Fast Terahertz Computed-Tomography Imaging with a Quantum-Cascade Laser and a Scanning Mirror

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***Abstract*—A terahertz transmission imaging system based on a quantum-cascade laser (QCL), a fast scanning mirror, and a sensitive Ge:Ga detector is demonstrated. In order to reduce artifacts, special care was taken on the optics and the conversion of the measured data into the image. Images with a diameter of approximately 40 mm and a signal-to-noise ratio of up to 28 dB were obtained within 1.1 s. The system was used to record three dimensional images of objects in an ellipsoidal volume with axes of approximately 40 mm by computed tomography within 87 s. In addition to the Ge:Ga detector, a more compact pyroelectric device was also used for detection.**

I. INTRODUCTION AND BACKGROUND

IMAGING with terahertz (THz) waves is very promising for many applications in biomedicine, non-destructive testing, art conservation, and security. In particular, THz waves penetrate many non-metallic and non-polar materials. Furthermore, characteristic absorption features in the THz range allow for object identification. A number of imaging approaches have been already demonstrated, for example by the use of commercial microbolometer array cameras in conjunction with quantum-cascade lasers (QCLs). While the use of an array enables fast imaging, such an approach often suffers from fringe artifacts caused by the coherent illumination. In contrast, imaging systems with single-pixel detectors and mechanical scanning are rather time consuming. We present an approach which provides both, sensitive single-pixel detection as well as fast image acquisition, by the use of a fast scanning mirror. As a source, a QCL is used, since it is compact as well as easy to handle and provides a high output power in continuous-wave mode.

II. RESULTS

The main components of the imaging system are a 2.5-THz QCL with about 300 µW output power, a fast scanning mirror, and a Ge:Ga or a pyroelectric detector. The QCL is integrated into a compact Stirling cooler [1] with about 240 W of electrical input power. The temperature achieved by this cooling is 31 K. In order to use phase-sensitive lock-in detection, the driving current of the QCL is modulated at a frequency of 100 kHz. A scheme of the setup is shown in Fig. 1. After passing a poly-4-methylpentene-1 (TPX) lens, the collimated beam of the QCL impinges on a flat two-axes scanning mirror with a maximum tilt angle of ±3° in each direction. The mirror deflects the beam toward a high-density polyethylene (HDPE) lens, which focuses the beam onto the object. By steering the mirror, the beam waist is spirally scanned across the object. Note that the beams at different mirror positions propagate parallel with respect to each other. The parallel beam propagation is a requirement for the correct reconstruction of the object by computed tomography (CT). The transmitted radiation is coupled into the Ge:Ga or the pyroelectric detector by an off-axis parabolic mirror. The setup is described in detail in Ref. [2]. A THz two-dimensional (2D) transmission image of the object is obtained by correlating the mirror position with the lock-in signal. Since the coupling into the detector depends on the mirror position, a flat field measurement is necessary. In Fig. 2(a), a 2D THz image of a metallic stripe target with 2 mm stripe width is shown. The stripes are well resolved with a contrast of 0.91. This image is acquired with the Ge:Ga detector within 1.1 s. The signal-to-noise ratio (SNR) of an image is up to 28 dB. Images taken by the pyroelectric device were recorded within 110 s. In order to reduce spiral artifacts, special care was taken with respect to the algorithm which transforms the measured data into the image. In particular, the mirror position has to be considered with sub-pixel accuracy.

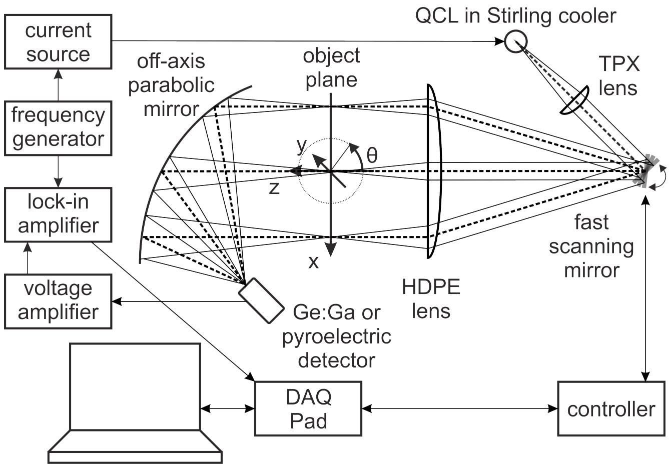

Fig. 1. Scheme of the experimental setup. The collimated beam is deflected by a steering mirror and focused onto the object. The transmitted radiation is coupled into the detector by an off-axis parabolic mirror.

Based on this imaging system, three-dimensional CT images were obtained from a series of 2D images taken from different illumination angles by rotating the object. The size of the measurement volume is determined by the field-of-view of the two-dimensional images. An ellipsoidal volume with axes of about 40 mm can be measured by the system. The images were reconstructed by filtered back-projection, which is based on several assumptions. First, it assumes that the beam propagates without any divergence through the object. This requirement is fulfilled by the correct adjustment of the TPX- and the HDPE-lenses. Second, the beam profile in the plane perpendicular to the beam propagation should not change across the whole measurement volume. To verify this, beam profiles at different positions within the volume were measured with a microbolometer array camera. We are able to demonstrate that the variation of the beam profiles within the volume is compatible with the CT requirements. At all positions in the 2D image, the beam profiles are well described by a Gaussian function. At the outer areas of the measurement volume, small side lobes appear. However, they do not affect the CT images. An example CT image of a pen cap [left part of Fig. 2(b)] is shown in Fig. 2(c). The pen cap with its clip and the hollow core are clearly recognizable. In Fig. 2(d), four cross sections of the object are shown [cf. right part of Fig 2(b)]. The 3D image was reconstructed from 60 2D images covering a total of 180° in steps of 3°. The quality of the reconstructed images does not improve by taking more images since at smaller step widths the difference between two neighboring images is not resolvable by the imaging system. This was proven by a comparison of 3D images reconstructed from the same dataset, but using different angular step widths for the reconstruction. The step-wise rotation of the object takes a total of 21 s, the acquisition time of the 60 2D images amounts to 66 s so that the total acquisition time of one three-dimensional image takes only 87 s using the Ge:Ga detector. This time is limited by the mechanical movement of the fast steering mirror. The scanning speed of the mirror was optimized resulting in an Archimedean spiral, being the scanning trajectory with linear increasing speed from the outer border to the center.

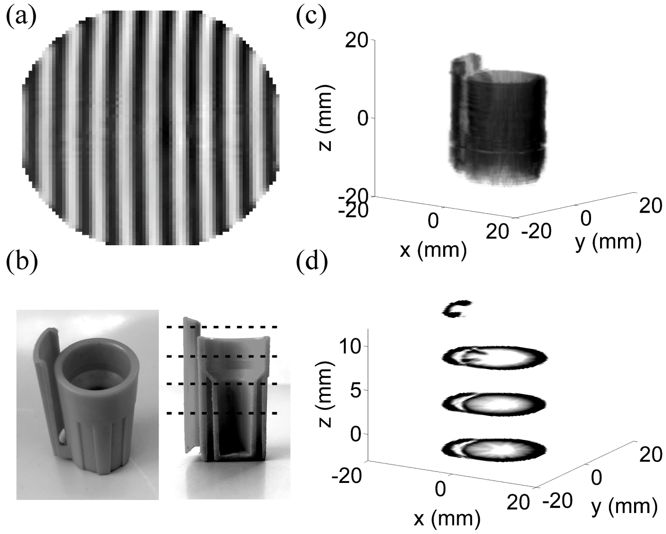

Fig. 2. (a) THz image of a 2 mm stripe target, (b) photographs and (c) THz CT image of a pen cap, and (d) four cross-sectional planes of the CT image. The dashed lines in (b) indicate the locations of the cross sections in (d).

III. SUMMARY

A single-pixel detection system for fast THz imaging with a compact QCL source is demonstrated. With this system, three-dimensional images of good quality can be obtained within 87 s with a Ge:Ga detector. It employs a fast steering mirror providing two-dimensional images within 1.1 s. The SNR is as high as 28 dB. Importantly, the image quality does not suffer from fringe artifacts. We also used a pyroelectric detector, for which images were recorded within 110 s. The object dimensions derived from the THz CT images are in agreement with the real dimensions of the object. We will present the design and performance of the imaging system and discuss its limitations and potential for practical applications. Such a system offers an elegant implementation of sensitive spectroscopic capabilities since all the power from the QCL is always concentrated in one pixel. The scanning mirror can direct the THz beam to the area of interest, which was identified in the THz image. This area might be spectroscopically analyzed with the same system using a tunable QCL and adding a spectrometer in front of the detector [3].

REFERENCES

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