

## Experimental Analysis of Terahertz Detection of Polyethylene Thickness

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**Abstract:** In the manufacturing process of polyethylene material pipelines, accurate measurement of pipe thickness is an important technical problem affecting the quality of pipeline production. In the process of terahertz non-metal thickness transmission measurement, the optical path time difference and material refractive index of two transmitted signals are measured. The sample thickness parameter is obtained. In this paper, the thickness error detection calibration of the test sample is firstly carried out, then the stepwise Butterworth bandpass filter is applied to the time domain signal, and the optimal filter interval is determined by the signal to noise ratio calculation formula, and the closest frequency of different samples is selected. The distribution interval is used as a basis for selecting the effective range of the refractive index. The experimental results show that the measurement accuracy is significantly improved, and the measurement error is significantly reduced.

### 1. Introduction

In recent years, due to the wide use of natural gas, pipelines are widely used as the most important carrier of natural gas. Polyethylene, as a kind of composite material, is also a non-metallic material commonly used in pressure special equipment and is usually used in pressure pipelines and containers. Moreover, it also undertakes the role of pipeline transportation in national projects such as “West-East Gas Transmission” and “Chuanqi East Transmission” and between gas vehicles and gas stations. According to statistics, in 2018, the new use of polyethylene gas pipes in China has reached 2 million tons, and its market demand is still growing rapidly<sup>[1]</sup>. The polyethylene materials currently used as gas pipes are mainly PE80 and PE100. Polyethylene pipes are preferred because of their excellent properties<sup>[2]</sup>. Natural gas is extremely vulnerable to safety hazards due to its flammable and explosive characteristics. Therefore, the quality control of natural gas pipelines is particularly important. In particular, the control of the thickness parameter of the pipeline is a difficult point in the industry. The thickness of the existing detection methods mainly for ultrasonic thickness testing, the ultrasonic<sup>[3]</sup> as a result of polyethylene material properties change with the environment (temperature, humidity) change is bigger, lead to different propagation velocity of ultrasound in polyethylene materials such as reason, cause the measurement error is bigger, difficult to guarantee the accuracy, more can't as a qualified quality inspection standards. Terahertz wave has a strong penetrability to non-metal and has been widely used in the determination of non-metal thickness parameters, providing a powerful supplement for the thickness detection of polyethylene pipes.

Lionel Duvillaret uses the difference in echo index of the reflected sample and the reflected echo in the sample to obtain the thickness parameter<sup>[4]</sup>. Wang Xiumin proposed an error theory analysis method to determine the thickness of the sample, determine the thickness range and then use the thickness reference value, calculate the refractive index at all frequencies, and then re-select the thickness reference value to repeat the above work until all thickness calculations are completed, and the thickness is obtained. The error curve, the point with the smallest error, is the sample thickness<sup>[5]</sup>. Li Lijuan uses the terahertz single point thickness extraction model to model the model based on terahertz propagation theory, and measures the thickness of the sample, but it only

analyzes the thickness of the layer <sup>[6]</sup>. Lu Qinghua mentioned the use of terahertz spectral imaging principle for the thickness detection of drugs by contrast <sup>[7]</sup>. On the basis of Lionel Duvillaret, Kou Kuan considers the terahertz wave to analyze the effective frequency band and the invalid frequency band through different frequencies of the sample, and eliminates the invalid frequency band for measurement, which improves the measurement accuracy <sup>[8]</sup>. Liu ZikYe proposed a method of terahertz photon mixing continuous wave transmission imaging, which uses phase information to measure the thickness of the sample <sup>[9]</sup>.

Pulse-based terahertz time-domain spectroscopy enables thickness measurements of polyethylene materials with high accuracy. In this paper, for the accurate thickness measurement of polyethylene materials, the 5-10mm thick polyethylene samples are repeatedly measured on the basis of the existing experimental platform. Firstly, the refractive index of the sample is measured, and then the thickness measurement and calculation are proposed according to the refractive index. Method and analyze its measurement accuracy.

## 2. Experimental principle

### 2.1 Single point thickness measurement model

In this paper, pulse-based terahertz time-domain spectroscopy is used to measure samples using transmissive detection methods to obtain experimental data. As shown in Fig. 1, the terahertz wave source generates a terahertz wave. First, the first pulse signal is received by the terahertz wave receiver through the first transmission, which is called the main wave signal. The terahertz wave is reflected on the bottom surface of the sample while it is first transmitted through the sample. The terahertz wave receives the second transmission signal at the receiving end of the terahertz wave after two reflections on the bottom surface of the sample and the surface of the sample. Is an echo signal. The unique main wave signal is measured without the sample being placed, and is called the air reference signal. The sample thickness can be accurately calculated by accurately measuring the time difference between the main pulse signal and the echo signal.

From the single point thickness measurement model, we can see:

$$d = \frac{c}{2n} \Delta T \quad (1)$$

Where:  $d$  is the thickness of the sample;  $n$  is the refractive index of the material;  $c$  is the propagation velocity of light in the air;  $\Delta T$  is the time difference between the main pulse of the sample and the primary echo signal.

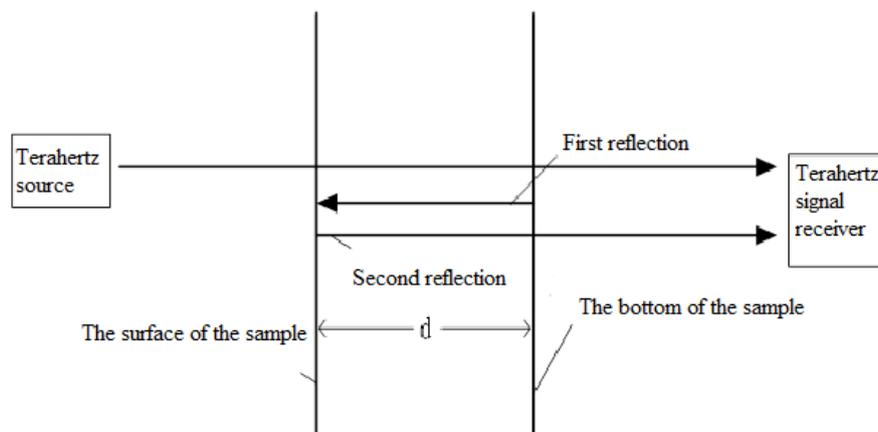


Figure 1. Schematic diagram of terahertz transmission thickness detection method

### 2.2 Parameter extraction

In the experiment, the terahertz time domain signal transmitted through the sample is recorded as  $E_0(t)$ , and the terahertz time domain reference signal of the air is recorded as  $E(t)$ . At this time, the two sets of time domain signals are Fourier transformed respectively. Obtain  $E_0(\omega)$  and  $E(\omega)$ . At this time,

the complex transmission function of the sample is obtained. After the complex transmission function is transformed, the terahertz time domain signal can be obtained for the first time through the main wave signal of the sample and the reflection in the sample. The complex transmission function corresponding to the echo signal [10]:

$$T_p(\omega) = \frac{4\tilde{n}_0(\tilde{n}_0 - 1)^{2p}}{(\tilde{n}_0 + 1)^{2p+2}} \times [\exp(-i\tilde{n}_0\omega L_0/c)]^{2p+1} \exp(i\omega L_0/c) = \rho_p(\omega) \exp[-i\phi_p(\omega)] \quad (2)$$

At this time:

$$n_0 = \frac{\phi_p(\omega) \cdot c}{\omega L_0} + 1 \quad (3)$$

### 3. Refractive index effective interval selection principle

#### 3.1 Filter principle and selection

The terahertz time domain measurement system can be simplified to the signal model as shown.



Figure 2. Time Domain System Simplified Model

Set as the system's impulse response function, there are:

$$y(t) = x(t) * h(t) \quad (4)$$

$$Y(\omega) = X(\omega)H(\omega) \quad (5)$$

$$|B1(\omega)|^2 = \frac{1}{1 + (\frac{\omega\omega_0}{\omega})^{2n}} \quad (6)$$

$$|B2(\omega)|^2 = \frac{1}{1 + (\frac{\omega}{\omega_0})^{2n}} \quad (7)$$

B1 and B2 respectively represent the filter upper and lower cutoff frequencies.

$$Y'(\omega + \omega_0) = Y(\omega + \omega_0)B(\omega) = Y(\omega) \times r + Y(\omega_0) \times l \quad (8)$$

#### 3.2 Filtering effect discrimination basis

As shown in the formula (9), the start and end of the primary echo signal are two nodes, and the two nodes are respectively extended to the left and right to take 100 pulse time points, and a total of 200 clutter signals are obtained to obtain the mean value, with one echo peak-to-peak value. The maximum value of the ratio of the mean value of the clutter is used as the basis for judging the signal-to-noise ratio and the optimization of the filtering effect.

$$SNR = \frac{signmm}{\text{var}(\sum_{i=1}^{100} signl + \sum_{j=1}^{100} signr)} \quad (9)$$

The signal-to-noise ratio indicates the peak-to-peak value of the signal, indicating that the echo signal takes a value from the point where the peak-to-peak value of the signal is to the left, indicating that the echo signal takes the value from the point where the peak-to-peak value of the signal is to the right. Indicates the average.

#### 3.3 Filter band selection

We pass narrow-band filtering (the upper and lower cutoff frequencies in the passband differ by 0.1THZ). Determine the signal to noise ratio. As shown in Fig. 6(a), we first measure the ratio of the peak

value of the main peak before filtering the original data to the average value of the input signal clutter. A reference signal to noise ratio  $S$  is obtained, and a filtered signal to noise ratio greater than  $S$  is specified as an effective filtering interval. From the experimental results, it can be concluded that the frequency at which the filtered SNR value is greater than the  $S$  value for the first time is the lower cutoff frequency of the passband filtering. The upper cutoff frequency appears at the peak of the filtered signal-to-noise ratio (at the inflection point). According to this method, the optimal filter bandpass filtering interval can be obtained.

## 4. Error calibration experiment

### 4.1 Sample preparation

The PTFE film material is purchased online and has specifications of 0.1mm, 0.2mm, 0.5mm and 1mm. The A sample is 0.1 mm, the B sample is 0.2 mm, the C sample is 0.5 mm, and the D sample is 1 mm.

### 4.2 Error calibration results

Firstly, according to the single-point thickness measurement model, the 1mm PTFE sample is used as the standard thickness reference, and then the refractive index of the PTFE material is obtained, and the thickness parameters are calculated for the three samples A, B and C.

The time domain information of the measured samples is shown in the figure below. Figures 3(a), (b) and (c) are time domain signal diagrams of three polytetrafluoroethylene samples A, B and C, respectively.

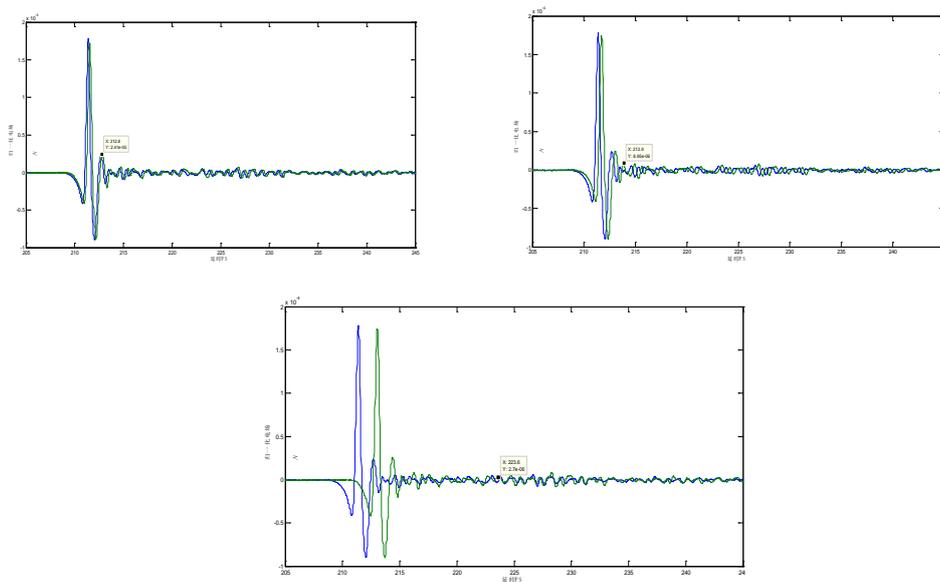


Figure 3 (a) Sample A normalized reference signal and sample signal time domain diagram (b) Sample B normalized reference signal and sample signal time domain diagram (c) Sample 6 normalized reference signal and sample signal time domain diagram

As shown in Figure 3(a): The primary echo point of the sample signal is at 212.8 ps. The retardation of the air reference signal is 1.2 ps, and the thickness  $d_A$  of the sample A is 0.113 mm by a single point thickness measurement formula with an error of 13%.

As shown in Figure 3(b): The primary echo point of the sample signal is at 213.9 ps. With a delay of 2.2 ps relative to the air reference signal, the thickness of the B sample can be found by a single point thickness measurement method,  $d_B = 0.107$  mm, with an error of 3.5%.

As shown in Figure 3(c): The primary echo point of the sample signal is at 223.6 ps. Compared with the air reference signal delay of 4.7ps, the thickness of the C sample can be obtained by the single point thickness measurement method.  $d_C = 0.443$ mm, the error is 11.4%.

Table 1 error calibration result chart

Specifications /mm	delay time /ps	thickness /mm	error
0.1	1.2	0.113	13%
0.2	2.2	0.207	3.5%
0.5	4.7	0.443	11.4%
1	10.6	1	/

Table 1 shows that the sample error is at least 3.5% and the maximum value is 13%. Considering that the sample is not a precision machined material, but the experimental polyethylene material is made of precision machined standard samples. It is reasonable to use 3.5% as the calibration error of the sample. The following thickness measurement errors are based on this error standard.

### 5. Refractive index measurement experiment

The white test piece sample was measured, numbered A, and A was known to be a standard test piece of thickness 8 mm. The measured refractive index is measured as shown in Fig. 4(a), and the yellow polyethylene sample is measured and numbered B. After measurement, the thickness of the sample B is 6.26 mm. The measured refractive index is shown in Figure 4(b):

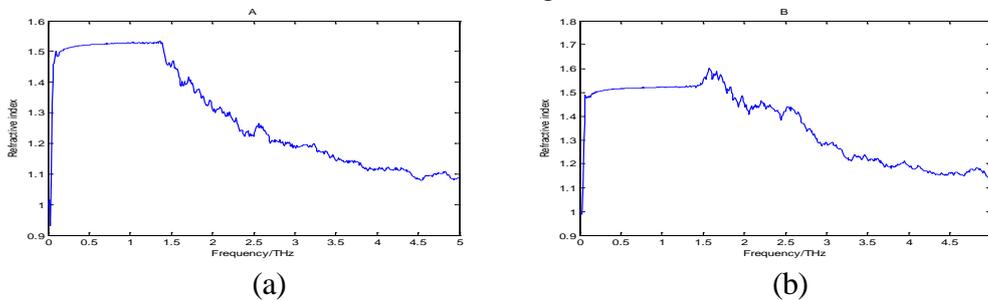


Figure 4 (a) Sample A complex refractive index (b) Sample B complex refractive index

As shown in figure 4 (a) and (b), the refractive index of sample a and b tends to a rapid growth stage in the terahertz wave frequency from 0 to 0.2thz, and from 0.2 to 1.5thz tends to be stable, and the refractive index changes less.

### 6. Thickness measurement experiment

A is known to be a standard test piece of thickness 8 mm. As shown in Table 2, the optimal filtering interval of the A sample is 0.84-1.09THZ, through the filtering frequency band selection method, in which the reference filtering signal-to-noise ratio is 138.5674. The filtered signal-to-noise ratio at the frequency of 0.84THZ is 144.5, 1.09THZ. The filtered SNR value reaches a maximum of 533.2. It is known that B is a standard test piece sample with a thickness of 6 mm. The calibration error is 3.5%, and the actual measured value should be 5.79-6.217. As shown in Table 2, the optimal filtering interval of the B sample is 0.75-0.95THZ by the filter band selection method, and the reference filter SNR is 244.3691. 0.75THZ The filtered signal-to-noise ratio at the frequency is 254.32, and the filtered SNR at 0.95THZ reaches a maximum of 799.68.

Table 2 refractive index effective interval

Sample	Benchmark of signal-to-noise ratio	Interval of wave filtering	Signal-to-noise ratio of upper cut off frequency	The signal-to-noise ratio of lower cut off frequency
A	138.5674	0.84-1.09	144.5	533.2
B	244.3691	0.75-0.95	254.32	799.68

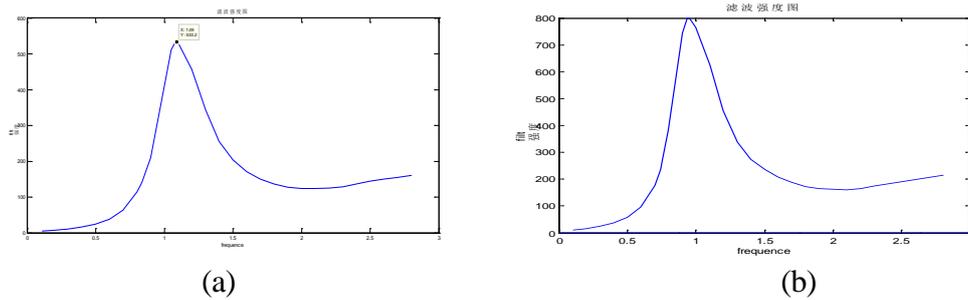


Figure 5 (a) A sample filter intensity value distribution (b) B sample filter intensity value distribution

Table 3 SNR comparison results

Sample	Refractive index(sTable interval)	Refractive index(effective frequency band)	Actual thickness	Thickness	Error
A	1.5238	1.5226	7.72-8.28	7.9053	2.4%
B	1.53	1.52	5.79-6.217	6.1142	1.7%

As shown in Table 3, the average refractive index is calculated using the formula (1) for the selected effective frequency band as  $n=1.5238$  (four digits after the decimal point). Here we use this refractive index to measure Sample A for verification. Substituting the previously measured refractive index  $n$  into the formula (1), the thickness of the test piece A is calculated as  $d=7.8991$  mm. The refractive index effective interval is obtained by the selected frequency band as  $n=1.5226$ ,  $d=7.9053$  mm. The effectiveness of the method is verified by comparing the subjectively selected effective frequency bands. The error is 2.4%. Substituting the previously measured refractive index  $n$  into the formula (1), the thickness of the test piece B is calculated as  $d=6.024$ mm. The refractive index effective interval is obtained by the selected frequency band as  $n=1.52$ ,  $d=6.1142$  mm. The effectiveness of the method is verified by comparing the subjectively selected effective frequency bands. The error is 1.7%.

## 7. Conclusion

In the case of a known thickness condition of the polyethylene material sample, this paper first confirms the parameter of error calibration by measuring the error calibration and the actual thickness of reference test piece, then obtains the interval of the refractive index frequency of samples to be tested by the extracting formula of time domain spectral parameter. The effective index selection is determined by the effective interval selection method. Then the method for detecting the thickness of terahertz non-metallic materials is standardized. Through the measurement of the two groups of samples, the measurement calculation error is less than 3%, which meets the requirement of 4% accuracy in the national standard GB15558.1. At the same time, it is believed that when measuring the refractive index and the thickness, certain errors can be brought when two samples are in different environments (different ambient temperature and humidity). Therefore, when the aforesaid factors are under control, it is predicted that the relative error of measurement in the future can be regulated to less than 1%, which will realize a better result of the measurement.

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