Experimental research on terahertz scanning imaging system based on S-parameters

Yanbo Zhang\textsuperscript{a}, Xiangdong Li\textsuperscript{b}, Xingwen Zhao\textsuperscript{c}, Xianzhong Tian\textsuperscript{d} and Zijiang Yang\textsuperscript{e}

\textsuperscript{a}Key Laboratory of UWB & THz of Shandong Academy of Sciences, Institute of Automation, Qilu University of Technology(Shandong Academy of Sciences), Jinan 250014, China

\textsuperscript{b}email:Lxd0191@163.com, \textsuperscript{c}email:zwl1671@163.com, \textsuperscript{d}email:tianxianzhong@gmail.com, \textsuperscript{e}email:yangzj@sdas.org.

*corresponding author: \textsuperscript{e}email:zhangyb@sdas.org.

Abstract—Due to the limitations of the detector in the terahertz (THz) scanning imaging process and the problems of low contrast and poor visualization effect of original image, a THz continuous-wave scanning imaging system from 75 to 110 GHz is presented. The system is comprised of vector network analyzer (VNA), spread spectrum module, transmit and receive antennas, scanning stage and host computer. In addition, the automatic acquisition and storage of S-parameters is realized by Virtual Instrument Software Architecture (VISA) protocol, and the gray imaging method based on S-parameters is proposed. High-precision structural resolution test board is designed based on printed circuit board (PCB) method and the imaging experiment for the resolution test board is carried out. By comparing with original imaging results, better imaging quality of the system designed in this paper is obtained and imaging results show that the resolution of 1.8 mm could be achieved.

1. Introduction
Terahertz (THz) radiation with a frequency range of 0.1~10THz (wavelength range of 3000~30μm), sandwiched between microwave and infrared, belongs to far infrared region\cite{1-2}. THz technology is regarded as an important frontier science and technology, and has developed rapidly in recent years. Compared with other electromagnetic waves, THz has the characteristics of low quantum energy, high coherence and penetrability for dielectric materials. Therefore, THz is suitable for non-contact and non-destructive imaging. Due to its unique properties, THz imaging technology has great potential application in security screening, nondestructive testing, aerospace and other fields \cite{3-4}.

THz imaging can be divided into continuous-wave imaging and pulse imaging according to the imaging mode. Compared with pulse imaging technology, THz continuous-wave imaging technology can provide higher radiation intensity than pulse source. During the whole emission period of THz source, there is continuous output of waveform, which can detect deeper samples\cite{5-6}. At present, THz continuous-wave imaging is mainly divided into scanning imaging and array imaging. Array imaging is limited by terahertz device technology and has high construction cost. THz continuous-wave scanning imaging is a common imaging method and it can obtain the THz image of the object by scanning the object point by point\cite{7-8}.
Due to the limitation of the detector in the THz scanning imaging process, it cannot respond to small signals and the signal-to-noise ratio is low, resulting in low resolution and blurred image of the original THz image. Here, we propose a THz continuous-wave reflection scanning imaging system with a frequency range of 75~110 GHz (as shown in Fig.1 and Fig.2). It is helpful for noise suppression and visual effect improvement by adopting image processing methods after imaging experiments.

2. Scanning Imaging System

2.1. System structure
In our work, the THz continuous-wave scanning imaging system includes a four-port vector network analyzer (VNA), a spread spectrum module, a two-dimensional scanning stage and a host computer, and adopts reflective imaging mechanism. The schematic diagram of the system is shown in Fig.1, while the physical device is shown in Fig.2.

In Fig.2, the VNA is Agilent N5247, the maximum output frequency is 67GHz, and the output power is 2dBm. The spread spectrum module adopts the WR10.0 TxRx transceiver module from VDI company, and the power of the module port is 0dBm. The fundamental frequency signal (Port1) and the local vibration signal (Port3) provided by the VNA are mixed and amplified for 3 times to produce 75~110 GHz electromagnetic wave by the module. The spread spectrum transmitter module provides the reference signal for measurement, and mixes it to obtain the reference intermediate frequency (IF) signal, which is sent to the receiver R1 port of the VNA. The spread spectrum receiving module detects the reflected signal of the sample and mixes it to obtain the measured IF signal, which is sent to the receiver A port of the VNA.

Fig.1 Schematic diagram of THz continuous-wave reflection scanning imaging system.

Fig.2 Photograph of the THz scanning reflection imaging system.
The imaging process of THz scanning system is shown in Fig.3. Firstly, the host computer sets the parameters such as the starting frequency, termination frequency, data points, data form, S-parameters (S11, S21, S12, S22) and other parameters of the VNA based on Virtual Instrument Software Architecture (VISA) protocol. Secondly, the sample is fixed on the two-dimensional scanning stage, and the scanning starting point of the sample is aligned directly below the horn antenna of the spread spectrum transmitter module, then the THz wave incidents to the sample surface. Thirdly, the continuous movement of the sample relative to the horn antenna of the spread spectrum transmitter module is realized under the control of the host computer. In the process of sample scanning, the host computer collects the position coordinates of each scanning point of the sample and the intensity information of S-parameters detected at this position in real time, and saves them as the two-dimensional array. Finally, when the scanning sample is finished, the host computer normalizes the above two-dimensional array and obtains the gray image of the sample.

Fig.3 Flow chart of the THz scanning imaging system.
2.2. Automatic reading of S-parameters

At present, for the measurement of S-parameters, it is generally necessary to manually operate the VNA, and copy the data to the computer through the mobile storage device for calculation and analysis, but the operation efficiency is relatively low. In this paper, the host computer and vector network analyzer are configured in the same IP segment, and the network communication between VNA and host computer is realized by VISA protocol, so as to complete the parameter configuration and the automatic reading and storage of S-parameters. The specific operation steps are shown in Fig.4.

![Flow chart of the S-parameters automatic reading and storage.](image)

The printed circuit board (PCB) shown in Fig.5(a) is used as the sample for experiment. S11 is used to the test variable of S-parameters, and other parameters of the VNA are set as follows, the starting frequency Fs is 75GHz, the termination frequency Ft is 110GHz, the number of sampling points Fn is 210, the data format is Log Mag, and the trigger mode is external trigger. When the THz wave is transmitted to a certain position of the PCB sample, a part of the signal is reflected back to the VNA through the spread spectrum receiving module, then the S11 can be described as

\[
S_{11} = 20 \log_{10} \frac{r}{i}
\]

where \( r \) is the reflection power of the Port1, and \( i \) is the input power of the Port1.

The host computer collects S11 of the PCB sample, which is shown in Fig.5.

![S11 of the PCB sample.](image)

In Fig.5, we can see that the amplitude of the S11 in the frequency range of 75~110GHz is between -5dB and -35dB. When the non-stripe of the PCB is detected, the amplitude of the S11 is weakened to -15.57dB at 110 GHz. When the metal stripe of the PCB is detected, the amplitude of the S11 is the largest, about -8.33dB at 110 GHz. Therefore, THz scanning imaging could be realized by using the difference of S11 amplitude.
2.3. Image processing

In the process of scanning imaging, the S11 amplitude of the scanning point stored by the host computer in real time could not be directly used for gray scale imaging. It is necessary to convert the amplitude to the image data, which is mapped to gray level data from 0 to 255. The transformation formula can be expressed as

\[
G_g = 255 \times \frac{S_c - S_{\min}}{S_{\max} - S_{\min}}
\]

where \(G_g\) is the image gray value after S11 amplitude conversion, \(S_c\) is the current S11 amplitude, \(S_{\min}\) is the minimum value in the collected S11 two-dimensional array, and \(S_{\max}\) is the maximum value in the collected S11 two-dimensional array.

Aiming at the characteristics of low contrast, low resolution and inhomogeneity in the local area of the THz original image, the gray level of the image is dynamically stretched to 0~255, then the influence of noise on THz image could be reduced, and image contrast could be improved. The transformation formula can be expressed as

\[
T_2 = (T_1 - 1) \times \frac{G_k - G_{\min}}{G_{\max} - G_{\min}}
\]

where \(T_2\) is the gray value of the image after stretching, \(T_1\) is the gray level of the image stretching, \(G_k\) is the gray value of the K pixel, \(G_{\min}\) is the minimum gray value in the image, and \(G_{\max}\) is the maximum gray value in the image.

After the contrast dynamic is stretched, the dynamic range of THz image gray distribution is narrow, resulting in little difference between the target and the background, then the image visualization effect is still poor. By use of the histogram equalization algorithm, the histogram components of the original image are transformed from uneven distribution to uniform distribution, so that the image can cover the whole gray range and realizes image enhancement. The calculation formula can be expressed as

\[
E_k = T(R_j) = \sum_{j=1}^{k} P_n(R_j) = \sum_{j=1}^{k} \frac{N_j}{N}
\]

where \(E_k\) is the gray level of the processed image, \(R_j\) is the gray level of the input image, \(N_j\) is the number of pixels with gray level \(R_j\), and \(N\) is the sum of image pixels.

3. Experiments

3.1. Experimental samples

In order to effectively detect the imaging performance of the THz continuous-wave reflection scanning imaging system, we adopt the methods of the PCB, copper coating and etching on the epoxy resin board, and make a high-precision structural resolution test board as experimental sample, the experimental samples are shown in Fig.6.

![Fig.6 The samples of resolution test board. (a) stripes width:2.2mm, (b) stripes width: 1.7 mm and 1.8mm, (c) circular hole diameter:1.7mm, 1.8mm and 2.2mm.](image)

In Fig.6(a), the width of the stripe is 2.2mm, the stripe spacing is 2.2mm, and the stripe spacing is 2.5mm. In Fig.6(b), the widths of transverse stripes are 1.7 and 1.8mm respectively, and the stripe...
spacing is 2.5mm. In Fig.6(c), the diameters of circular holes are 1.7mm, 1.8mm and 2.2mm respectively, and the spacing between the outer edges of circular holes is 3.0mm.

In view of the fact that polytetrafluoroethylene (PTFE) is opaque in the visible band and has great transmittance in the THz band, PTFE is used as the base plate to fix the resolution test board on the two-dimensional scanning table. Firstly, the distance between the horn antenna of the spread spectrum module and the sample surface is adjusted to keep it in the range of 5~6mm. Secondly, the parameters configured by the host computer are as follows: the starting frequency is 75 GHz, the termination frequency is 110 GHz, the number of data acquisition points is 201, the S-parameters is S11, the sample scanning area is 24mm*14mm, 30mm*14mm and 18mm*6mm respectively, the scanning step is 0.2mm, and the scanning speed is 2.5mm/s. Finally, start scanning imaging experiment.

3.2. Experimental result

Based on the reflection scanning imaging system and the imaging methods provided in this paper, the transverse stripes and circular holes of the resolution test board are scanned and imaged. The experimental results are shown in Fig.7.

From the original imaging results shown in Fig.7(a), Fig.7(c) and Fig7(e), the transverse bright stripes on the resolution test board can be clearly observed. In Fig.7(a), the imaging effect of 2.2mm transverse stripes is the best, with clear contour and smooth edge. In Fig.7(c), the contours of 1.7mm and 1.8mm transverse stripes could be distinguished, but the edges of 1.7mm transverse stripes are blurred and there are sawtooth stripes. In Fig.7(e), three circular holes with different diameters could be clearly distinguished, and there is no obvious deformation of the circular holes. The 2.2mm and 1.8mm diameter circular holes are relatively clear, and the edge of the 1.7mm diameter circular hole is somewhat blurred, which is greatly affected by noise near the imaging area. From the imaging histogram shown in Fig.7, we can see that the gray value of 2.2mm transverse stripes is mainly concentrated in the range of 75~175, the gray value of 1.7mm and 1.8mm transverse stripes is mainly concentrated in the range of 150~220, and the gray value of 1.7mm, 1.8mm and 2.2mm diameter circular holes is mainly concentrated in the range of 50~150. Therefore, the dynamic range of gray value is about 100, which leads to darkness and poor image contrast of the original image.

By Using the gray dynamic stretching and histogram equalization processing methods proposed in this paper, the original image is processed, and the results are shown in Fig.7(b), Fig.7(d) and Fig7(f). We can see that the gray value is obviously separated and almost uniformly distributed in the whole gray level, the gray value is mainly concentrated in the range of 50~200, the dynamic range of gray value can reach more than 150, which results in a 50% increase in the grayscale range. Therefore, the clarity, visualization, brightness and the contrast of the processed image are obviously enhanced, and the quality of the THz image is improved. It can clearly distinguish the edge contour of 2.2mm, 1.7mm, 1.8mm transverse stripes and circular holes, but the 1.7mm transverse stripes have a certain degree of distortion, and the circular hole of 1.7 mm have noise interference. Therefore, it can be concluded that the imaging resolution of the system is at least 1.8mm at 110 GHz.

In addition, sawtooth stripes with different intensities appear in the image shown in Fig.7, and the direction of sawtooth is consistent with the scanning direction of the sample, which is operated by the vibration of the scanning stage[9-10]. When the scanning speed of the stage is significantly accelerated, the corresponding operating noise will also become larger.
Fig. 7 THz image of the sample and its histogram at 110GHz. (a) original image of the sample a, (b) processed image of the sample a, (c) original image of the sample b, (d) processed image of the sample b, (e) original image of the sample c, (f) processed image of the sample c.

4. Conclusion
In summary, we built a 75~110 GHz continuous-wave scanning imaging system based on VNA, at the same time, the automatic acquisition and storage of S-parameters is realized by VISA protocol, and the gray imaging method based on S-parameters is proposed. Self-made resolution test sample is designed based on the PCB, so that system resolution could be correctly evaluated by imaging the test sample and the experimental results show that the resolution of 1.8 mm could be achieved at 110 GHz. Compared with original imaging, the dynamic range of gray value is increased by 50% by adopting image processing methods. Then, the THz image edge contour is clearer, and the imaging quality is improved. These lay the foundation for the realization of high-quality THz continuous-wave scanning imaging and provide an effective way for nondestructive testing of non-metallic materials.

Acknowledgments
This work was supported in part by Science, education and industry integration and innovation pilot project of Qilu University of Technology (Shandong Academy of Sciences) under grant 2020KJC-ZD20, in part by Collaborative innovation fund of Shandong Academy of Sciences of Qilu University of Technology (Shandong Academy of Sciences) under grants (2020-CXY14, 2020-CXY33), in part by Key research and development program of Shandong Province 2021JMRH0108.
References
[1] MITTLEMAN D M. Twenty years of terahertz imaging[J]. Optics Express, 2018, 26(8):9417-9431.
[2] STANTCHEV R I, SUN B, HORNETT S M, et al. Noninvasive near-field terahertz imaging of hidden objects using a single-pixel detector[J]. Science Advances, 2016, 2(6): e1600190.
[3] DONG J, LOCQUET A, CITRIN D. Depth resolution enhancement of terahertz deconvolution by autoregressive spectral extrapolation[J]. Optics Letters, 2017, 42(9):1828-1831.
[4] Wang B, Wang X K, YU Y, etal. Terahertz linear array fast scanning imaging[J]. Chinese Journal of Lasers, 2019, 46(6):0614029.9.
[5] L.Minkevičius, S.Indrišiūnas, R.Šniaukas, G. Račiukaitis, V. Janonis, V. Tamošiūnas, I. Kašalynas, ir G. Valušis, Compact diffractive optics for THz imaging[J]. Lith. J. Phys. 2018, 58(1):1210-1215.
[6] I.Mehdi, J.V.Siles, C.Lee, and E.Schlecht, THz diode technology: Status, prospects, and applications[J]. Proc. IEEE, 2017, 105(6):990-1007.
[7] C.L. Koch-Dandolo, T.Filtenborg, K.Fukunaga, J.Skou-Hansen,and P.U.Jepsen, Reflection terahertz time-domain imaging for analysis of an 18th century neoclassical easel painting, Appl. Opt., 2015, 54(16):5123-5129.
[8] S. Brinkmann, N. Vieweg, G. Gärtner, P. Plew, and A. Deninger, Towards Quality Control in Pharmaceutical Packaging: Screening Folded Boxes for Package Inserts[J]. Infrared, Millimeter, Terahertz Waves, 2017, 38(3): 339-346.
[9] ZHANG X C, SHKURINOV A, ZHANG Y. Extreme terahertz science[J]. Nature photonics, 2017, 11(1):16-18.
[10] KOWALSKI M, KASTE K M, WALCZAKOWSKI M, et al. Passive imaging of concealed objects in terahertz and long-wavelength infrared [J]. Applied optics, 2015, 54(17):3826-383.