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Line Beam Scanning-Based Ultra-Fast THz Imaging Platform

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Featured Application: The work could be applied to the field of human body security.

Abstract: In order to realize rapid THz detecting and imaging, a line beam scanning-based ultra-fast THz imaging platform is designed combining simple optical components and lightweight mechanical system. The designed THz imaging platform has the resolution of 12 mm, the scanning angle range of ±10.5°, the scanning speed of 0.17 s/frame, and the scanning range of 2 m × 0.8 m; moreover, it can realize rapid human body THz imaging and distinguish metallic objects. Considering its high-quality performance in THz imaging and detecting, it is believed the proposed line beam scanning-based ultra-fast THz imaging platform can be used in the future in various safe screening applications.

Keywords: Ultra-fast THz imaging; security screening platform; multiple-input multiple-output; line beam scanning; human body imaging

1. Introduction

In order to contain the increasing threat of terrorism, public security screening systems, especially at airports and railway stations, are becoming increasingly significant. Classical security screening systems include metal scanners for people and X-ray detectors for luggage and have been widely used [1–4]. Unfortunately, these traditional techniques are no longer capable of fulfilling the demands due to their low detection efficiency and high false alarm rate; therefore, developing rapid and precise security screening system is required [5,6].

Recently developed X-ray imaging can easily detect contraband, even concealed under cloths due to the strong X-ray absorption by metals [7–9]. However, considering its high photon energy and ionizing potential, it is harmful to human bodies and only suited for luggage detections. Different from X-ray imaging, THz imaging can also provide target details in another perspective [10–16]: After penetrating the cloths, THz wave is often absorbed by the human body but strongly reflected by metals; therefore, the received reflected THz wave marks the metallic objects [17]. Compared to X-ray, THz wave has a much lower frequency band, which is nonionizing and poses no known health risks [18–22], indicating that THz imaging is especially suitable for security screening for both people and luggage, though there is a lack of efficient sources and detectors [23–25]. The currently proposed THz imaging systems include two fundamental tactics based on synthetic aperture radar (SAR) [26,27] and multiple-input multiple-output (MIMO) [28–31], respectively. SAR-based THz imaging suffers from slow imaging efficiency for each scan, limiting their applications in high-speed security screening. In order to accelerate the efficiency, MIMO-based THz imaging can reduce the scanning time using parallel measurement with an entire array of transmitters and receivers, illustrating that MIMO-based THz imaging is preferred for high-speed security screening platform construction. Here, in order to further accelerate the THz imaging speed, as well as to simplify the system, a line beam scanning-based ultra-fast THz imaging platform is proposed. Its optical system is rather simple, only composed of a source/sensor chip for THz wave emitting and receiving, a cylindrical reflector for wavefront reshaping, and a scanning mirror for line beam scanning. To assemble the optical system, as well as to control the mirror for line beam scanning, a lightweight mechanical system is designed and fabricated. The designed THz imaging platform realizes human body scanning within 0.17 sec in a high resolution of 12 mm and easily distinguishes metallic objects, it is believed the proposed line scanning-based ultra-fast THz imaging platform is a potential tool for fast safe public screening applications.

2. Platform Design and Construction

The optical system of the line beam scanning-based ultra-fast THz imaging platform shown in Figure 1A is rather simple, only composed of a source/sensor chip in Figure 1B, an elliptical cylindrical reflector in Figure 1C, and a scanning mirror in Figure 1A. The source/sensor chip not only emits THz spherical wavefront generated by the emitting antenna, but also detects the THz signals reflected from the target with the receiving antenna: The THz signal with the central frequency of 340 GHz, the bandwidth of 20 GHz, and the peak output power of 0.5 mW, is transmitted from the 4-Tx channels and generates a narrow beam line based on the optical system, and the reflected THz signal from the detecting sample is collected by all the 16-Rx channels. In our case, the THz wave is generated from microwave through frequency multiplication, in which the efficiencies are rather low in both emitting and receiving, much lower than the efficiencies of the THz generation based on photoconductive antenna [23–25], but a rather narrow wavelength band can often be maintained, which can hardly be achieved using photoconductive antenna. Moreover, an elliptical cylindrical reflector was used to reshape the spherical wavefront from the source into the cylindrical wavefront to generate the line beam, as well as to collect the reflected THz signals to the THz sensors. For the elliptical cylindrical reflector, two elliptical foci were conjugated, as the source/sensor chip was located at one focus, the line beam was well generated at another elliptical focus. Moreover, the scanning mirror can realize the line beam scanning with a rather large range and high speed. Considering the practical applications of the THz imaging platform, the distance between the working plane and the scanning mirror was set as 3 m, and the scanning range should reach 2 m $\times$ 0.8 m at the working plane. In order to optimize the optical system, ray tracing algorithm [32] was implemented: after inputting the parameters of the scanning mirror and the elliptical cylindrical reflector, as well as their positions, the THz intensity distribution can be estimated using multiple rays, and according to the numerically computed THz intensity distribution, the configuration of the elliptical cylindrical reflector was finally obtained: The optimized elliptical cylindrical reflector has the radius of the curvature of 554.1 mm and the Conic factor of -0.724. According to the optimized optical system, the intensity distribution at the working plane was then computed as shown in Figure 1D. It is shown that the length of the line beam can reach 0.8 m as provided by the central intensity distribution along the x-axis; besides, according to the central intensity distribution along the y-axis, the full width at half maximum (FWHM) reached 12 mm, indicating the resolution of the THz imaging platform. Via numerical simulations, it is proved that the designed optical system can achieve fast safe screening.

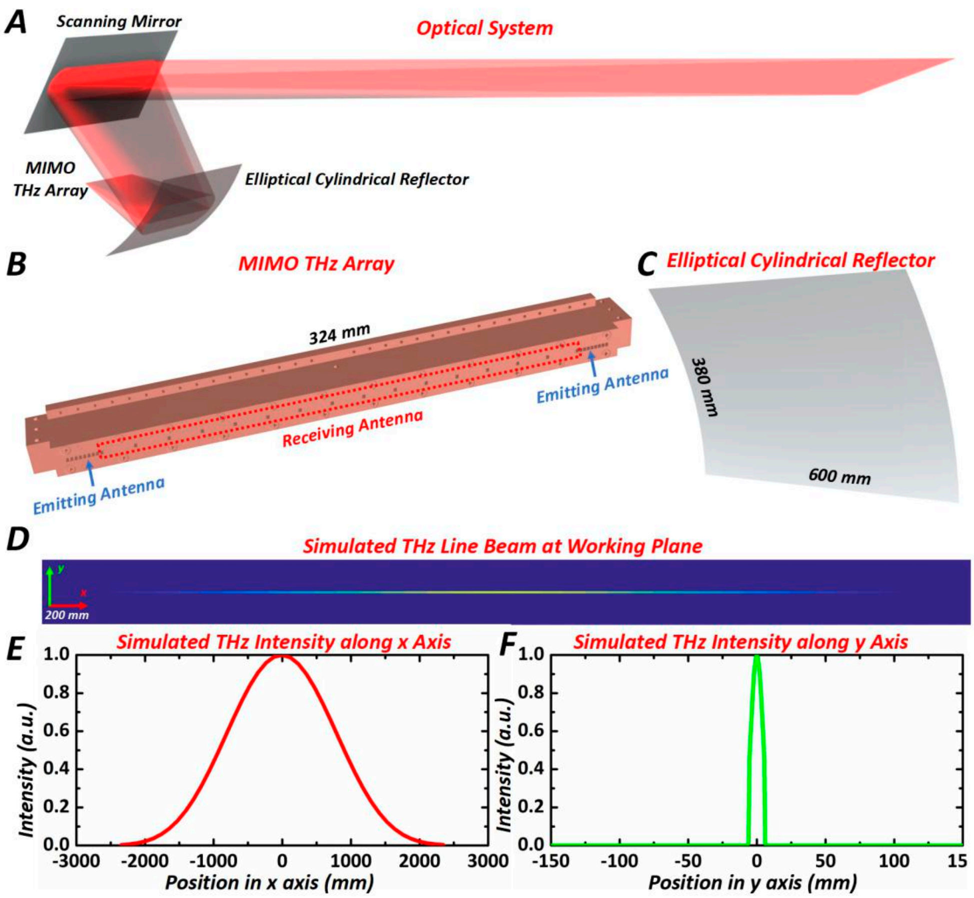

Figure 1. The optical system of the line beam scanning-based ultra-fast THz imaging platform. (**A**) Framework of the optical system; (**B**) the source/sensor chip; (**C**) the elliptical cylindrical reflector; (**D**) the calculated intensity distribution at the working plane; (**E**,**F**) the calculated sectional intensity distributions along the x and y axes.

Next, the mechanical system of the line beam scanning-based ultra-fast THz imaging platform shown in Figure 2A was designed and constructed not only to assemble the optical system, but also to realize line beam scanning by controlling the scanning mirror. In order to realize lightweight design, super-hard aluminum alloy 7075 was used as the materials of both the mechanical system and the mirrors (including the elliptical cylindrical reflector and the scanning mirror); moreover, honeycomb hole array were drilled at the back side of the scanning mirror as shown in Figure 2B to further decrease its weight to 17 kg, which is 34% lighter than without hole drilling. Both the source/sensor chip and the elliptical cylindrical reflector with the size of 380 mm × 600 mm as shown in Figure 2C were fixed at the bottom of the mechanical system, and the scanning mirror with the size of 403 mm × 792 mm combining with the rotation motor (Kollmogen KBMS 43H03, USA, Radford) and the encoder (Heidenhain RCN 2380, Germany, Traunreut) was designed as the scanning section. The encoder chosen had 26-bit circular grating with a precision of ±5″; the rotation motor selected was frameless, which can obtain the rotation range larger than ±9°. Considering the weight of the scanning mirror was less than 250 N required by rotation motor, it is proved that the scanning section could realize the line beam scanning with high precision and a wide range. Moreover, with the quantitative analysis on the vibration mode of the whole mechanical system, its inherent frequency is around 47.7 Hz, much higher than that of the scanning mirror as 2.5 Hz; therefore, no resonance occurred during line beam scanning. In addition, the whole THz imaging platform including the source/sensor part and the mechanical part uses the power supply of 220 V AC, and the total power of the whole system is ~2500 W.

With the platform design and construction in both optical and mechanical systems, the main optimization on the THz imaging platform includes (1) optimizing the optical system composed of the elliptical cylindrical reflector and the scanning mirror to pursue high imaging resolution; (2) lightening the mechanical structure, and (3) precisely controlling the scanning using the rotation motor and the encoder to improve the mechanical system. After the design and construction of both the optical and mechanical systems, the performance of the line beam scanning-based ultra-fast THz imaging platform was tested, and it was then adopted for practical applications for safe screening on the human body, which are both described in the following section.

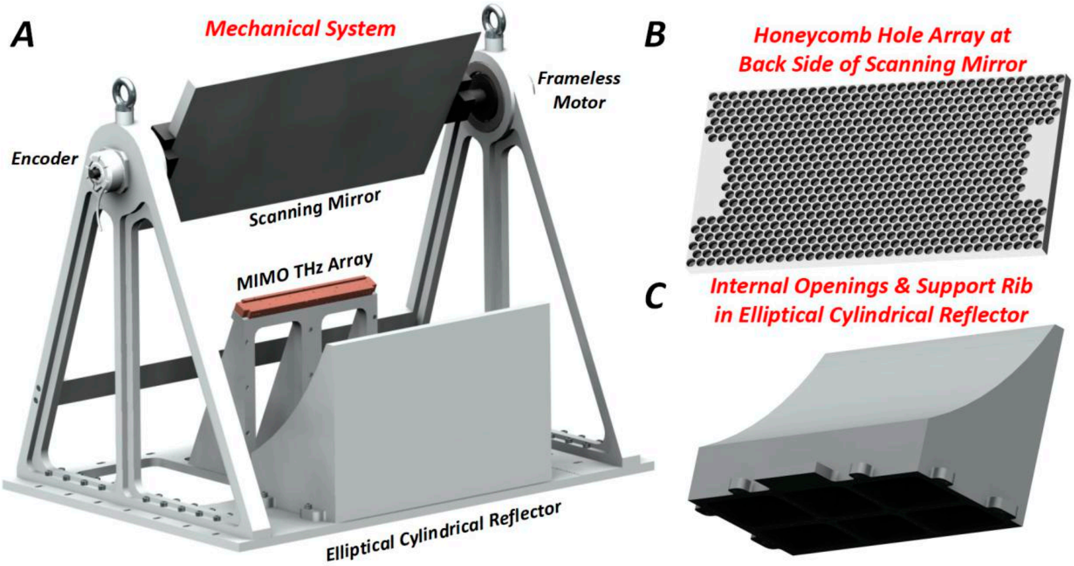

Figure 2. The mechanical system of the line beam scanning-based ultra-fast THz imaging platform. (**A**) Framework of the mechanical system; (**B**) Scanning mirror and the honeycomb hole array at its back side; (**C**) The elliptical cylindrical reflector.

3. Experiments

After designing and constructing the line beam scanning-based ultra-fast THz imaging platform, its performance was tested. The scanning mirror was adjusted to keep the optical axis parallel with the ground coordinate, and a Brunei tube working as a THz single point detector was scanned along the vertical direction to determine the optical axis position. The Brunei tube was scanned along the optical axis, since the intensity at the working plane should have the highest value, indicating that the distance between the working plane and the scanning mirror was 3.02 m. After the determination of the working plane, the Brunei tube was scanned in the working plane to measure the intensity distribution. The intensity distributions along the x and y axes (marked in Figure 1D) are shown in Figure 3A,B, respectively. There is a little difference between the numerically computed and practically measured results, it is often because the numerically calculated intensity distributions were obtained in the ideal condition which did not consider the aberration in the THz system caused by errors in the system fabrication and integration; however, these errors inevitably occurred in the designed THz imaging system, thus, broadening the THz intensity distribution; moreover, the noise of the THz detector also introduced background errors in THz intensity measurements, which also broadened the THz intensity distribution along the y-axis. Though intensity distribution broadened in the measured results, both the numerically computed and practically measured results are still close, via Gaussian fitting, it indicates that the FWHM of the measured line beam was 12.04 mm, close to the numerically evaluated FWHM as ~12 mm, proving the proposed THz imaging platform can reach the resolution of ~12 mm. Besides, both the numerically computed and practically measured intensity distributions along the y-axis with 200 mm, 300 mm, and 400 mm away from the central axis were also listed in Figure 3C–E, respectively. The coincidence between the numerically calculated and the practically measured results in Figure 3A–E proved the high-quality construction of the THz imaging platform. Since the line beam scanning-based THz imaging platform requires high-speed scanning for two-dimensional imaging, both the detecting region and the scanning speed were then measured. Figure 3F shows the scanning trajectory, indicating that the scanning speed could reach 170 ms/frame, the scanning range of the mirror was within ±10.5°, and the scanning range at the working plane could reach 2 m × 0.8 m, all satisfying the scanning requirements.

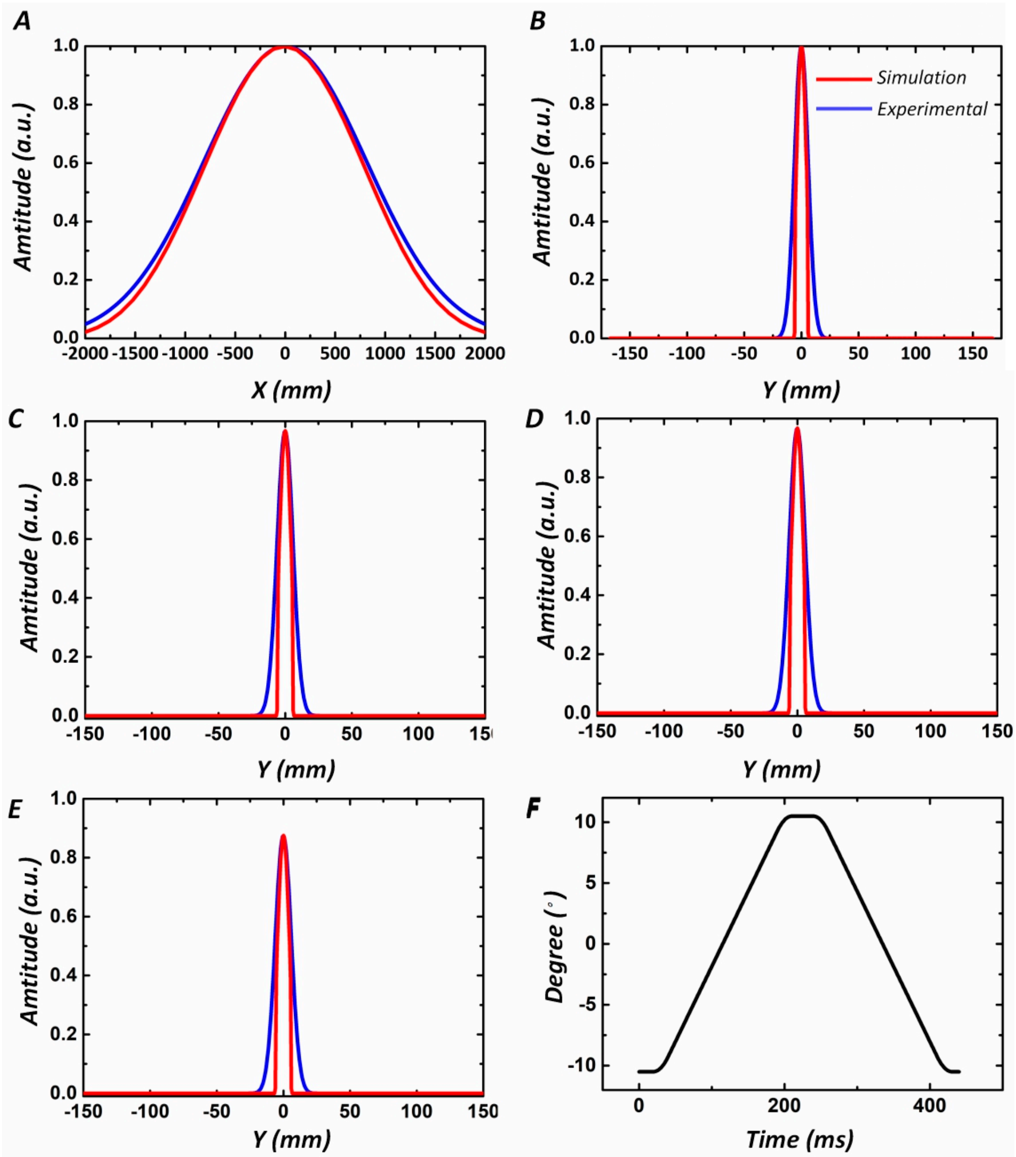

Figure 3. Certification on the line beam scanning-based THz imaging platform. (**A**,**B**) Practically measured and numerically computed sectional intensity distributions along the x and y; (**C**–**E**) Practically measured and numerically computed sectional intensity distributions along the y-axis with 100 mm, 200 mm, and 300 mm away from the central axis. (**F**) The scanning trajectory of the line beam scanning-based THz imaging platform.

After the certification on the line beam scanning-based THz imaging platform, it was finally adopted in the safe screening of the human body THz imaging as shown in Figure 4. Both the images captured by the direct optical device and the proposed THz imaging platform provide information from different perspectives. With the reconstructed THz image, the metal fabricated objects as the metallic gun can be easily distinguished according to the high intensity of the collected THz signals as shown in Figure 4. However, besides the distinguished contraband, a few spots of high intensity still occurred in the THz image, some of them were generated by the THz signals reflected from the metallic parts such as the metallic zipper, and some of them were generated from the THz signals reflected from bones. However, with improved image processing methods [33,34], the contraband can be accurately distinguished according to their special configuration and reflectivity. Moreover, the line beam scanning-based ultra-fast THz imaging platform can realize complete human body imaging within 0.2 s, indicating high-speed scanning and imaging capability.

It is worth noting that the high relative humidity decreases the contrast in THz imaging due to the THz signal loss in the water vapor, therefore, high relative humidity affects the performance of the device. In our experiments, the THz imaging was implemented in an open environment with room temperature, and the image was captured with the relative humidity of ~60%, and the contrast is still satisfied since the metallic gun can be clearly distinguished, indicating that the proposed THz imaging platform can be adopted in practical applications.

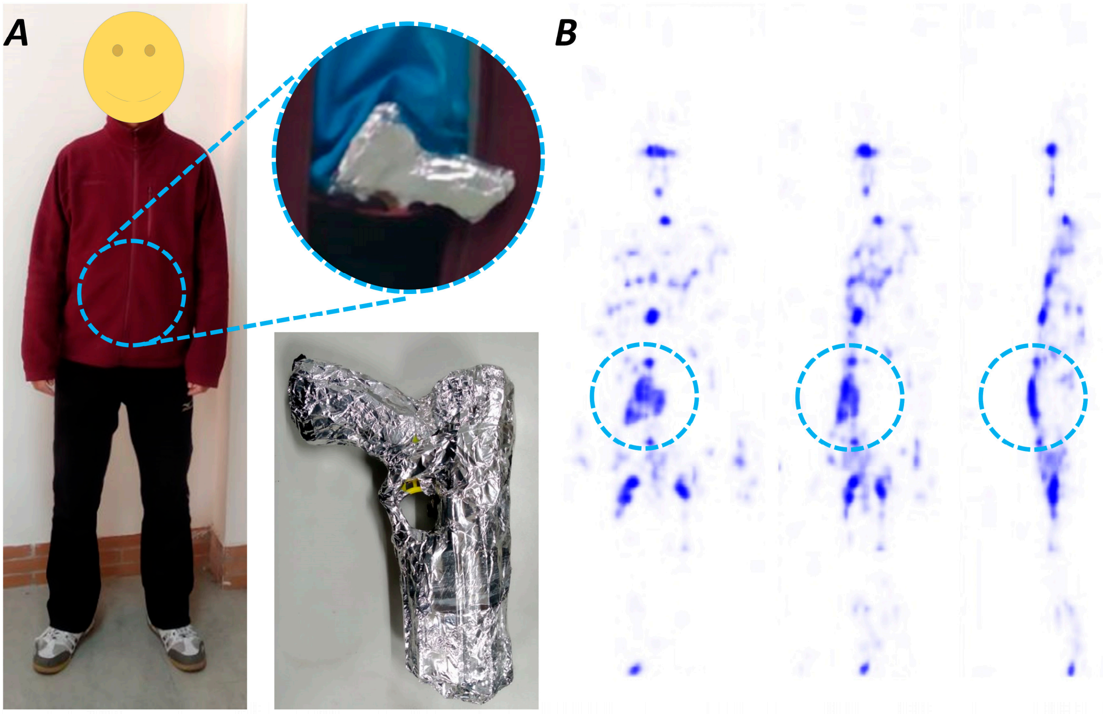

Figure 4. (**A**) Human body optical image. (**B**) Human body THz image obtained using the line beam scanning-based THz imaging platform. The gun is marked in red circle.

Moreover, compared to the devices as PNNL [35,36], JPL [37,38], and TeraScreen [28,29], the proposed line beam scanning-based ultra-fast THz imaging platform still has high-quality performance in THz imaging. The scanning range of the proposed platform reaches 2 m × 0.8 m, which is comparable with the TeraScreen, but much larger than the 0.5 m × 0.5 m of JPL. The scanning speed of the proposed platform is 0.17 s/frame, a little lower than the 0.13 s/frame of TeraScreen, but still much faster than the 1 s/frame of JPL. According to its high-quality performance and practical application in safe screening of the human body, as well as the comparison with the existing systems, it is believed the proposed line beam scanning-based ultra-fast THz imaging platform can be adopted for THz imaging and detecting in various applications.

4. Conclusions

In order to realize ultra-fast THz detecting, a line beam scanning-based THz imaging platform has been designed and constructed in this paper. The optical system is rather simple only composing of a source/sensor chip for THz wave emitting and receiving, an elliptical cylindrical reflector for cylindrical wavefront reshaping and a scanning mirror for line beam scanning. Moreover, the mechanical system is fabricated not only to assemble the optical system, but also to realize line beam scanning rapidly and precisely by controlling the scanning mirror with the frameless rotation motor and the circular grating-based encoder. With the quantitative characterization on the line beam scanning-based ultra-fast THz imaging platform, it has the resolution of ~12 mm, the scanning speed of 0.17 s/frame, the scanning angle range of ±10.5° and the scanning range of 2 m × 0.8 m, proving its high-quality performance in THz imaging. Moreover, it is finally adopted in fast safe screening, indicating that the platform not only realizes rapid human body THz imaging within 0.2 s, but also accurately distinguishes metal fabricated objects. Considering its high-quality performance in THz imaging and successful adoption in fast safe screening, it is believed the proposed line beam scanning-based ultra-fast THz imaging platform can be used in various conditions such as contraband inspections and human body THz imaging.

Author Contributions: H.H., Z.L. (Zhenhua Li), and Z.L. (Zeren Li) conceived and designed the methodology and experiments; H.H. performed the experiments; H.H., Q.L., Y.Z., and L.Z. analyzed the data; H.H., Z.L. (Zhenhua Li) and Z.L. (Zeren Li) wrote and reviewed the paper.

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