

# Real-time reflection imaging with terahertz camera and quantum-cascade laser

Zhiyong Tan (谭智勇), Li Gu (顾立), Tianhong Xu (徐天鸿), Tao Zhou (周涛),  
and Juncheng Cao (曹俊诚)\*

Key Laboratory of Terahertz Solid-State Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China

\*Corresponding author: [jccao@mail.sim.ac.cn](mailto:jccao@mail.sim.ac.cn).

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A real-time reflection imaging employing a terahertz (THz) camera as the imager and a 3.9 THz quantum-cascade laser (QCL) as the light source is demonstrated. The imaging light is collected and guided by only one off-axis parabolic mirror. The imaging distance is about 1 m. THz images of a coin and a knife are acquired and analyzed. An actual spatial resolution with a value of about 0.33 mm is achieved.

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The terahertz (THz) imaging technology has been developed for many years after its first demonstration in 1995<sup>[1]</sup>. It is a promising technology for applications in biomedical imaging, material characterizations<sup>[2]</sup>, hazardous article (such as illicit drugs) analysis<sup>[3]</sup>, and scale-model targets radar<sup>[4]</sup>, etc. The THz quantum-cascade laser (QCL) is one of the promising lasers, and with about tens of mW<sup>[5]</sup> that is suitable for imaging and communication applications<sup>[6,7]</sup>. The first THz QCL-based real-time imaging demonstration of a concealed razor blade had been realized by using an infrared focal-plane array camera<sup>[8]</sup>. In the subsequent applications, the THz QCL had been generally used in stand-off distance imaging<sup>[9]</sup>, transmission-type terahertz microscope<sup>[10]</sup>, etc. In the early studies, the used focal-plane array cameras which mainly response at infrared frequency should be recalibrated at THz frequency, and then the image process and correction technique must be used to acquire the THz images<sup>[11]</sup>. The NEC Company developed a THz camera on the basis of infrared array detector in 2008. It can work at 1–7 THz range with a NEP level of about 40 pW<sup>[12]</sup>. Most of these works are concerned on transmission mode to get the concealed information. In this letter, a reflected configuration is used to obtain the real-time information of the samples. The real-time reflection imaging of a coin and a concealed knife is demonstrated by employing a quantum-cascade laser and a THz camera. The reflected THz images are directly acquired by using this camera. The actual imaging resolution is analyzed and discussed.

The schematic of real-time reflection imaging setup is shown in Fig. 1. Only one off-axis parabolic (OAP) mirror with focal length of 101.6 mm is used to collect and guide the terahertz light. The QCL is placed on the focus of the OAP mirror. The sample is fixed on the focal plane of the camera array and irradiated by a parallel THz light from the OAP mirror. The reflected angle on the surface of sample is adjusted to a certain value, about 10° to 25°, to obtain distortionless images and to make the reflected light be collected appropriately by the inner lens of the camera.

The QCL, operating at 12 K in continuous wave (CW) mode, is fixed inner a closed-cycle cryostat<sup>[13]</sup>. It is driven by a direct current (DC) power supply (PSM 6003) with a driven current of 0.2 A. The terahertz camera (IRV T0831C), with 320×240 pixels (23.5 μm per pixel), is driven by a DC bias with a value of 12 V and controlled by a commercial software to acquire the image data. The actual NEP of this camera is less than 100 pW at 3.9 THz. The frame rate of the camera is set as 8.5 Hz to get a good signal-to-noise ratio (SNR). The sample is fixed onto a metal plate or clamped by a clip to get a stable reflection plane. The imaging distance is about 1 m from the laser to the camera.

The beam spot reflected by the metal plate with no sample is collected by the camera and shown in Fig. 2. It is noted that the beam spot has a ring like property because of the metal-metal waveguide of the laser ridge<sup>[14]</sup>. This property will affect the imaging quality and spatial resolution although the camera has a small pixel size. The values along the X or Y axis in Fig. 2 are on behalf of pixel number of the terahertz camera array (the same below in Fig. 4).

The reflected terahertz images of two sides of the coin are acquired by using the ‘snap’ button in the control software connected to the camera. For comparison, their

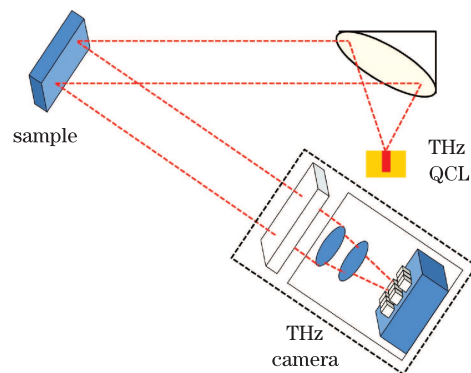


Fig. 1. Schematic of the real-time reflection setup based on a terahertz camera and a 3.9 THz quantum-cascade laser (QCL).

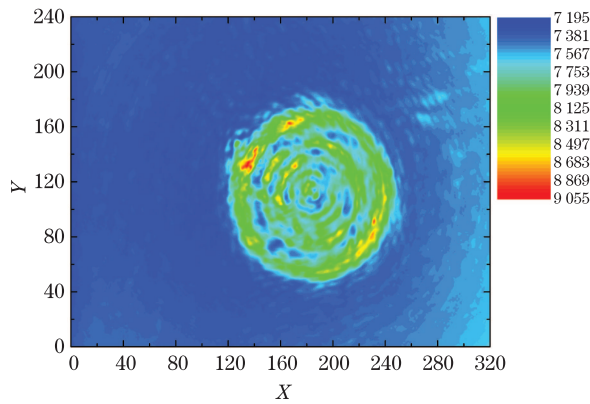


Fig. 2. Reflected beam pattern of real-time imaging.

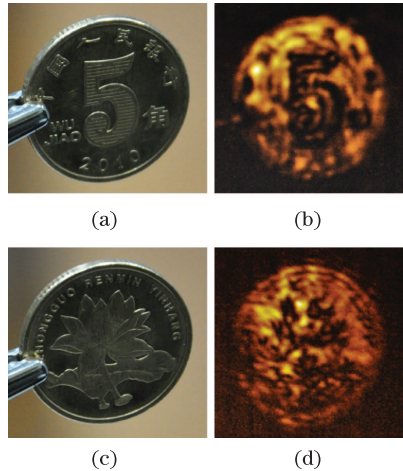


Fig. 3. (a) Optical images and (b) real-time reflected THz images of the two sides of a coin.

optical images (photograph) are shown in Fig. 3(a). Figure 3(b) shows the resulting THz real-time images from the obverse (upper part) and reverse (lower part) of the coin. In order to get the similar color to the optical images, the high reflection region is displayed in bright copper. The number '5' region and the flower pattern can be clearly seen in the THz images. Nevertheless, the reflected signal from patterns is lower than other regions, which is owing to that the patterns are embossed. The edges of the patterns are obscure, which results from the ring like property of the imaging beam spot.

To estimate the actual spatial resolution of the images in Fig. 3, the obverse facet of the coin is re-plotted in Fig. 4(b) and the reflection amplitude of a cross section at  $Y=50$  (the short dotted line) in the image is drawn in Fig. 4(a). We choose half amplitude of reflection amplitude as the threshold to estimate the spatial resolution. In Fig. 4(b), point A represents the amplitude in the no pattern area, and point B represents the amplitude at the edge of number '5'. The distance between point A and point B represents the spatial resolution on the camera, is equal to the width of two pixels, namely,  $47.0 \mu\text{m}$ . The diameter of the image on the camera array is estimated to the total width of 120 pixels, namely,  $2.82 \text{ mm}$ . The actual diameter of the coin is  $20 \text{ mm}$ . Therefore, the diameter ratio between coin and its image is about 7.1. According to this ratio, the spatial resolution of real-time imaging is estimated to about  $0.33 \text{ mm}$  which is approximately equal to the actual width on the coin,

with a value of about  $0.3 \text{ mm}$ . This result is better than that, with a value of about  $0.5 \text{ mm}$ , in Ref. [11].

The real-time reflection imaging of a concealed metal knife is also demonstrated. Figure 5 shows its optical image (a) and THz image (b). In the optical image, the knife is concealed by a white paper. In Fig. 5(b), the profile of the knife is obvious although it is concealed under a paper, which illustrates that the  $3.9\text{-THz}$  light can penetrate one paper twice. In the center of the profile, with lower reflection amplitude and displayed in blue color, indicates that this is the hollow out region of the knife.

The results acquired in our real-time reflection imaging system provide a proof-of-concept demonstration with an imaging resolution of about  $0.33 \text{ mm}$  and a frame rate of  $8.5 \text{ Hz}$ . The actual imaging resolution is mainly limited by the homogeneity of the imaging beam spot. Beam quality improvement should be done to obtain a homogeneous light beam by employing the wobbling mirrors<sup>[15]</sup> to eliminate the ring like beam pattern. The lasers with good beam quality by waveguide processing could make the imaging resolution and quality better. Such as using three-order DFB gratings<sup>[5]</sup> or the THz metamaterials<sup>[16,17]</sup> that could work from  $1$  to  $5 \text{ THz}$  in the future to improve the beam profile. Meanwhile, to image for a larger object, the size ratio between sample and image should be taken into account.

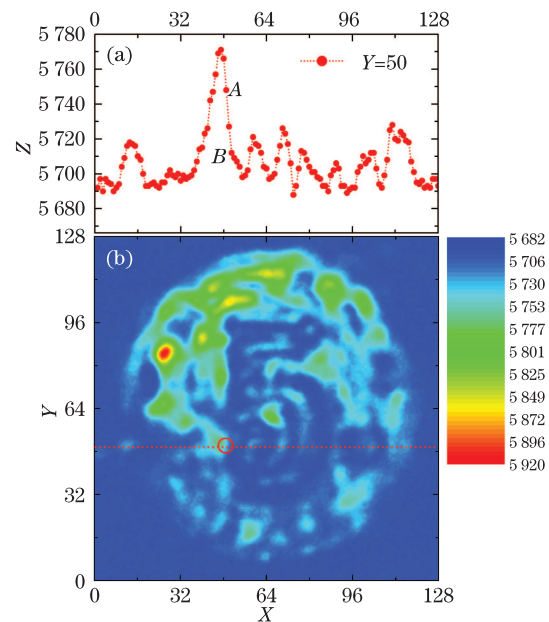


Fig. 4. Real-time reflected THz image (lower) of the obverse facet of a coin and the reflection amplitude (upper) of a cross section of the THz image in lower part, the red short dotted line indicates the location  $Y=50$ .

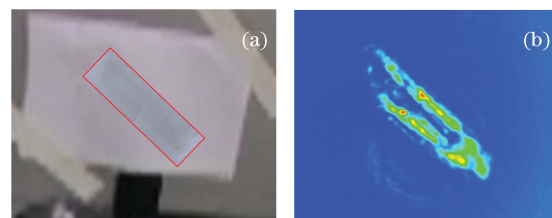


Fig. 5. (a) Optical image and (b) real-time reflected THz image of a concealed knife.

In conclusion, we demonstrate the real-time reflection imaging of a coin and a concealed knife by employing a terahertz camera and a 3.9 THz QCL as the imager and the light source, respectively. The imaging distance is about 1 m. The real-time images of the coin and the concealed knife are acquired by using the control software of the camera. An about 0.33-mm imaging resolution is achieved, which is limited by the beam profile. To get better imaging resolution and quality, the wobbling mirrors could be used to eliminate the ring like beam pattern in this experiment, or choose the THz lasers with good beam quality, and the size ratio between sample and image should be taken into account while imaging for a larger object.

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