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Terahertz composite imaging method

QIAO Xiaoli[a]，REN Jiaojiao[b]，ZHANG Dandan[b]，CAO Guohua[a]，LI Lijuan[b]，ZHANG Xinming[a*]

(a.College of Mechanical and Electronic Engineering；b.College of Opto-electronic Engineering，
Changchun University of Science and Technology，Changchun Jilin 130022，China)

Abstract: In order to improve the imaging quality of terahertz(THz) spectroscopy, Terahertz Composite Imaging Method(TCIM) is proposed. The traditional methods of improving THz spectroscopy image quality are mainly from the aspects of de-noising and image enhancement. TCIM breaks through this limitation. A set of images, reconstructed in a single data collection, can be utilized to construct two kinds of composite images. One algorithm, called Function Superposition Imaging Algorithm(FSIA), is to construct a new gray image utilizing multiple gray images through a certain function. The features of the Region Of Interest (ROI) are more obvious after operating, and it has capability of merging ROIs in multiple images. The other, called Multi-characteristics Pseudo-color Imaging Algorithm(McPcIA), is to construct a pseudo-color image by combining multiple reconstructed gray images in a single data collection. The features of ROI are enhanced by color differences. Two algorithms can not only improve the contrast of ROIs, but also increase the amount of information resulting in analysis convenience. The experimental results show that TCIM is a simple and effective tool for THz spectroscopy image analysis.

Keywords: composite imaging；function superposition imaging；multi-characteristics pseudo-color imaging；terahertz spectroscopy image analysis

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1 Introduction

THz spectroscopy carries a large number of physical and chemical properties, and it is an important role for studying optical properties of a sample in THz band[1-3]. The imaging technology is a very important research direction in THz spectroscopy analysis. The general imaging process is that scanning the sample, and reconstructing image based on the spectral matrix. A reconstructed characteristic parameter image can show the internal structure from a certain aspect. Obviously, multiple images can be reconstructed with different spectral characteristic parameters. For example, the spectral maximum amplitude flight delay image, the power spectrum image and so on[4-6]. Despite the images have differences between each other, the internal structures depicted are strictly coincident. This feature is a prerequisite for TCIM.

THz spectroscopy image analysis requires to combine manual judgment with data analysis, especially in nondestructive testing[7-10]. The image is required to clearly and intuitively show the structure of the sample, and has capability of guiding the observer to accurately locate ROI. After locking ROIs, the observer utilizes one or more characteristic images for qualitative or quantitative analysis[11]. For example, to determine whether there are inclusions in the multilayer bonding structure sample, the power spectrum imaging is generally chosen, and the power of the inclusions area is generally different from that of the normal region. After selecting ROIs, the depth of the inclusions buried will be determined through the maximum amplitude flight delay parameter. As can be seen from this example, THz spectroscopy image plays a crucial role, which guides the observer to right analysis directions.

A single characteristic image is only a view abstraction of the sample. Therefore, it is difficult to qualitatively or quantitatively analyze only depending on a single image. In experiments of this paper, a Ceramic Matrix Composite(CMC) sample is fabricated, which includes staples and a thin plastic plate in the adhesive layer. In the reconstructed maximum

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***Corresponding author:** ZHANG Xinming　email:zxm@cust.edu.cn

amplitude flight time image, the staples are almost invisible, and the plastic plate is very clear. In the reconstructed power spectrum image, the staples and the edge of the plastic plate are clear, but the gray value in interior of the plastic plate is very similar to that in normal area. This indicates that there are certain relationships between the imaging methods and analytical purposes.

In order to achieve the purpose of rapid analysis, the best image should have two features: firstly, the image clearly shows the internal structure; secondly, the image contains the integrated information of multiple characteristic parameters. At present, researchers have done a lot of work in improving image quality. The main techniques are the following two aspects:

1) Filtering the noise of the THz spectroscopy[12-13];

2) Utilizing image enhancement algorithm[14-15].

These approaches can improve the image quality, but with limited capacities. In this paper, we propose TCIM basing on the existing research results including two aspects:

1) FSIA. Establishing a function basing on several different characteristic parameter images, to construct a new grad image. FSIA is an image enhancement algorithm, but its coefficient enhancement algorithm is different. The coefficient enhancement algorithm of general methods is only based on their own features, for example, gray stretching algorithm[16], histogram equalization algorithm[17-18], Retinex image enhancement algorithm[19-20] and so on. The coefficient enhancement of FSIA is calculated from other relative images. An image is the basis, and the others provide the enhancement scale. Since the image lost physical significance after enhancement operating[21-23], the handled image can only be utilized to improve image quality or determine ROIs , not to analyze data.

2) Multi-characteristics Pseudo-color Imaging Algorithm(McPcIA). Partial images including the FSIs are selected and inserted into RGB channels of a color image. Three characteristic parameter images can be used to analyze in a single pseudo-color image at the same time. Obviously, analysis efficiency is drastically promoted.

2 Principle

2.1 FSIA principle

FSIA can be described as:

$$T_{n+1} = f(T_0, T_1, T_2, \dots T_n) \tag{1}$$

Where, $T_0 \sim T_n$, a set of reconstructed characteristic images in a single data collection, are the superposition functions built on this image set; and T_{n+1} is the constructed new image. Function f can operate the entire or part of images set. It can be very simple four arithmetic operations, power operation, logarithmic operation and so on. In particular, it can even be a logical operation. There are two main purposes of FSIA:

1) Multiple ORIs are superimposed on a single image. The different characteristic images are sensitive to different structures or properties of the samples. Therefore, there are only a part of ROIs to be shown in a single image. FSIA has a capability of superimposing ORIs distributing in the multiple images and avoiding omitting analysis targets.

2) Image enhancement for ROIs. We could select some isotropic images to add or multiply, or select same anisotropic images to do subtract or divide. After operating, the features of ROIs will be outstanding.

In order to improve the analysis efficiency, it is necessary to construct Multi-characteristics Pseudo-color Image(McPcI).

2.2 McPcIA principle

McPcIA can be described as:

$$T = \{T_{ij} = (TR_{ij}, TG_{ij}, TB_{ij}) \mid 0 \leqslant i < M, 0 \leqslant j < N\} \tag{2}$$

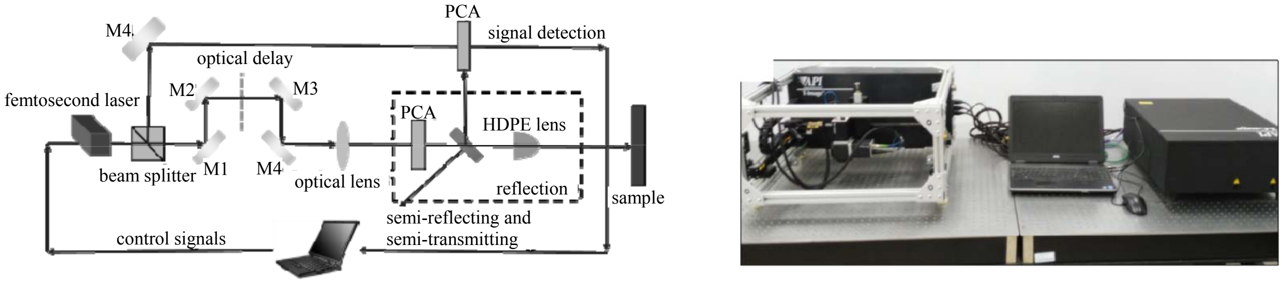
Where, M and N are the number of the rows and the columns in McPcI. TR means red channel image; TG means green channel image; TB means blue channel image.

Through inserting different characteristic images into different color channels, a pseudo-color image showing the internal structure of the tested sample, can be constructed. The normal pseudo-color image construction approach is that mapping the grayscale into RGB color space[24-25]. Essentially, this approach improves the image resolution, but does not increase the amount of information. McPcIA is an essential and effective tool for improving the amount of information carried in a single color image. The RGB value of every point will show multiple properties information about this location of a sample. At the same time, different color distributions emphasize the feature of ROIs.

3 Experiments

3.1 Measurement principle and experimental equipment

We did same experiments based on Terahertz Time-Domain Spectroscopy(THz-TDS). Measurement principle[26-27] and the experimental equipment are shown in Fig.1. The femtosecond laser pulse is divided into a high-energy beam and a low-energy one. The high-energy beam, as the pump pulse, irradiates the Photoconductive Antenna(PCA) and generates THz-TDS pulse. The low-energy beam, as the probe pulse, and THz pulse act on the PCA together. Finally, through the electro-optic sampling measurement, we can obtain the time-resolved THz pulse.



(a) the view of measurement principle (b) the view of the experimental equipment

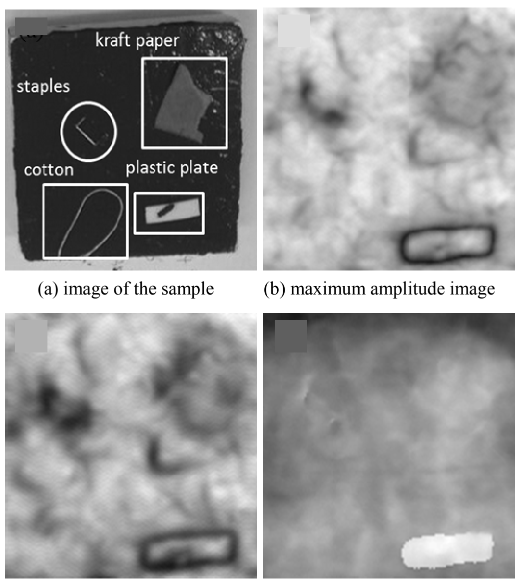
Fig.1 The views of measurement principle and the experimental equipment

The experimental equipment is T-ray 5 000 spectroscope of Picometrix with reflected and transmitted modes. Our experiments are based on the reflected mode.

3.2 Sample preparation

The two Ceramic Matrix Composites(CMCs) are pasted together into an experimental sample. During the preparation process, some inclusions are added, including a piece of irregular craft paper, a staple and a thin plastic plate, as shown in Fig.2(a).The cotton is too thin to be observed in the characteristic images.

The samples are scanned, and the images are reconstructed based on maximum amplitude, power spectrum and maximum amplitude flight time, as shown in Fig.2(b), 2(c) and 2(d).



(a) image of the sample (b) maximum amplitude image

(c) power spectrum image (d) maximum amplitude flight time image

Fig.2 The views of the sample and reconstruction

3.3 FSIA experiments

Superimposing the maximum value image defined *M* image, the power spectrum image defined *P* image, the maximum amplitude flight time image defined *F* image to construct same new gray images, by FSIA, as shown in Fig.3. Obviously, we obtain a set of clearer gray images based on same simple functions.

These images enhanced are different from the conventional enhanced images as followed:

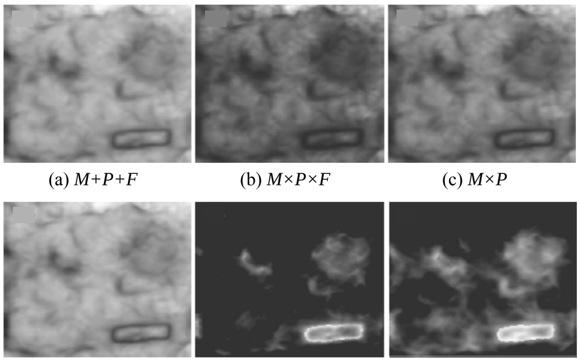
1) The simple algorithm, avoiding threshold and coefficient selections, can obtain satisfactory results.

2) Superimposing the information of a set of images into a single image.

3.4 McPcIA experiments

McPcIA is generated by inserting M image into R channel, inserting P image into G channel and inserting F image into B channel, as shown in Fig.4(a).

Picture 4(a) shows the imaging result with un-enhanced image. Picture 4(b) is the result of which B channel is replaced with $M+F$ image. Picture 4(c) is the square operation result on every channel of picture 4(a). Since the physical meaning of the reconstructed image by FSIA has lost, only one handled image is selected and input into B channel based on picture 4(a). We obtained a set of images according to the order in Fig.3, as shown in Fig.4(d)–(i). The experiment results show that McPcIA is helpful for ROIs determinations and improving analysis efficiency.



(a) $M+P+F$　(b) $M\times P\times F$　(c) $M\times P$　(d) $M+P$　(e) $F-M$　(f) $F-P$

Fig.3 FSIA results

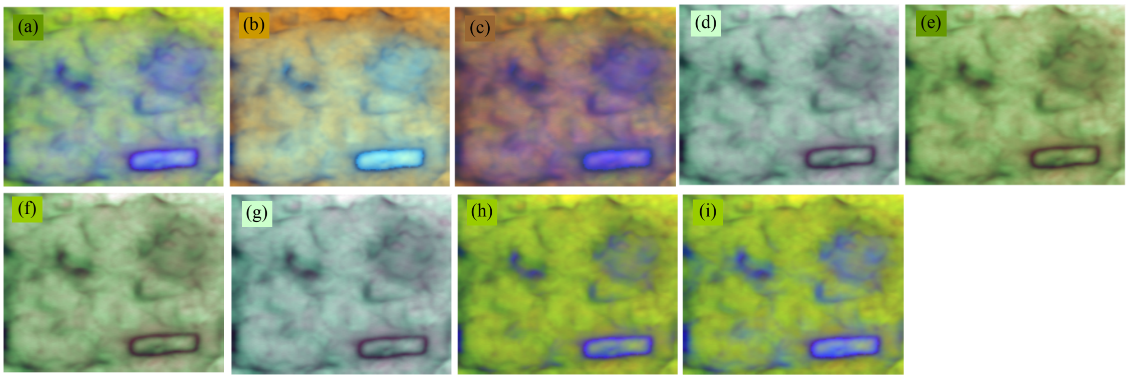
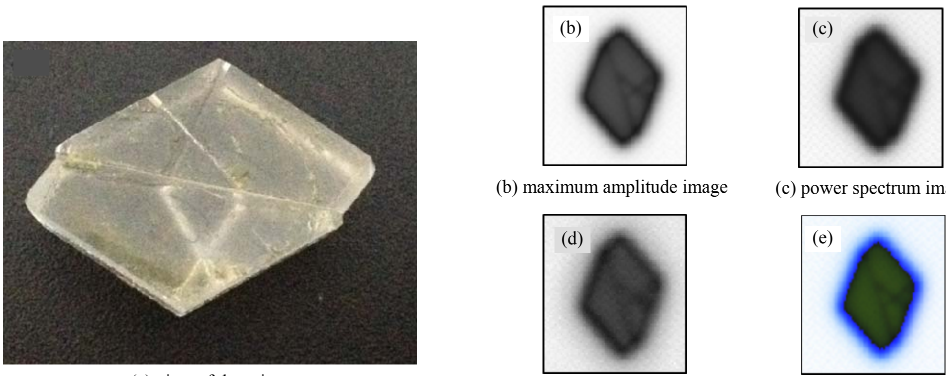


Fig.4 McPcIA results

3.5 Other samples experiments

A piece of multifaceted prism is scanned and reconstructed, as shown in Fig.5. The intersection lines of the prism is shown more clearly in picture 5(e).



(a) view of the prism　(b) maximum amplitude image　(c) power spectrum image　(d) maximum amplitude flight time image　(e) McPcI

Fig.5 Experiment results of multifaceted prism

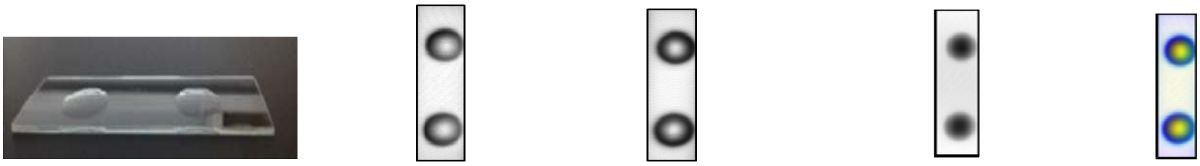
A slide glass substrate is scanned and reconstructed, as shown in Fig.6. In this experiment, we analyze the structure of the sample utilizing picture 6(e).

3.6 Algorithm complexity analysis

The algorithm execution efficiency can usually be measured by the time and space complexity. With the fall in the price-performance ratio of storage, space complexity is barely noticed, but higher executive speed is still expected. The time complexity of restructuring an image by FSIA can be described as:

$$T(n) = O(n) \tag{3}$$

Where, $T(n)$ is the calculation quantity and $O(n)$ is the linear order time complexity. Equation (3) shows the FSIA execution efficiency is only relative with the size of the image. Therefore, the algorithm has a high execution efficiency.



(a) view of the sample (b) maximum amplitude image (c) power spectrum image (d) maximum amplitude flight time image (e) McPcI.

Fig.6 Experiment results of a slide glass substrate

4 Conclusion

FSIA and McPcIA are the cores of TCIM. FSIA expands the set of terahertz spectroscopy images, and can generate numerous of new images being utilized to determinate ROIs. McPcIA can provide more information for analysis and result in higher efficiency and accuracy. We have already applied TCIM to terahertz nondestructive examination(THz-NDE) and achieve good effect. We can draw a conclusion that TCIM is a simple and effective tool for terahertz spectroscopy image analysis based on theoretical analysis, verification experiments and applications.

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About the author：

QIAO Xiaoli(1979-), was born in Liaoyuan, Jilin Province, assistant research fellow, current research involves THz imaging technologies, nondestructive testing and digital signal processing. email: qiaoxiaoli@cust.edu.cn.

CAO Guohua(1965-), was born in Jiamusi, Heilongjiang Province, professor, current research involves electromechanical system control.

ZHANG Xinming(1967-), was born in Qiqihar, Heilongjiang Province, professor, current research involves ultra-precision machining, testing and assembling.

REN Jiaojiao(1988-), was born in Lyuliang, Shanxi Province, doctor degree, current research involves THz imaging technologies and nondestructive testing.

ZHANG Dandan(1990-), was born in Changchun, Jilin Province, doctor degree, current research involves THz imaging technologies and nondestructive testing.

LI Lijuan(1972-), was born in Henan Province, professor, current research involves digital assembly and precision measurement.