THz based non-destructive testing system for Security and Inspection Applications

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Abstract—Terahertz (THz) technology has garnered significant attention in non-invasive inspection and security applications due to its ability to penetrate common materials like paper, plastics, and fabrics while remaining non-ionizing. This study presents a package THz scanner utilizing a commercially available 292 GHz wave IMPATT source and a custom-designed 3D-printed multifunctional diffractive optical component for beam shaping. The novelty lies in applying the THz source with limited coherence and broadband detector line. Thus, coherent noise can be suppressed. We discuss the system's design, construction, and performance, demonstrating its feasibility as a cost-effective and adaptable solution for package inspection.

Non-destructive testing (NDT) methods provide valuable information about the material properties of objects without significantly altering their structural or surface characteristics. Traditional NDT techniques for machinery and equipment are widely discussed in the literature [1].

In recent years, terahertz (THz) radiation has become a promising tool in non-destructive material testing [2]. THz radiation, with wavelengths ranging from fractions of a millimeter to a few millimeters, occupies a spectral region between microwaves and infrared light. Its key advantage lies in its ability to penetrate non-polar, non-metallic materials - such as paper, plastics, textiles, wood, porcelain, and cardboard - typically opaque to visible light.

THz imaging has emerged as an efficient and safe method for inspecting concealed structures and anomalies, making it particularly relevant for security applications, such as package and envelope scanning [3]. In this work, we present the design and construction of a THz scanner for non-destructive inspection of packages. The system integrates commercially available components with customized optics to enhance imaging capabilities and effectively detect hidden irregularities.

The system utilizes a continuous-wave 292 GHz IMPATT source with an output power of 15 mW, valued for its high reliability and compact design. IMPATT (Impact Avalanche and Transit Time) diodes are crucial in high-frequency semiconductor applications, especially within the microwave and millimeter-wave ranges. Their operation is based on avalanche breakdown and the transit-time effect, which allows them to generate signals across a wide frequency range, from several gigahertz to terahertz. A significant advantage of IMPATT diodes is their capability to deliver relatively high power.

Compared to electronic sources based on Schottky multipliers [3], IMPATT sources exhibit lower temporal coherence. This fact and microbolometer-based broadband detectors can suppress unwanted interference patterns in the captured images.

The detector used in the experiment is a linear array of 128 detectors from LUVITERA, sensitive to the polarization of incoming radiation and equipped with log-periodic antennas. It allows fast scanning of a 320 mm wide area with a pixel pitch of 2.5 mm and features high sensitivity (more than 200 kV/W). The integrated log-periodic antenna offers a wide operational bandwidth from 0.09 THz to 1.1 THz, ensuring extensive frequency coverage. Additionally, the detector can be paired with THz lenses, increasing its versatility for terahertz imaging applications. A general view of the constructed scanner is shown in Fig. 1.

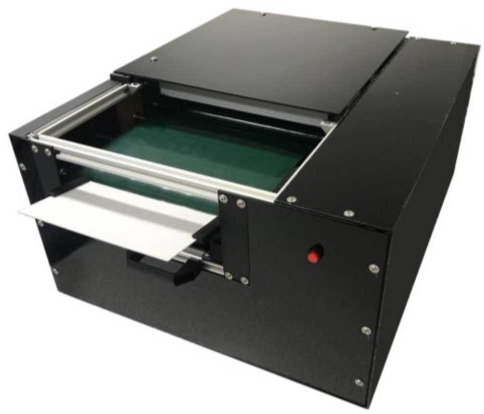

Fig. 1. A general view of the constructed scanner. Noteworthy are the compact dimensions of the device – only 67 cm × 57 cm × 30 cm.

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The THz beam emitted by the source was directed onto a custom-designed diffractive optical element that converts a divergent beam from a point-like source into a focal line segment perpendicular to the optical axis. The optical path of the scanner is shown in Fig. 2. The optical element was fabricated using 3D printing technology based on selective laser sintering (SLS) with PA12 polymer. The SLS technique provides high resolution and precision, making it well-suited for producing THz optical components [4]. PA12, a synthetic thermoplastic polymer, is ideal for 3D printing due to its excellent processability and design flexibility. For frequencies around 0.3 THz, PA12 has a refractive index of approximately 1.6, which is high enough for optical applications while minimizing Fresnel losses [5]. Additionally, its absorption coefficient at this frequency is around 0.6 cm^{-1}, further enhancing its suitability for terahertz applications.

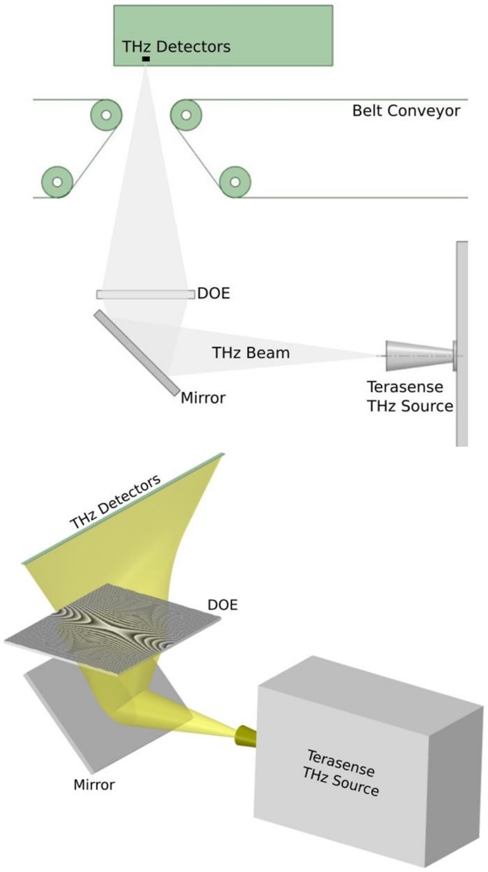

Fig. 2. Optical path of the scanner: a side cross-section in a plane perpendicular to the linear array detectors (top diagram) and a perspective view (bottom diagram).

The custom-designed diffractive optical element, shown in Fig. 3, was created as a combination of two optical components: a hyperbolic lens and a collimating Fresnel lens. The phase of the resulting optical structure is the outcome of the complex multiplication of the phase of both the hyperbolic lens and the collimating Fresnel lens. The phase of a non-paraxial hyperbolic lens is given by:

$$\varphi(x,y) = -\frac{k}{\beta}\sqrt{\beta^2 x^2 + \left[\beta\sqrt{y^2+f^2}+f\right]^2}, \quad \beta = b/a - 1, \tag{1}$$

where k is the wavenumber, f is the focal length, and x and y are coordinates in the planar diffractive structure. The structure focuses the radiation into a line segment at a distance f equal to 140 mm. In the designed case, the line segment length a was equal to 300 mm, while b was 30 mm. The collimating lens phase is given by:

$$\varphi_{col}(x,y) = -k\sqrt{x^2+y^2+f_{col}^2}, \tag{2}$$

where f_{col} is the distance between the point-like source and the diffractive element equal to 180 mm, the design wavelength for the structures was 1.03 mm.

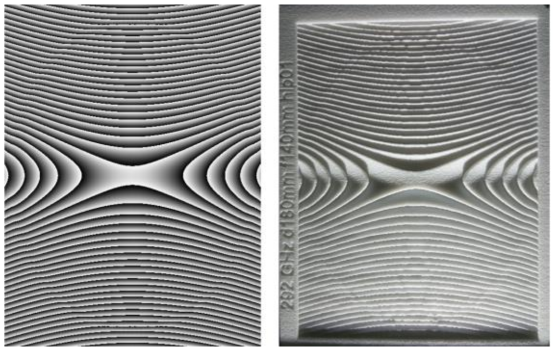

Fig. 3. Custom-designed diffractive optical element: phase of the beam-shaping DOE (left side) and an image of the structure printed using SLS technology with PA12 (right side).

A custom software interface was developed to process the linear sensor's output, enabling the reconstruction of 2D images of the scanned items and providing the analysis of the resulting images based on various parameters and properties.

The package THz scanner successfully imaged various materials, with two examples presented below. Fig. 4 shows a metal spanner placed inside an envelope and a scanned image. Similarly, Fig. 5 shows a sugar sachet inside an envelope (left side) and its respective scan (right side). In both cases, the contours of the objects placed inside the envelopes are clearly visible in the scans. There is noticeable image noise in the paper region. This is caused by multiple reflections inside the scanner housing. The use of flexible low-reflection coatings [6] inside the scanner could improve image quality.

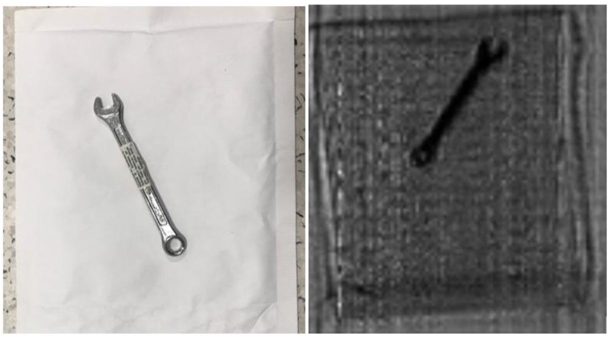

Fig. 4. Metal spanner in an envelope (left side) and image from the scanner (right side).

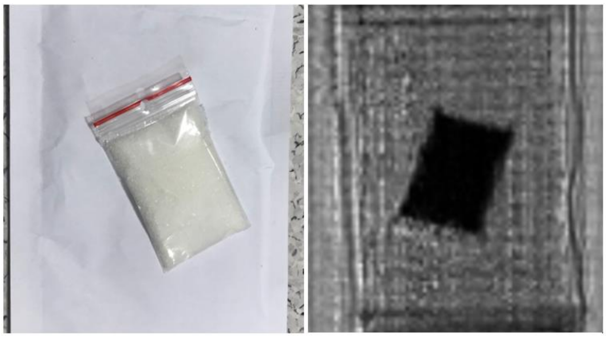

Fig. 5. Sugar sachet in an envelope (left side) and image from the scanner (right side).

Current detection technologies need to be improved for detecting hazardous objects made of dielectric materials, such as ceramic or plastic knives. For example, these objects are entirely undetectable in X-ray imaging. However, a terahertz-based scanner can successfully detect such items. The rapid phase shifts at the edges of dielectric objects allow for the visualization of their outlines using the THz scanner, which is shown in Fig. 6.

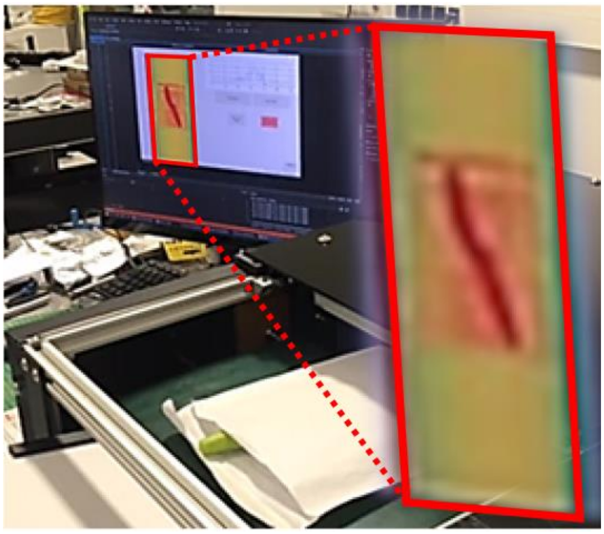

Fig. 6. A package THz scanner in operation. The scanned item is a ceramic knife with a plastic handle placed inside an envelope. The outline of the knife is clearly visible in the real-time scans.

Developing a postal THz scanner featuring a 292 GHz IMPATT source, a 3D-printed custom-designed optical element, and a linear array of microbolometer-based broadband detectors represents a significant step toward practical THz imaging systems. Proposal configuration has demonstrated excellent potential for noninvasive and nondestructive inspection in postal and security applications. Utilizing non-ionizing terahertz radiation at several tens of milliwatts power levels allows rapid scanning while maintaining adequate resolution and dynamic range. For example, scanning an A4-sized sheet takes approximately 10 seconds, with a spatial resolution of around 3 mm. The proposed device is more cost-effective than existing solutions, thanks to the use of commercially available components, and it is highly portable due to its compact size. High temporal coherence of the source induces coherent noise, which negatively affects image quality. A key advantage of the proposed scanner is using line-array broadband detectors and radiation sources with lower temporal coherence, eliminating coherent noise and improving the quality of the obtained scans.

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