Diffuse Terahertz Reflection Imaging Using Quantum Cascade Lasers

P. Dean, S. P. Khanna, S. Chakraborty, M. Lachab, A. G. Davies, and E. H Linfield

***Abstract*— We report diffuse reflection imaging using a quantum cascade laser at 2.83 THz. Both diffuse and specular imaging are demonstrated without purging the apparatus, initially using a coin concealed within a FedEx envelope as an exemplar, and the contrast mechanisms forming such images are discussed. The applicability of diffuse imaging to the detection of powdered samples concealed within various packages is then shown, and the effect of particle size is investigated. Measurements of the spatial resolution of the system indicate an imaging resolution of approximately 250 µm.**

I. INTRODUCTION

THE terahertz (THz) region of the electromagnetic spectrum has long been identified as being potentially well-suited to a range of security applications including stand-off imaging of concealed weapons, and sensing of chemical and biological agents. Such applications will ultimately require a tuneable, compact solid-state source that can deliver high-power narrowband radiation whilst operating at room temperature. THz frequency quantum cascade lasers (QCLs) have the potential to satisfy these requirements and have already been demonstrated as practical imaging sources for imaging.

In cases where the sample under investigation is suitably thin and exhibits low absorption at THz frequencies, a transmission imaging geometry can be employed. For bulky or highly-absorbing samples, one is restricted to a reflective geometry in which radiation specularly reflected or back-scattered from the sample is detected. For stand-off imaging, however, the exact alignment required for collection of specular reflections cannot be guaranteed in practice. Furthermore, the specific tomography of the sample surface can generate localised regions of high-intensity in the specular image that can lead to severely reduced image contrast or saturation of the detector. A practical stand-off imaging system should therefore monitor diffusely reflected radiation returning from the sample. Diffuse imaging also enables the detection of samples from which there is a strong component of scattered radiation such as from powders and crystals. Such a scheme is thus highly applicable for drug-screening applications.

In this paper we demonstrate diffuse reflection imaging in air using a QCL at 2.83 THz. Images of a five-pence coin, taken in both diffuse and specular geometries, are first presented as an exemplar. The detection of concealed powders using a diffuse geometry is then demonstrated. Initial measurements of the relationship between particle size and the strength of the backscattered signal are also presented.

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the imaging apparatus used for this work. The laser was a 2.5-mm-long bound-to-continuum QCL emitting at 2.83 THz [1], which was cooled to ~5 K in a closed-cycle pulse tube refrigerator. Radiation from the QCL was focused onto the sample with a 30° angle of incidence, and collected using a 30°, f/4.3 parabolic reflector in addition to an 90°, f/2 reflector. The former of these collection mirrors was coupled onto a room temperature pyroelectric sensor (D1), with the latter being coupled into a helium-cooled silicon bolometer (D2). The off-axis configuration of the 90° mirror ensured that no specular reflection was collected. Our system thus permits simultaneous detection of scattered THz radiation in addition to specularly reflected light. Current pulses were supplied to the QCL at a frequency of 50 kHz and a duty cycle of 40%, with lock-in detection at a frequency of 160 Hz being employed to improve the detection sensitivity. The sample was mounted on a two-axis translation stage that was raster scanned for image acquisition.

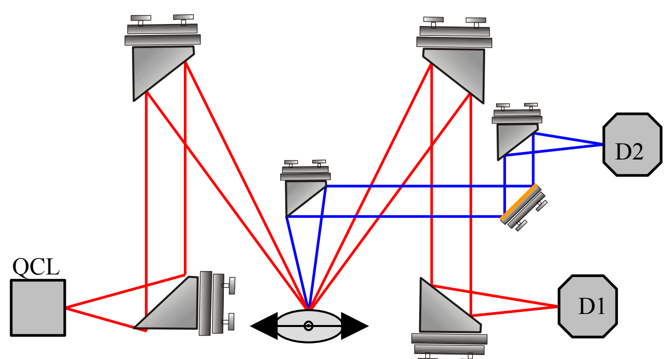

Fig. 1. Experimental apparatus for simultaneous specular (red) and diffuse (blue) imaging using a THz frequency QCL. D1 – Silicon bolometer; D2 – Pyroelectric sensor. No purging of the system was used.

The authors acknowledge the support of HMGCC, RCUK's 'Basic Technology' programme, and EPSRC(UK).

All authors are members of the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK.

Corresponding author email: p.dean@leeds.ac.uk

III. RESULTS

The resolution of the system was analysed using a series of gold-on-glass resolution targets [2]. For a target with a 1 mm pitch, modulation transfer functions equal to 0.75 and 0.74 were measured for the vertical and horizontal orientations, respectively. The resolution of the system, defined at the 20 % modulation threshold, is estimated to be 250 µm for both orientations.

Figures 2 (a) and (b) show the specular and diffuse images of a five-pence coin, concealed behind a fibrous HDPE FedEx envelope, taken with a 250 µm step-size. In the specular image, only surfaces that are both adequately flat to THz radiation and aligned in a suitable orientation generate resolvable image intensity. Contrast is provided by the reduced collection efficiency associated with areas of the coin that are not optically flat for THz waves. The diffuse reflection image, however, is sensitive to such regions where small surface irregularities result in randomly distributed 'diffuse Fresnel' reflections from the sample. Detection of these weaker isotropic reflections is more applicable to real-world stand-off sensing.

Initial diffuse detection of powdered samples, for which the incident radiation is partially back-scattered, is shown in Figures 2 (c) and (d). In this example, 800 mg of free polyethylene powder (55 µm mean particle diameter) was contained within a thin, 35-mm-wide resealable polythene bag. The powder is clearly resolved, as are creases in the front surface of the polythene bag, which produce a diffuse Fresnel component to the image. The peak THz power coupled into the detector, after scattering from this low-absorbing sample, was estimated to be ~5 µW, and the image acquisition time for this 180 x 108 pixel image was 27 minutes.

It is expected that the degree of scattering from powdered samples is dependent on the refractive index and absorption coefficient of the material as well as the particle size of the powder. The dependence on particle size was investigated using four samples of loose Teflon (PTFE) powders with mean particle sizes equal to 1, 12, 55 and 100 µm. Approximately 1 g of each powder was loosely packed into separate compartments of a polystyrene sample holder. The resulting diffuse image is shown in Figure 2 (e). The specular image in this case shows only reflections from the box lid and does not allow the powders to be located. As can be seen, the largest particle size (100 µm) generates the largest specular signal, with the second largest (55 µm) generating approximately 30 % of this intensity. The two finest powders produce smaller and similar scattered components. According to Mie scattering theory, the 100 µm powder results in the largest scattering coefficient for this wavelength of radiation, with the 1 µm producing the smallest. A greater component of back-scattered radiation is therefore expected for the larger particle size. In a further investigation, a series of admixtures consisting of systematically controlled relative concentrations of 100 µm and 12 µm loose PTFE powder were imaged. This is shown in Figure 2 (f) for nine admixtures with concentrations of the 100 µm powder ranging from 10% to 90% in equal steps. A clear linear relationship between concentration and signal intensity is observed, which is again consistent with trends predicted from scattering theory.

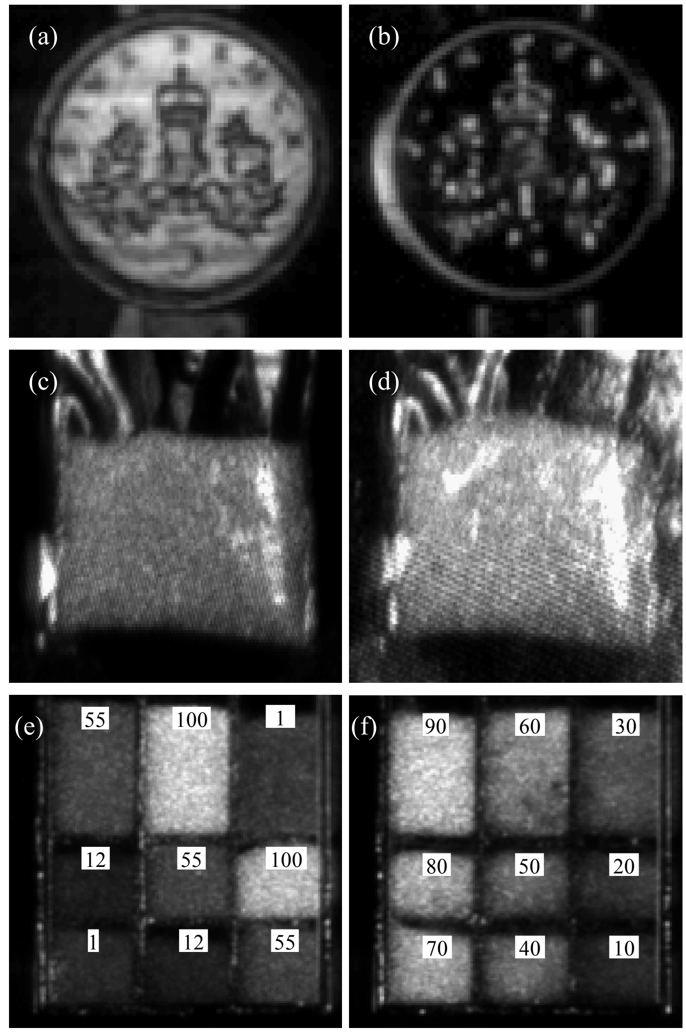

Fig. 2. (a) Specular and (b) diffuse image of a five-pence coin; diffuse image of free polyethylene powder in (c) a polythene bag and (d) a polythene bag concealed behind a FedEx envelope; (e) diffuse image of free Teflon powder in a Perspex box (mean particle sizes shown in µm); (f) diffuse image of Teflon admixtures of 12 µm and 100 µm powders (% concentrations of the 100-µm powder are shown).

IV. CONCLUSIONS

In conclusion, we have demonstrated diffuse reflection imaging of various samples using a THz frequency QCL. The detection of concealed loose powders has been demonstrated, and the dependence of the collected scattered intensity on particle size has been investigated. Initial results are consistent with predictions from scattering theory. Our investigation suggests that THz diffuse reflection imaging has the potential for stand-off detection of concealed powders.

References

[1] S. Barbieri *et al.*, "2.9 THz quantum cascade laser operating up to 70 K in continuous wave," *Appl. Phys. Lett.*, 85, 1674 (2004).

[2] P. Dean *et al.*, "Three-dimensional Characterisation of the Non-Gaussian Focused Beam from a Terahertz Quantum Cascade Laser," *Proc. Conference on Lasers and Electro-optics (CLEO), 2007.*