Feedback interferometry and diffuse reflectance imaging with terahertz quantum cascade lasers

A. Valavanis[1], P. Dean[1], Y. L. Lim[2], R. Alhathlool[1], A. D. Burnett[1], S. Chowdhury[1], R. Kliese[2], M. Nikolić[2], S. P. Khanna[1], M. Lachab[1], A. Rakić[2], A. G. Davies[1] and E. H. Linfield[1]
[1]School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom
[2]School of IT and Electrical Engineering, University of Queensland, QLD 4072, Australia

***Abstract*- We demonstrate security-relevant imaging and sensing techniques that exploit the intense coherent THz emission from quantum-cascade lasers (QCLs). Imaging and spectral discrimination (in the 3–3.4 THz range) between visibly-concealed powdered compounds is achieved through diffuse-reflectance imaging using a frequency-switchable THz QCL. Feedback-interferometry techniques are used to perform imaging and surface-profiling at 2.6 THz with no need for any external radiation detector. This coherent (homodyne) detection scheme allows THz imaging at round-trip distances of > 20 m through air, or with resolutions of ~200 µm.**

I. INTRODUCTION

Terahertz-frequency quantum cascade lasers (THz QCLs) [1] present a number of potential advantages as solid-state sources for security imaging in the 1–5 THz range, compared with broadband photoconductive antennas. Specifically, the substantially greater THz emission intensities may permit scanning at larger stand-off distances, and allow better-concealed or highly-absorbing compounds to be detected. The continuous-wave coherent THz emission from QCLs also offers the prospect of realizing phase-sensitive real-time detection schemes.

We present a range of security-relevant THz sensing schemes that exploit the high power and/or coherence of the THz emission from QCLs. A multi-frequency diffuse-reflectance imaging system is demonstrated, in which a frequency-switchable QCL is used to illuminate samples at four frequencies in the 3–3.4 THz range. By detecting the radiation scattered away from the specular reflection path, we obtain images of concealed powders at < 1 mm resolution, and observe material-specific spectral responses.

We also demonstrate the ability to obtain images of concealed objects using feedback interferometry. Here, detection is achieved by monitoring perturbations to the voltage across a THz QCL in response to feedback of radiation from a remote object. The high sensitivity of this homodyne detection scheme allows imaging to be performed at round-trip distances of 21 m through air—the longest-range interferometric sensing with a THz QCL to date. By observing the phase of the feedback, it is possible to track the displacement and velocity of remote objects and to generate three-dimensional profiles of their surfaces.

II. MULTI-FREQUENCY DIFFUSE REFLECTANCE IMAGING

Diffuse-reflectance imaging geometries offer several advantages over specular-reflection or transmission imaging when studying powdered samples. Objects of arbitrary thickness may be used, and precise alignment of collection optics is not required since diffuse reflections are spread over a large solid-angle. Furthermore, many smooth packaging materials have little effect upon diffuse reflectance images [2].

Although broadband photoconductive antennas allow spectroscopic analysis of diffuse reflections from explosives [3], the much greater emission powers of THz QCLs allow imaging of samples with a large range of scattering cross-sections [2], [4]. In this work, we have used a frequency-switchable QCL, in which a heterogeneous active-region design allows switching between single-mode emission at 3.05, 3.21, 3.28 and 3.35 THz by adjusting the bias [5]. Fig. 1 shows that the diffuse reflectance measurements reveal spectral discrimination between pure samples of powdered solids. The frequencies of the spectral resonances are found to be in agreement with those obtained using broadband THz time-domain spectroscopy. The ~8 mW emission intensity of the QCL enabled scanning at 1.5 m range through air.

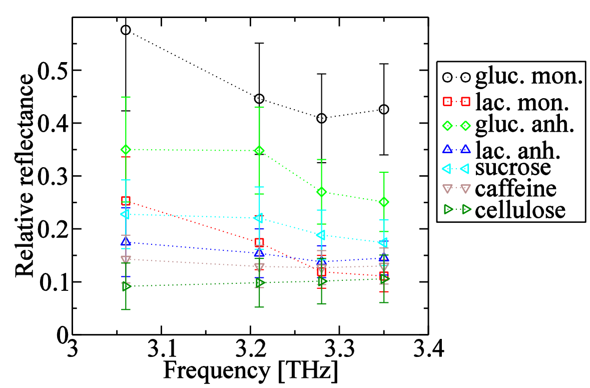

Figure 1. Diffuse reflectance of a range of powdered solids at 3.05, 3.21, 3.28 and 3.35 THz, relative to that of a PTFE reference powder.

III. FEEDBACK INTERFEROMETRY

The practicality of THz sensors for commercial applications is potentially limited by the lack of compact, sensitive and fast THz detection systems. Although THz imaging has been performed using thermal detectors such as helium-cooled bolometers [6], pyroelectric detectors [2], or microbolometer arrays [7], these are insensitive to the phase of the THz field.

We use a recently-developed THz feedback interferometry technique [8–10] to demonstrate phase-sensitive imaging and sensing. Here, a 2.6-THz QCL is driven by a fixed current and radiation is reflected from a target object back into the laser cavity. Intracavity interference causes a phase-sensitive perturbation to the laser voltage, which is monitored using a differential amplifier. From this, it is possible to deduce both the reflectivity and relative displacement of the object. The QCL itself therefore acts as both a radiation source and a detector. This removes the need for external thermal detectors, and simplifies the optical configuration of the sensor system.

Features smaller than ~200 μm may be resolved in raster-scanned images of concealed objects, and interference fringes in the images may be used to reconstruct 3-dimensional surface profiles. Figure 2 shows exemplar images of scalpel blades obtained with distances of 50 cm (top image) and 10.5 m (bottom image) between the QCL and the blade. The latter represents the longest-range THz interferometry with a QCL to date. A figure-of-merit $K = (\mu_f - \mu_b)/\sigma_b$ is defined for the images, where μ_f and μ_b are the mean signals in the foreground and background of the images, and σ_b is the standard deviation in the background signal. We observe only a modest reduction in K from 61.5 to 43.5 between the two images, indicating that substantially longer scanning ranges could be achieved.

We also demonstrate that the Beer–Lambert absorption coefficient for solid materials may be determined by observing the reduction in feedback signal as successive layers of PTFE sheeting are inserted in the beam-path.

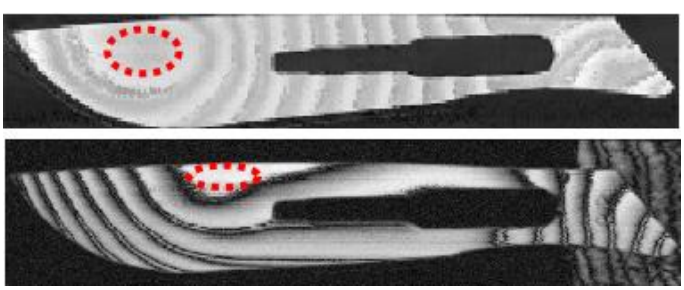

Figure 2: 2.6 THz feedback interferometry images of scalpel blades obtained at ranges of 50 cm (top) and at 10.5 m (bottom). The flat part of the blade used for calculating the figure-of-merit in each image is indicated by a dashed ellipse.

IV. CONCLUSIONS

We have exploited the coherent and high intensity THz emission from THz QCLs to demonstrate security-relevant imaging and sensing techniques that could not readily be achieved with broadband photoconductive antenna sources. Multi-frequency diffuse-reflectance imaging could be applied to the detection and spectral discrimination of explosive compounds, while feedback interferometry allows high-resolution imaging at large stand-off distances with no external detector. This sensing technique could potentially be used in 3D surface-profiling for concealed-threat identification, and (with tunable narrowband QCLs) for remote gas spectroscopy.

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