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多层介质中隐含层的太赫兹无损检测

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摘 要：在工业应用中，大多数情况下的复合结构介质仅有一面可以被检测，因此需要研究反射模式下检测介质内部参数的太赫兹无损检测方法. 推导了反射模式下太赫兹波在三层结构介质中的传输模型，通过遗传算法共同反演估计得到中间分层的厚度，以及它的折射率，从而获得中间隐藏层的具体信息. 制备了具有 200 μm 的隐藏分层的三层结构样品，利用太赫兹时域光谱系统对其进行了测量，将理论模型与实测数据进行对比，利用遗传算法估计得到隐藏层的厚度和折射率，将厚度估计值与测厚仪测量结果对比，误差保持在 4% 以内，折射率估计值与实际值相比，误差范围波动较大，平均误差为 6% 左右，最后对误差来源进行了分析，为多层复合材料内部缺陷、中间层材料的介电参数估计提供了理论和实验依据. 研究表明该系统作为一种无损评价方法可以广泛应用于层状结构的可靠性评价.

关键词：无损检测；太赫兹时域光谱；遗传算法；多层结构；反射模式
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Terahertz Nondestructive Detection of the Hidden Layer in Multilayer Medium

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Abstract：In industrial applications，only one side of the composite media can be detected in most cases，so it is necessary to study the terahertz nondestructive testing method to detect the internal parameters of the desired media based on the reflection mode. The transmission model of terahertz waves in the medium of a three-layer structure is derived under the reflection mode. The thickness of the middle layer together and its refractive index are estimated by a genetic algorithm to attain the specific information about the middle hidden layer. At the same time，samples with the three-layer structure consisting of the hidden layer with the thickness of 200 μm are prepared and subjected to a terahertz time-domain spectroscopic system. In

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addition, a theoretical model is designed to compare the achieved measurements. Thereafter, a genetic algorithm is designed to estimate the thickness of the hidden layer and the respective refractive index to verify the effectiveness of the proposed method. Compared the estimated value of thickness with the measurement result of the thickness gauge, the error is kept within 4%. Compared with the actual value, the error range of the estimate refractive index fluctuates greatly, the average error is about 6%. Finally, the error sources is analysed, which provides the theoretical and experimental basis for the iternal defects of the multilayer composite material and the dielectric parameter of the intermediate layer material. The practice shows that the system as a nondestructive evaluation method can be widely used in the reliability evaluation of layered structures.

Key words: Non-destructive; Terahertz time-domain spectroscopy; Genetic algorithm; Multilayered structure; Reflection mode

OCIS Codes: 120.4825; 120.5700; 150.1135

0 Introduction

The application of the terahertz wave has been known as a hotspot in the field of nondestructive testing. Furthermore, this methodology overcomes the limitations of traditional nondestructive testing technologies, penetrates into common nonmetallic materials, and provides non-invasive, non-contact, and non-ionizing methods without any health risk. On the other hand, the terahertz wave methodology can also provide valuable information on the properties of materials. In recent years, terahertz radiation in the domain of 0.1 ~ 3 THz has been used to analyze the internal structure and thickness of the layered materials including multilayer composites, thermal barrier coatings, multilayer polymer structures, etc. These materials are opaque under the irradiation of visible and infrared lights, but permeable towards terahertz waves. This technology has been successfully used to characterize and identify materials with composite structures such as Glass Fiber Reinforced Plastic (GFRP) composites, integrated circuit packaging systems, pharmaceutical tablets, polymer-coated steels, plastic welding and so on[1].

Ref. [2] revealed that THz-TDS (THz time-domain spectroscopy) can reveal the glass transition temperature of polymers. Ref. [3] has demonstrated the use of THz-TDS system to in situ monitor concentration of the additives in a melting polymer. In Ref. [4], THz-TDS is applied to measure the air stratification thickness in the welded plastic structural parts and enables evaluation of the welding quality. These are some specific application prospects to the THz technology in the inspection of quality of the welded plastic joints. Thus, THz-NDT technology can be applied to the whole industrial chains including characterization of polymers, quality control of the online production, detection of the polymers in the synthetic processes, and demonstrating the potential of THz in the production of polymers.

In the process of THz nondestructive testing of composite polymers, it is necessary to measure the thickness of each layer, refractive index and other material parameters to achieve the internal defects or lamination of a polymer[5]. In general, the complex refractive indices of various materials can be obtained via the transmission mode in the terahertz spectrum. However, thickness of a material should be determined via the thickness gauge or through the reflection measurement, as is based on the time difference between the surface reflection before and after coating. If the sample is too thin, it is difficult to separate the time difference, maybe due to the superposition of the reflection peak of the fabry-perot effect. Therefore, the time difference can not be separated accurately, resulting in errors in the calculation of the refractive index and other important parameters. In industrial applications, only one side of the composite structure can be detected in most cases. Herein, we introduce the principles of a new method to extract the hidden stratification parameters of the composite materials through the reflection mode of the THz-TDS technology[6].

On the one hand, the reflection mode of THz wave can be deduced in the three-layer medium transmission model, made from a polyethylene powder and Polyvinyl Chloride (PVC) sheets of the three-layer composite structure of the tablet sample. Then, we can measure the transfer function of the sample by the terahertz time-domain spectroscopic system through a genetic algorithm calculation theory based on the minimum error and measured transfer functions to estimate the thickness and refractive index of the hidden layer of a PVC sheet. Compared to the results of the thickness gauge, we can estimate the results of the error sources and verify the accuracy of this procedure.

1 Theoretical principle

1.1 Theoretical model

When the terahertz pulse was propagated in the multilayer medium, the transmitted and reflected electric fields involved all the dielectric information about the medium. In such a case, the interface between the layers reflected the incident THz pulse and caused attenuation of the transmitted pulse. Different delay propagation pulses and their delay layer reflections can provide the thickness and internal structural states of the material[7]. In order to obtain the unknown dielectric parameters of the media middle layer that satisfies the composite structure, we established a model based on the transfer function. Moreover, a suitable medium parameter extraction model was derived for both transmission and reflection modes. Parameters such as thickness and refractive index were also calculated by an analytical method[8].

Assuming that terahertz is a vertical incident on the sample surface, the analyzing material would be uniform, isotropic, and non-magnetic. The sample transmission model due to the terahertz pulse, directed towards an internal sandwich, as is shown in Fig. 1. The sample containing the sandwich can be seen as a medium with a three-layer structure. When the THz pulse was coincided with the specimen, part of the terahertz wave was reflected back from a series of interfaces between layers after attenuation of each layer, and repeated transmissions and reflections between the adjacent interfaces. The other part of the terahertz wave was entered the free space of the sample through the back of the specimen. The real index of the refraction can describe the dispersion of the sample and the corresponding extinction coefficient illustrates the absorption characteristics of the sample, both of which depend on the frequency[9].

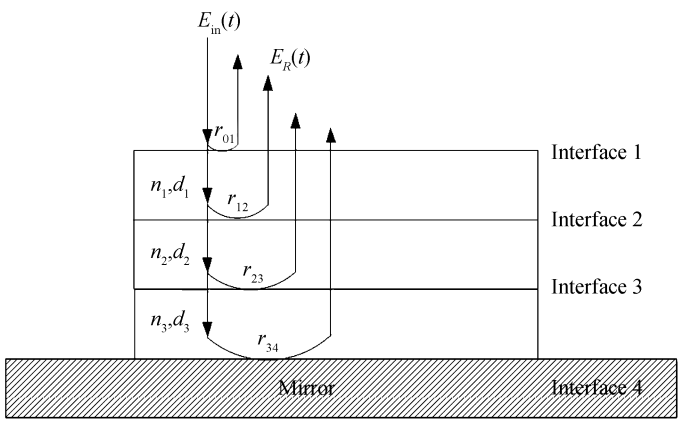

Fig.1 Diagram of interaction between terahertz wave and three-layer medium

The schematic diagram of the interaction between the terahertz wave and the three-layer medium is shown in Fig. 1[10]. According to the principles due to the interaction of the electromagnetic radiation with a material, the terahertz wave interacts vertically with the sample surface and transmits/reflects at the interfaces 1, 2, 3 and 4, respectively. The effective reflection coefficient of the interface l can be expressed as follows[11] .

$$R_l(f)=\frac{r_{l-1,l}(f)+r_{1,l+1}(f)\mathrm{p}_l^{-2}(f,n_l,d_l)}{1+r_{l-1,l}(f)r_{1,l+1}(f)p_l^{-2}(f,n_l,d_l)} \tag{1}$$

where $l=1, 2, 3$, and r_{ij} is the Fresnel reflection coefficient, and transmission factor of the medium is expressed as follows .

$$p_1(f,n_1,d_1)=\mathrm{e}^{-j2\pi fn_1(f)d_1/c} \tag{2}$$

The terahertz wave passes through the multiple transmissions and reflections in the three-layer structure. Thus, the Rouard equivalent interface theory can be applied to describe the wave propagation in a multi-layer structure. The specific calculation steps are as follows: first, the effective reflection coefficient $R_3(f)$ of medium 3 was calculated, as shown in Eq.(3). As the media 2 and 3 were equivalent to one medium, the effective reflection coefficient R_3 of the medium 3 can be replaced with r_{23}. The effective reflection coefficient of the equivalent medium 2, R_{eq}^{2}, was calculated, as shown in Eq.(4). Then, the equivalent media 2 and 1 are equivalent to medium 1 and R_{eq}^{2} can be used instead of r_{12}[12]. Finally, the effective reflection coefficient, R_{total}, of the entire three-layer structure was obtained, as shown in Eq.(5)[13].

$$R_3(f)=\frac{r_{23}(f)+r_{34}(f)p_3^{-2}(f,n_3,d_3)}{1+r_{23}(f)r_{34}(f)p_3^{-2}(f,n_3,d_3)} \tag{3}$$

$$R_{eq}^2=\frac{r_{12}(f)+R_3(f)p_2^{-2}(f,n_2,d_2)}{1+r_{12}(f)p_2^{-2}(f,n_2,d_2)} \tag{4}$$

$$R_{total}^3=\frac{r_{01}(f)+R_{eq}^2(f)p_1^{-2}(f,n_1,d_1)}{1+r_{12}(f)R_{eq}^2(f)p_1^{-2}(f,n_1,d_1)} \tag{5}$$

In the reflection measurement, the total reflection signal obtained from the conductive metal mirror was used as a reference and the ratio of the reflected signal to the reference signal of the sample was introduced as the transfer function, which can be obtained as follows.

$$H_{model}(f)=\frac{E_{model}(f)}{E_{model\_ref}(f)}=\frac{R_{total}^3(f)E_{in}(f)}{-E_{in}(f)}=-R_{total}^3(f) \tag{6}$$

1.2 Parameter extraction algorithm

The genetic algorithm, as a kind of the searching optimal solution, can be obtained by simulating the natural evolution process. Fig. 2 shows the flowchart of the Genetic Algorithm (GA) that calculetes the concentration of the thickness and refractive index. First, the method of a genetic algorithm works bases on the coding of the initial population, the initial values of thickness and refractive index are set, each individual is composed of two 15-bit binary data strings, which represents the thickness and refractive index of the middle layer. Secondly, all individuals in the population fitness are calculated. Third, through a series of selection, crossover and a mutation genetic, which operators according to the principle of selection and keeps individuals in a high fitness, a new generation of the population is obtained. Therefore, the genetic search direction in a part of the solution space can be more adapted to disclose the optimal solutions. Finally, the best result of the thickness and refractive index are obtained by decoding. A genetic algorithm relies on the selection of optimization function of the initial value and function of convergence. However, repeated operations may provide different results. Thus, in order to guarantee the stability of the results, on the one hand, strict restriction conditions are given, and on the other hand, the fitness value of the best chromosome is compared through multiple runs, and the minimum fitness value is selected to obtain the optimal solution[14-15].

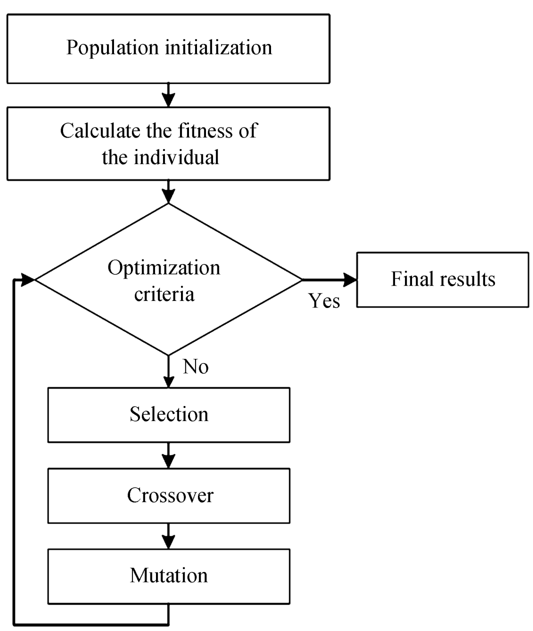

Fig. 2 Flow chart of genetic algorithm

The fitness function in the above method is obtained by calculating the Mean Squared Error (MSE) of the measured transfer function and the modeled function obtained by the model. As shown in Fig. 3, the incident wave $E_{in}(t)$ was directly coincided with the sample surface in an actual measurement. Whereas, the reflected wave $E_R(t)$ contained information (d_i, n_i) on the medium in the middle layer, etc. When only the conductive mirror is available, the reference reflected wave $E_{ref}(f)$ can be obtained. The deconvolution of the frequency of the measured time signal can be shown as

$$H_{meas}(f)=\frac{E_{meas}(f)}{E_{meas\_ref}(f)} \tag{7}$$

$E_{meas}(f)$ is the Fourier transform of the time domain signal $E_R(t)$, and $E_{ref}(f)$ is the Fourier transform of the reference reflected wave $E_{ref}(t)$, in the frequency domain. Therefore, Fig. 3 is a simplified parameter estimation flow chart. Since this model contains unknown quantities such as material parameters, we compared the measured signals with that of the model. By comparing the mean square error and using the genetic algorithm, the unknown parameter set was constantly updated and, therefore, the optimal parameter combination solution was solved.

$$\mathrm{MSE}=\frac{1}{n}\sum_{i=1}^{n}|H_{model}(f_i)-H_{meas}(f_i)|^2 \tag{8}$$

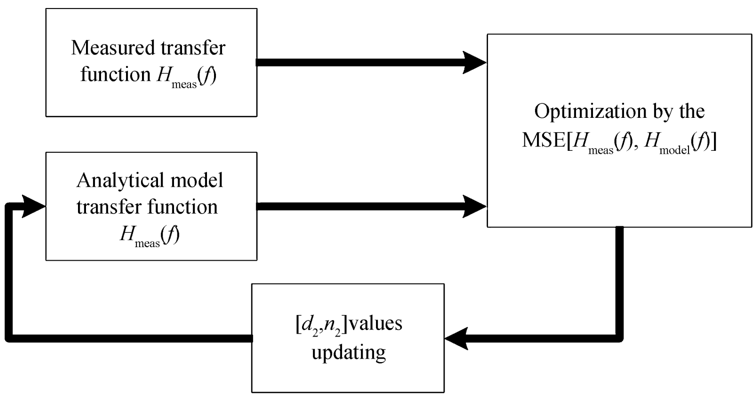

Fig. 3 Flow chart of parameter estimation algorithm

2 Experimental setup and samples

2.1 Experimental setup

THz-TDS is a new physical method for measuring and analysis, which has been developed rapidly in recent years. THz-TDS is a powerful tool to detect and analyze the physical properties of materials. It adopts the coherent detection technology to obtain the spectral signal of the terahertz transmitted or reflected from samples and is generally based on an electric-field time-domain waveform. After transformation of the frequency domain, the spectral information related to the essence of samples such as refractive index and absorption coefficient can be directly obtained[16].

The THz time-domain spectral system used in this study is produced by the Zomega company in the United States. The bandwidth range of the system is 0.1 ~ 4 THz, the dynamic range is greater than 58 dB, and the measurement delay time is up to 100 ps. The system can provide transmission and reflection modes and the output power is 20 ~ 30 mW, include fiber optic femtosecond lasers, emitters and detectors. The laser pulse interacts with the optical conducting antenna to produce a THz pulse with a terahertz pulse width of 250 fs, a time-domain range of 0 to 100 ps, a resolution of 0.05 ps, and a spot diameter of 1 mm for the terahertz wave. The structure of this system is shown in Fig. 4[17], the reflection mode and vertical incidence are used in the paper. The femtosecond laser emits a linearly polarized femtosecond pulse laser with a pulse width of less than 20 fs, which is divided into two beams by a Beam Splitter (BS), a pump laser and a detection laser. The femtosecond pulse laser emitted by the femtosecond laser is divided into two beams by the BS, which are the pump laser and the detection laser. The detection laser is adjusted by the polygon mirror and incident on the

ZnTe crystal together with the sample reflected pulse. The detection laser and the reflected pulse of the sample produce a second-order nonlinear effect on the ZnTe crystal to change the polarization state of the detection laser, and the polarization angle of the beam is adjusted through a Quarter Wave Plate (QWP). The Wollaston Prism (WP) divides the orthogonal polarization component of the beam into two beams at a specific angle, and the balanced and amplified photodetector performs photoelectric conversion and differential output electrical signals. In this process, the terahertz detector converts the reflected pulse of the sample containing the position information into the corresponding electrical signal. The size of this signal is proportional to the intensity of the reflected pulse and the corresponding data can be finally collected and processed by a computer[18-19].

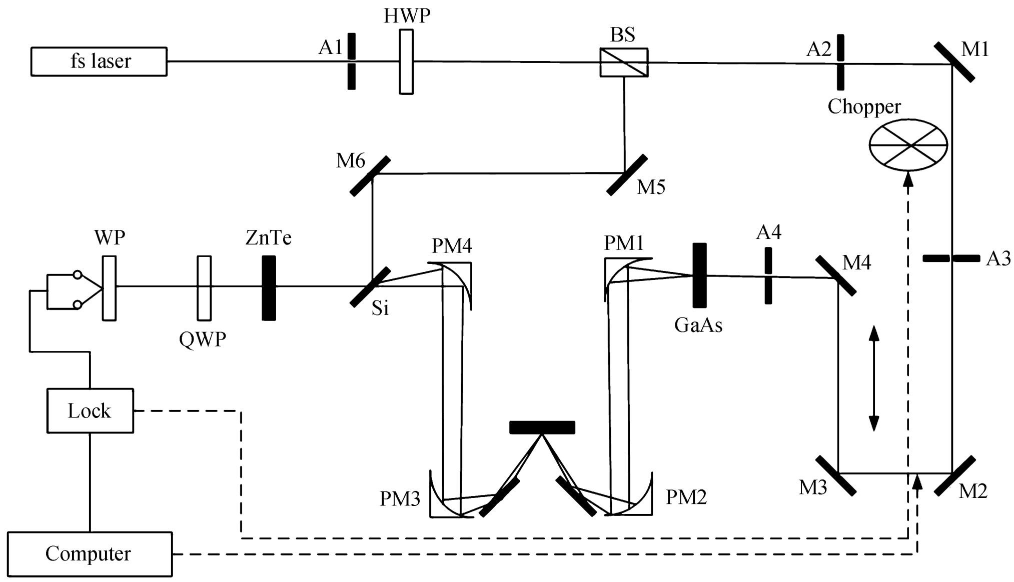

Fig. 4 Schematic diagram of reflection mode measurement method

2.2 Sample preparation

In order to verify the accuracy of the multi-layer model parameter extraction method, polyethylene (PE) powder and PVC thin sheets were pressed to obtain a sample of the three-layer including pe-pvc-pe, as shown in Fig. 5. Both materials are dispersion-free. The polyethylene powder and PVC film used in this experiment showed low absorption characteristics to the terahertz waves and, thus, a low refractive index was attained because the terahertz wave can pass through these two materials[20].

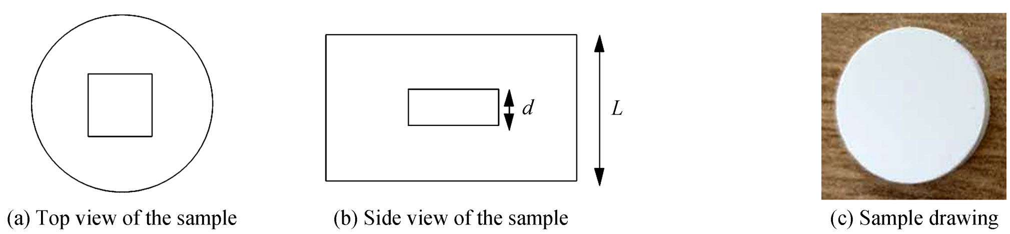

Fig.5 Sample design drawing and physical appearance drawing

A specific route for the preparation of the PE powder embedded with a PVC sheet (0.2 mm×0.2 mm thickness) after hydraulic pressure, firstly involves a PVC sheet with a 0.2 mm specification, cutting for 1 mm×1 mm square with the weight of 0.150 g. Then, poured into a diameter of 2 mm mould and induced by a powder pressing pressure to attain the cut out good PVC sheet (called 0.15 g PE powder). Again a 10 MPa hydraulic pressure was induced to the PVC sheet to get the tablets.

A PVC sheet (0.2 mm) was embedded in the middle of PE powder, which was put into a mold and pressed into a tablet with a diameter of 2 mm by a hydraulic press. Hold the tablet at the pressure of 10 MPa for 30 s, then relaxed for one min. 0.3 g weight and 0.2 g weight of PE powders were prepared, respectively. The tablets without PVC sheet were used to compare and extract the absorption coefficient and refractive index of the PE powder. The size of each sample was 2 mm in diameter and the thickness was about 1.8 mm.

3 Results and discussions

To validate the method proposed in the paper, we designed eight samples with three layers. Each sample was measured by THz-TDS to obtain the reflection spectrum and reference spectrum, as shown in Fig. 6. In the experiment, the reflective THz-TDS technique was used to obtain the test data, and the angle of incidence is normal. Firstly, the time domain waveform of THz, passing through the air was extracted as the reference signal. Then, the time domain waveform of the THz wave passing through the sample was extracted as the sample signal waveform. Secondly, Fourier transform was carried out on the reference and sample signal waveforms, respectively, and the transfer function of the measured sample was obtained through deconvolution. The measured transfer function was compared with the theoretical model derived in 3.1 and the GA (genetic algorithm) was used to solve the two unknown parameters, including the hidden layer thickness and refractive index in the theoretical model. In order to reduce the random error, three groups of samples were prepared in this experiment. Table 1 shows the true thicknesses measured by the thickness gauge, the true value of refractive index, the estimated hidden layer thickness, and the comparative refractive indices.

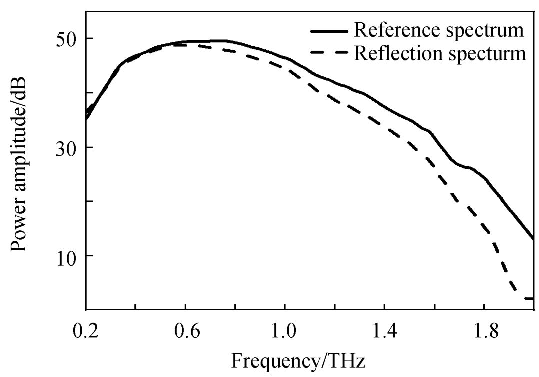

Fig.6 Reference spectrum and reflection spectrum of terahertz waves incident vertically on the surface of the sampl

Table 1 The sample thickness, refractive index and quantitative error were obtained by genetic algorithm

No.	Method	Thickness/mm	Error/%	Refravtive index	Error/%
1	Mesured value	0.200	1	1.670	0.8
	Estimated value	0.202		1.684	
2	Mesured value	0.200	2.5	1.670	12.8
	Estimated value	0.205		1.885	
3	Mesured value	0.200	4	1.670	12.8
	Estimated value	0.208		1.884	
4	Mesured value	0.200	0.15	1.670	1.5
	Estimated value	0.203		1.695	
5	Mesured value	0.200	1	1.670	12.7
	Estimated value	0.202		1.882	
6	Mesured value	0.200	1	1.670	0.9
	Estimated value	0.198		1.685	
7	Mesured value	0.200	2	1.670	0.6
	Estimated value	0.204		1.680	
8	Mesured value	0.200	0.5	1.670	0.5
	Estimated value	0.201		1.679	

As for the thickness estimation error, it can be seen that the thickness estimation error was less than 4%. In addition, the reason for the error was due to the hidden layer, which can not be placed completely horizontally in the sample pressing process. Therefore, a certain tilt may exist, leading to deviation of the measurements. On the other hand, the crossover and mutation probability in GA may have a certain influence on the obtained results.

As for the refractive index error, it can be seen from Table 1 that the errors of No. 2 and 3 samples are as high as 12.8%. On the other hand, the error of the estimated refractive index of other samples is relatively small. On the one hand, the selection of the initial value of genetic algorithm, the number of iterations and other factors will have a great impact on the estimated result; on the other hand, the measurement result of the system will be affected by the system noise, sample uniformity and so on, leading to a large deviation of the measured value. In the end, if the refractive index of the medium is calculated from the complex dielectric constant model, the refractive index estimation will be more accurate.

4 Conclusion

The THz-TDS system is firstly introduced in the reflection mode by consideration of the low absorptivity of the terahertz in the polyethylene powder and polyvinyl choride (PVC). Another research objective is focused on the specific production of polyethylene powder inside the tablet containing PVC, which leads to a three-layered sample with a composite structure. THz-TDS system can measure the samples through the deconvolution process and gets the transfer function data. Then, the transmission model of the terahertz waves in the three-layer medium in the reflection mode is derived according to the transmission characteristics of the terahertz waves through multiple transmissions and reflections in the three-layer structure by using the Rouard equivalent interface theory to describe the propagation of waves in a multi-layer structure. The unknown quantities in the model include the thickness and refractive index of the middle layer, which can be ascribed in this method. Finally, through calculation of the GA theory of minimum error and measured transfer functions, we can estimate the thickness of the hidden layer of PVC sheet along with the refractive index to guarantee the stability of the results. In addition, this investigation puts forward strict restrictions, through many times running and by every time comparison of the best fitness value of chromosome with fitness value of the minimum to get the optimal solution. Compared to the results of thickness gauge, the error sources of the estimated results are analyzed and the accuracy of this method is verified.

References

[1] DONG Junliang, LOCQUET A, CITRIN DS. terahertz quantitative nondestructive evaluation of failure modes inpolymer-coated steel[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2017, 23(4): 1-7.

[2] WIETZKE S, JANSEN C, JUNG T, et al. Terahertz time-domain spectroscopy as a tool to monitor the glass transition in polymers[J]. Optics Express, 2009, 17(21): 19006-19014.

[3] PALKA N, RYBAK A, JAKUBOWSKI T. Monitoring of air voids at plastic-metal interfaces by terahertz radiation[J]. Infrared Physics & Technology, 2020, 104: 9.

[4] MURATE K, KAWASE K. Perspective: terahertz wave parametric generator and its applications[J]. Journal of Applied Physics, 2018, 124(16): 10.

[5] IM K H, KIM S K, JUNG J A, et al. NDE characterization and inspection techniques of trailing edges in wind turbine blades using terahertz waves[J]. Journal of Mechanical Science and Technology, 2019, 33(10): 4745-4753.

[6] LOPATO P. Automatic defect recognition for pulsed terahertz inspection of basalt fiber reinforced composites[J]. Compel - The international Journal for Computation and Mathematics in Electrical and Electronic Engineering, 2016, 35(4): 1346-1359.

[7] IM K H, KIM S K, JUNG J A. Terahertz scanning techniques for paint thickness on CFRP composite solid laminates[J]. Journal of Mechanical Science and Technology 2016; 30(10): 4413-4416.

[8] CAO Binghua, WANG Mengyun, LI Xiaohan, et al. Noncontact thickness measurement of multilayer coatings on metallic substrate using pulsed terahertz technology[J]. IEEE Sensors Journal, 2020, 20(6): 3162-3171.

[9] KRIMI S, KLIER J, JONUSCHEIT J, et al. Highly accurate thickness measurement of multi-layered automotive paints using terahertz technology[J]. Applied Physics Letters, 2016, 109(2): 021105.

[10] DONG Junliang, POMARÈDE P, CHEHAMI L, et al. Visualization of subsurface damage in woven carbon fiber-reinforced composites using polarization-sensitive terahertz imaging [J]. NDT and E International, 2018(99): 72-79.

[11] KRIMI S, TOROSYAN G, BEIGANG R. Advanced GPU-based terahertz approach for in-line multilayer thickness measurements[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2017, 23(4): 1-12.

[12] KNIFFIN G P, SCHECKLMAN S, CHEN J, et al. Measurement and modeling of terahertz spectral signatures from

layered material[C]. Conference on Active and Passive Signatures, 2010, 7687(8): 1-11.

[13] WANG Jie, ZHANG Jin, CHANG Tianying, et al. Terahertz nondestructive imaging for foreign object detection in glass fibre-reinforced polymer composite panels[J]. Infrared Physics & Technology, 2019, 98: 36-44.

[14] LI Zhi. Genetic algorithm that considers scattering for THz quantitative analysis[J]. IEEE Transactions on Terahertz Science and Technology 2015, 5(6): 1062-1067.

[15] KNIFFIN G P, ZURK L M. Model-based material parameter estimation for terahertz reflection spectroscopy[J]. IEEE Transactions on Terahertz Science and Technology, 2012, 2(2): 231-241.

[16] RYU C H, PARK S H, KIM D H, et al. Nondestructive evaluation of hidden multi-delamination in a glass-fiber-reinforced plastic composite using terahertz spectroscopy[J]. Composite Structures, 2016, 156: 338-347.

[17] ZHANG Jin, WANG Jie, HAN Xiaohui, et al. Noncontact detection of teflon inclusions in glass-fiber-reinforced polymer composites using terahertz imaging[J]. Applied Optics, 2016, 55(36): 10215-10222.

[18] ABINA A, PUC U, JEGLIČ A, et al. Structural characterization of thermal building insulation materials using terahertz spectroscopy and terahertz pulsed imaging[J]. NDT & E International, 2016, 77: 11-18.

[19] ZHONG Shuncong. Progress in terahertz nondestructive testing: A review[J]. Frontiers of Mechanical Engineering, 2018, 14(3): 273-281.

[20] CATAPANO I, SOLDOVIERI F, MAZZOLA L, et al. THz imaging as a method to detect defects of aeronautical coatings[J]. Journal of Infrared, Millimeter, and Terahertz Waves, 2017, 38(10): 1264-1277.