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New Ultra-Fast Sub-Terahertz Linear Scanner for Postal Security Screening

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Abstract

To meet increasingly demanding technological needs in modern security and industrial applications involving rapid close-range screening, we have developed a 100-GHz linear scanner. Having incorporated a novel approach in terahertz sensing and an advanced IMPATT-diode signal generating technique, the proposed system offers an efficient non-destructive testing (NDT) solution that is absolutely safe, fast, highly portable, and cost-effective. The test results demonstrate outstanding capability of the scanner to provide continuous, high-throughput security screening of mail. The system can perform real-time imaging with effective resolution approaching 5 mm at conveyor speeds of up to 15 m/s.

Keywords Terahertz (THz) · THz imaging · Linear scanner · Security screening · Mail inspection · NDT inspection

1 Introduction

Over the years, THz technologies have proven valuable and powerful in various industrial solutions [1, 2]. In particular, THz radiation has been used successfully as a safe and effective means of non-destructive testing (NDT) [3, 4] since having non-ionizing nature does not compromise the integrity of an object under investigation. Bridging the gap between microwave and infrared spectra, the terahertz range offers exceptional possibilities. THz imaging has an advantage over microwave technology in that it provides superior spatial resolution owing to the shorter wavelength. Furthermore, unlike infrared and visible radiation, terahertz waves can transmit through

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a number of common materials [5], which enables detecting, imaging, or analyzing internal defects or concealed objects and substances in quality control or security screening applications [6, 7].

Although there are few conventional techniques, such as X-ray scanning and microwave detection, that have been successfully applied in security inspection, the hazardous nature, complexity, low imaging speed, and relatively high cost of these scanners have precluded their widespread use for NDT. Hence, security screening of mail, for example, is still carried out, for the most part, by manual inspection of parcels and envelopes, without any modern automated equipment or computer-aided support. To overcome the limitations of traditional systems in meeting the urgent demand for optimal postal screening instrumentation, terahertz scanners have been considered a very promising alternative.

Thus far, there have been proposed several THz imaging techniques [8–18] based on different operational principles and sensing methods. One class of such modern THz systems is the time domain spectrometers (TDS) designed to identify hazardous or illicit substances by analyzing their refracted, diffracted, or scattered THz spectra [19–24]. According to most recent reports [22], some of the most advanced THz-TDS scanners can perform 3D imaging over a 5-THz bandwidth with nearly 100-dB dynamic range. However, these highly sophisticated systems are still limited in their capabilities of video-rate spectroscopic imaging. They also remain rather complex in operation and prohibitively expensive for wide commercial use in postal industry. Another approach is based on irradiating a sample with continuous wave radiation and analyzing the resultant transmitted or reflected signal. The comparison of these two methods for the case of postal security screening may be found, for example, in [25]. Initially, the image of a target in this approach was constructed by slow raster scans [26–29]; more recently, there have been a number of breakthroughs in development of focal-plane arrays on the basis of microbolometers, silicon CMOS circuits, pyroelectric devices, and high-electron mobility transistors (HEMTs) [30–35]. Although these commercially available detector arrays permit video-rate imaging at room temperature, they are significantly restricted in their overall size, as determined by pixel dimensions and the number of pixels, which makes them unsuitable for industrial-scale linear scanners.

As an optimal solution in context of the current technological advancements and limitations, we have devised a new sub-THz linear scanner for postal security screening. Unlike the TDS approach, in this system, the 2D target image is constructed based on measurements of the transmitted radiation at a single sub-terahertz frequency. In this case, the livestream imaging speed has been accomplished due to a novel-type THz sensor technology, which allows for scalable detector array capable of ultra-fast operation at room temperature [36, 37]. The presented linear scanner is exceptionally compact and simple to operate compared not only with X-ray and microwave technology, but also with the aforementioned modern competitive solutions. With this linear scanner, postal inspectors can carry out the screening of mail promptly and smoothly, from simple customs checks for undeclared parcel content to detection of concealed hazardous substances or potentially life-threatening items.

In this paper, we introduce the new ultra-fast sub-terahertz linear scanner with primary focus on its application in postal security inspection. We describe the key components of the system, outline its distinctive features, and summarize the measurement results to demonstrate its outstanding functional capabilities. We also address current limitations of the system and consider the ways of its further improvement.

2 System Description

The new 100-GHz high-speed security scanner is a complete imaging system comprised of the TeraSense^{TM} instrumentation—an 80-mW IMPATT-diode source tuned to 100 GHz, a linear camera with 1 × 256 detector array, and specially designed beam-shaping optics including a horn antenna and a cylindrical concave mirror. The overall setup of the system is described schematically in Fig. 1.

The foremost feature of the scanner is its real-time imaging camera, a compact sub-THz linear sensor array based on a novel method of plasmonic detection [36, 37]. This technique enables ultra-fast sensing of THz radiation at room temperature with response time of each plasmonic detector reaching 150 ps [37]. Each sensor is tuned to a single narrow band centered at 100 GHz. The sensor has a rectangular shape and 3 mm × 1.4 mm size. In total, 256 sensors are arranged side-by-side lengthwise with 1.5-mm pitch to form a 1D array. This linear camera is designed to be used primarily with conveyor lines or other similar close-range screening configurations. Owing to its high acquisition rate of up to 5000 lines per second (lps), it can accommodate scanning speeds as high as 15 m/s. Depending on the acquisition rate, the camera provides detection threshold levels of 100 nW at 5000 lps, 45 nW at 1000 lps, and 14 nW at 100 fps. The camera is controlled by a PC via USB interface to enable data acquisition and image post-processing.

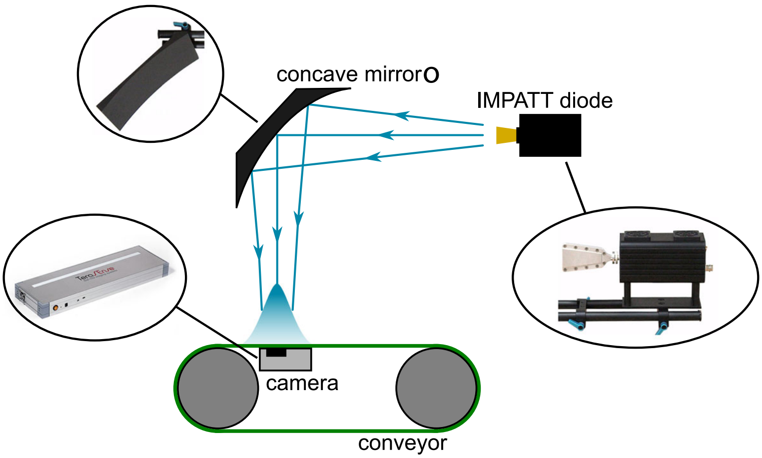

Fig. 1 Diagram of the new 100-GHz linear scanner configured for continuous security inspection of mail. For the illustrative purpose, also shown are enlarged photos of the fundamental elements of the system: the IMPATT-diode source with the output horn antenna, the linear camera, and the cylindrical concave mirror

Another distinctive component of the system is the IMPATT-100/80 wave generator—an extra compact, high-power sub-terahertz source that employs advanced IMPATT-diode technology. It is designed to supply a 100-GHz continuous wave (CW) signal at $P > 80$ mW power level. The source is characterized by high stability of such critical parameters as output power level and frequency, which ensures reliable operation of the scanner setup over the long term. The device is synchronized with the camera, which makes possible lock-in like detection, and thus considerably reduces the total background noise of the camera sensors.

As indicated in Fig. 1, two additional elements are used to transform the divergent power beam of the source into a focal line-spot in order to achieve optimal illumination of the sensor array. Firstly, the generator is fitted with an external high-directivity horn antenna with a narrow rectangular aperture of 25 mm $\times$ 6 mm. The small width of the aperture causes horizontal widening of the beam to cover the full 384-mm length of the sensor array. Secondly, a specially designed cylindrical stainless steel concave mirror with 0.5-m curvature radius is positioned at between the source and the camera, as shown in the figure. The mirror acts as a lens focusing the beam in transverse direction to maximize the amount of radiation incident over the width of the detector array.

According to the geometrical arrangement of the scanner depicted in Fig. 1, the camera is placed immediately underneath the conveyor belt while the source and reflector are positioned at a distance above it. As illustrated in the figure, the system is designed to function in transmission mode, when the area of interest is irradiated with the source and the transmitted radiation is sensed and imaged by the camera. Since camera sensors are sensitive to polarization of the incident radiation, their optimal performance is achieved provided the direction of the incident electric field is transverse to the 1D sensor array. Therefore, as the IMPATT-diode source produces radiation with A high degree of linear polarization, its orientation with respect to the sensor array is fixed as shown in Fig. 1.

Modular design of the presented linear scanner ensures its easy maintenance, as any faulty component can be replaced promptly. In addition, it provides a great deal of flexibility in adapting the system to a particular application. For example, instead of a standard IMPATT-100/80 generator, there can be installed a source with greater power level or higher operating frequency. Due to exceptionally compact size of its modules, the entire system is highly portable, and quick and easy to install, setup and operate, which makes it perfectly suitable for many NDT solutions in various industrial and security applications.

3 Measurement Results

Several tests have been conducted to estimate the key functional parameters of the new 100-GHz linear scanner and to evaluate its overall performance. Figure 2 displays the incident power distribution measured over the surface plane of the camera by means of mechanical scanning with a single calibrated detector 1.5×1.5 mm^2 in size. The given shape of the beam spot is achieved by applying special optics described in Section 2, in which case the initial circular-shaped power beam

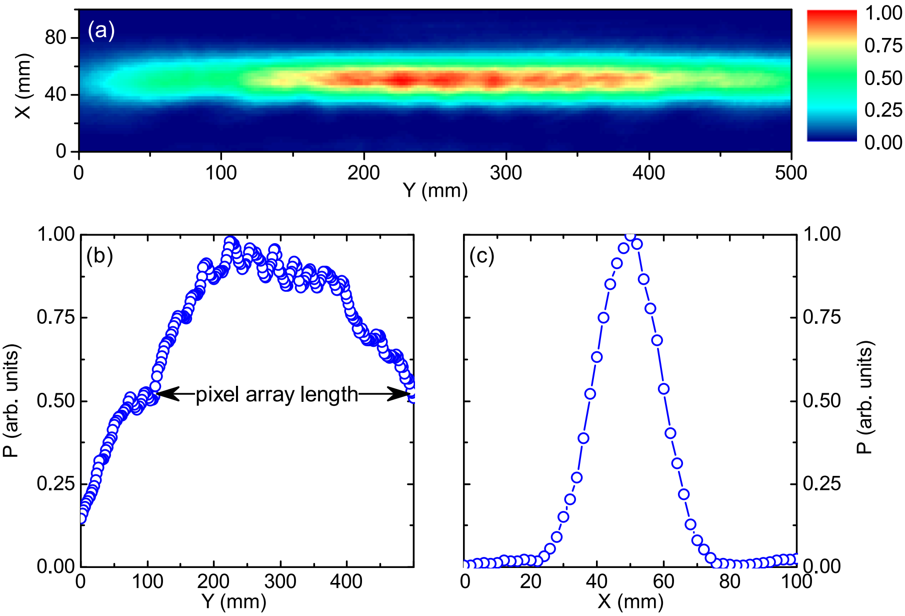

Fig. 2 **a** Measured 2D profile of the radiation incident onto the plane of the camera. The source power beam has been collimated with specially designed horn antenna and cylindrical concave mirror to maximally match the narrow-line shape of the detector array. **b**, **c** Cross sections of the beam in *Y* and *X* directions, respectively

generated by the source has been collimated to take the form of an elongated ellipse to maximally focus incident radiation on the detector array. Introduction of both the mirror and the horn antenna has allowed us to increase the average radiation power incident on a single pixel to 140 μW. As a result, the dynamic range of the imaging system has been improved by nearly two orders of magnitude, reaching a 40-dB figure.

For experimental estimate of the resolving power of the given system, there was imaged a target manufactured from a 1-mm-thick, 244 mm $\times$ 244 mm stainless steel plate with a special laser-cut pattern. The photograph of the target in the optical range is presented in the upper left panel of Fig. 3. The pattern cut in the target represents the adaptation of the standard 1951 USAF resolution chart for the sub-THz range. It consists of several blocks with each block comprised of three vertical and three horizontal bars. Within each block, all bars have constant width equal half the distance between the bars. Between the blocks, the bar width is varied in logarithmic steps from 0.5 up to 8 mm.

The resultant image of the target shown in the upper right panel of Fig. 3 demonstrates that scanner resolution approaches 5.6 mm in *X* direction, perpendicular to the detector array, and 5 mm in *Y* direction, along the array. For clarity purpose, the lower panel of the figure includes three graphs that illustrate how the resolution was estimated. The traces in plots (a), (b), and (c) represent the cross-section data

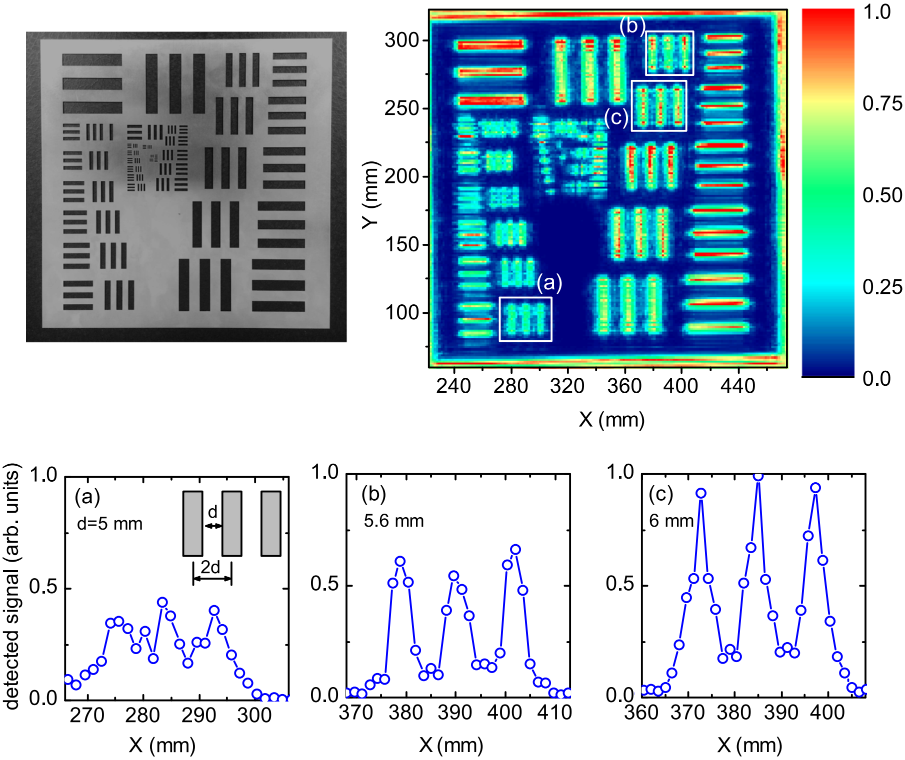

Fig. 3 Optical photograph and sub-THz transmission image of the steel plate specially designed to test the resolution of the linear scanner. The scanning speed is 5 m/min. The lower graphs **a**, **b**, and **c** represent the cross-section data sets corresponding to the outlined pattern segments of the target image. The respective bar width of the target is indicated in each plot

from the respective pattern segments outlined in the target image. The bar widths corresponding to the selected segments are indicated in each plot, accordingly.

The lateral resolution of the system in both directions appears nearly equal. Importantly, it exceeds the sensor size and the pitch of the sensor array, which implies that system resolution is diffraction limited. Slight discrepancy in resolution observed in X and Y directions may be ascribed to the different orientation of the radiation polarization with respect to the target pattern.

Finally, Fig. 4 illustrates real-life visualization of the threats concealed inside typical postal packaging accomplished by transmission imaging of the new security scanner. As shown in the figure, the contrast images are adequate for target detection and general classification as they clearly convey in sufficient detail the proportions, the relative size, the shape, and the spatial orientation of each hidden object. Thus, the devised system may be utilized as the first stage of the multilevel postal security screening system [38] to differentiate postal packages with potentially

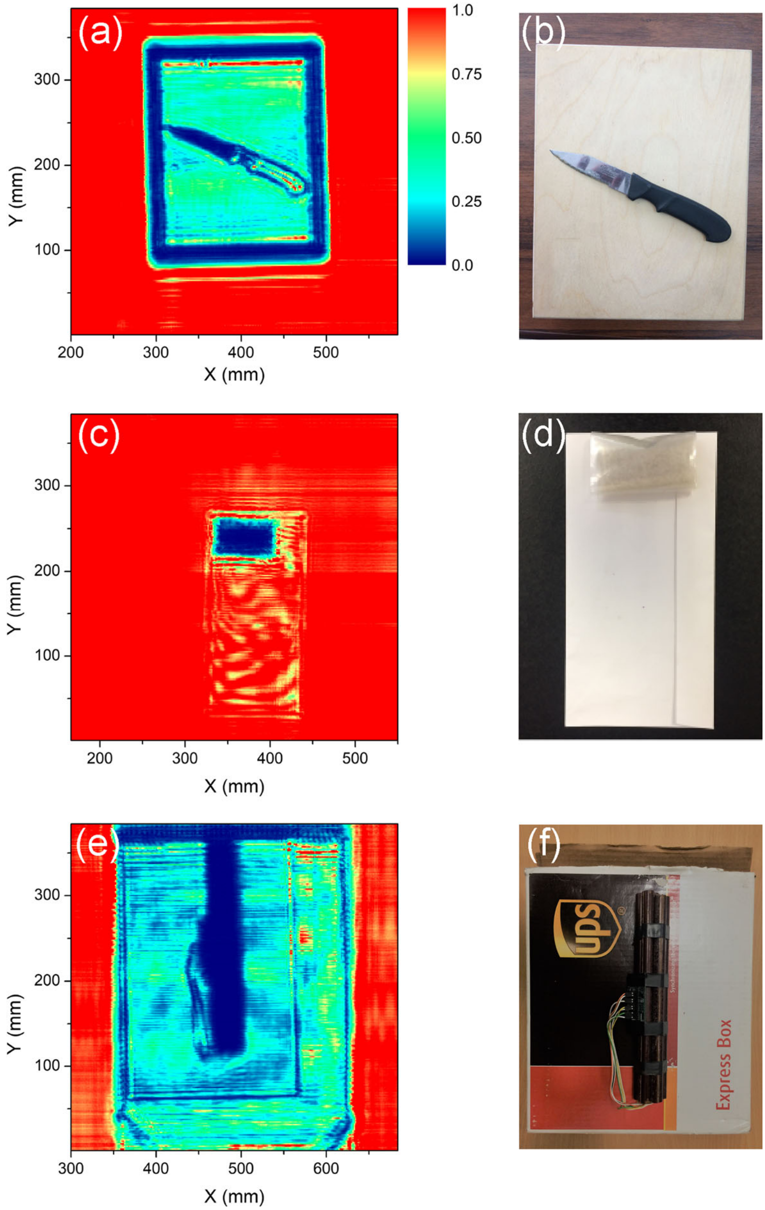

Fig. 4 Transmission imaging results of real-life visualization of suspicious substance or potentially dangerous objects hidden inside mail: **a** and **b**, a knife in a wooden box; **c** and **d**, a sachet of flour in an envelope; **e** and **f**, a dummy bomb in a cardboard box. The scanning speed is 5 m/min

dangerous items, as a result, substantially reducing the amount of scans that need to be performed by next level more complex, yet more expensive and slow security systems.

4 Conclusion

We have introduced the new 100-GHz security linear scanner. We have given an overview of its main innovative components that enable livestream THz imaging of threats concealed inside mail, which is the key competitive feature of the system. Being highly portable, the scanner can be deployed in minutes and does not require any special qualifications to operate. Modular composition of the setup enables easy maintenance and provides considerable flexibility in accommodating particular needs of most NDT security and industrial applications.

Experimental evaluation of the most critical operational parameters of the given linear imaging system has been presented. The dynamic range of the scanner is estimated to be 40 dB while its resolution is shown to approach 5 mm. The ultimate real-life test has demonstrated the system capable of detecting weapons, explosives, and illicit powdered or liquid substances concealed in mail.

One limitation of the current system is its moderate lateral resolution. Since this parameter is inversely proportional to the operating frequency, upgrading the system to 300 GHz will provide for threefold improvement in resolution. In addition, better focusing of the emitted radiation can be achieved by switching to an aspherical mirror, which will lead to more efficient illumination of the camera, with a substantial increase in delivered power per pixel. Finally, it is possible to boost the source power level considerably, as there are presently available more powerful, 500-mW generators developed by TeraSense. This will improve the SNR of the system and further enhance image quality.

All things considered, the new 100-GHz security linear scanner is an original, powerful, and cost-effective solution with real potential for meeting the great demand for safe, fast, and reliable security screening of mail.

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