the detection results of traditional thickness gauge are shown in Table1. Results show that, except at the last line with the maximum thickness(31.5 mm,34.69 mm), the relative error of the other three are within 5%, and that the thickness detection method of the terahertz pulse is more suitable for thin thickness. For the thicker samples, the error is bigger because the attenuation of THz wave in internal transmission increases.

Table1 Comparison of terahertz thickness test results of polyester amide plate

the thickness measured by a thickness gauge/mm	the thickness measured by a terahertz pulse/mm	relative error/(±%)
15	14.37	4.2
20	19.50	2.5
25	24.00	4.0
31.5	34.69	10.1

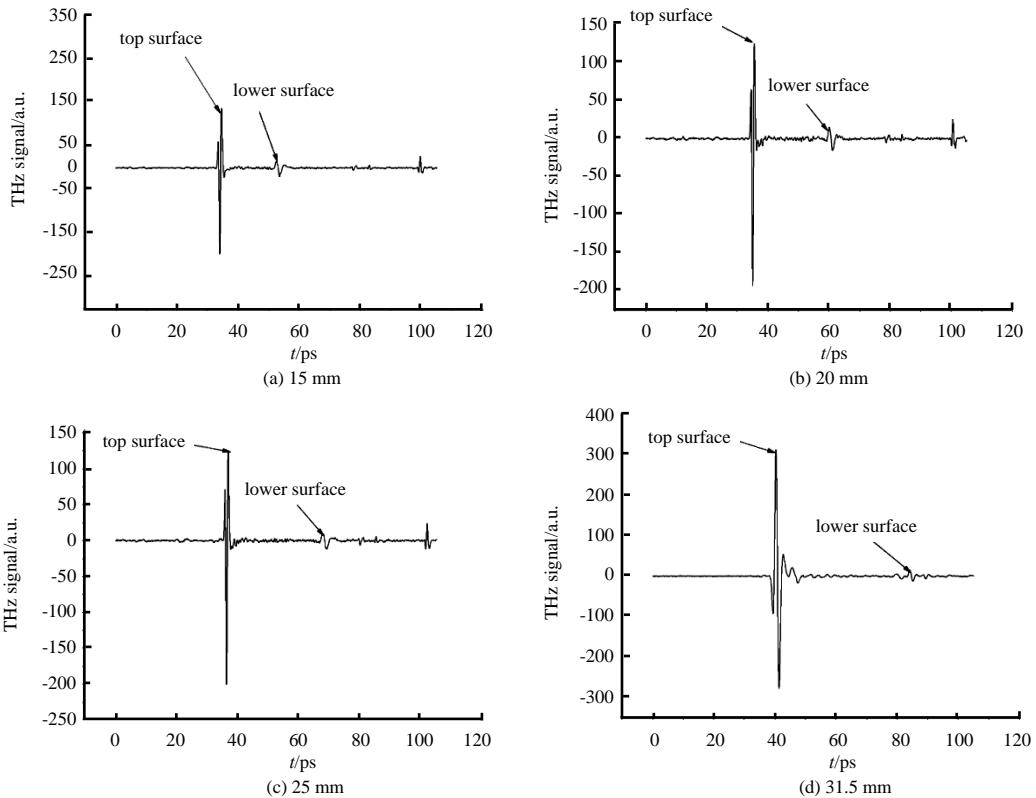


Fig.6 Reflective time domain signals of the sample with different thicknesses

### 2.3.2 Measurement error analysis

It can be seen from formula(1) that the factors affecting the accuracy of thickness include the angle of terahertz wave incident on the sample surface, the accuracy of time of flight measurement, and whether the refractive index is accurate<sup>[10]</sup>.

First of all, the terahertz incident wave is set perpendicular to the sample surface in the experiment. However, the setting process is manual and visually vertical, which can inevitably cause certain angle error. Secondly, the smoothness of the sample is uncertain either.

Terahertz wave generates multiple reflections in the sample, and the superposition of reflection peaks increases the difficulty of extracting the actual interface reflection peaks, resulting in the peak selection errors<sup>[11-12]</sup>. When measuring the refractive index of polyamide plate, the error of estimating the refractive index comes not only from the randomness of the signal, but also from the imperfection of the physical setting and parameter extraction process. These defects are related to the sample thickness measurement and the sample alignment, etc.

The inevitable random error and systematic error of the measurement system will also affect the measurement results. The signal to noise ratio, dynamic range and frequency resolution of the THz-TDS system all determine the accuracy of the optical parameters of the measurable sample, resulting in obvious errors in the measurement of the strong absorption and the thicker sample<sup>[13-15]</sup>. Femtosecond laser intensity fluctuation, optical and electronic noise, delay line jitter, registration error and other system noise sources will affect the amplitude of the time domain signal, so the system reduces the influence of random and systematic errors on the amplitude by averaging the time domain signal for a period of time, which undoubtedly increases the uncertainty of the output signal.

### 2.3.3 Results and analysis of polyamide plate defect detection capability

In Fig.7, on the left, the imaging results of frequency domain of polyamide plate in different thicknesses attached with a metal shape to the back in 0.48 THz are showed; on the right, the result of binarization is showed. In the case of the maximum thickness of 31.5 mm, the sample attached with a metal shape can also be clearly imaged, and the signal intensity is the same as the other two thicknesses, so it proves that terahertz technology can detect the polyamide plate with defects and foreign body.

## 3 Conclusion

Firstly the paper introduces the principle that the terahertz time domain system extracts the sample thickness by the reflection method, and then polyamide plate is utilized as the samples. The samples with different thicknesses are measured by terahertz time-domain spectroscopy system, at the same time, the delay time is got, and terahertz time-domain pulse system is employed to measure the refractive index. The calculation results are compared with that of the traditional thickness gauge measurement, and the reasons of the error are analyzed. The terahertz specific frequency imaging method is adopted to image the metal plates attached to the back of the samples, and the images are processed with some suitable image processing methods. In the process of measuring the thickness of the sample by terahertz time domain spectroscopy, various noises will be introduced due to the dither of the laser and the unevenness of the intermediate substance of the experimental sample, so the accuracy of thickness measurement will be affected and error will be caused. Further signal processing methods in time domain need to be proposed to improve the signal-to-noise ratio, which is helpful to improve the accuracy of thickness detection.

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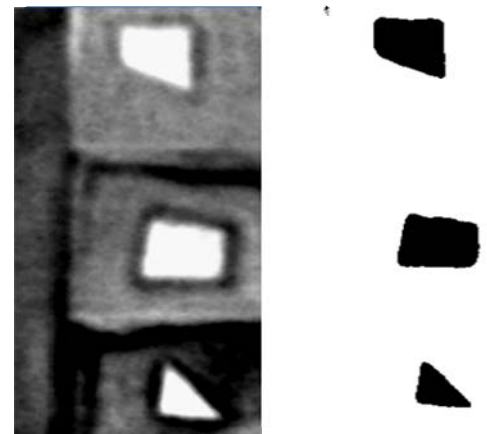


Fig.7 Frequency domain imaging at 0.48 THz(left); after binarization(right)

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