Terahertz sensing and imaging through self-mixing in a quantum cascade laser

R. Alhathlool[1,a], P. Dean[1], A. Valavanis[1], Y. L. Lim[2], R. Kliese[2], M. Nikolić[2], S. P. Khanna[1], L. H. Li[1], D. Indjin[1], J. Cunningham[1], S. J. Wilson[2], A. D. Rakić[2], A. G. Davies[1] and E. H. Linfield[1]

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Quantum cascade lasers (QCLs) [1] are compact, semiconductor sources of narrowband terahertz (THz) frequency radiation. Owing to their coherence and high power, they are potentially well-suited for use in a broad range of application areas, including chemical sensing and biomedical imaging [1]. However, their implementation in such applications requires a compact and sensitive detection system. We address this by using the THz QCL not only as the source but also as an interferometric (self-mixing (SM)) detector. SM occurs when radiation from a laser is partially reflected from an external object and injected back into the laser cavity. The reflected radiation interferes ('mixes') with radiation in the laser cavity, producing variations in the threshold gain, emitted power, lasing spectrum and terminal voltage [2]. This technique thus allows simple, self-aligned and robust system to be constructed for measuring displacement and reflectivity [3, 4].

We investigate the use of SM sensing with a THz QCL for three-dimensional imaging and surface profiling. Figure 1 shows a three-dimensional image of a stepped GaAs structure fabricated by wet etching, in which the surface morphology has been extracted from the phase of the SM signal. Whilst the laser SM signals in [3, 4] were obtained by monitoring the voltage variations across the laser terminals, we have also demonstrated that SM signals can also be obtained by monitoring the perturbations in power collected from the back facet of the laser. Figure 2 shows electrical and optical SM signals taken by monitoring the voltage and power variation in response to a moving remote object, and demonstrates the equivalence of these two measurement approaches.

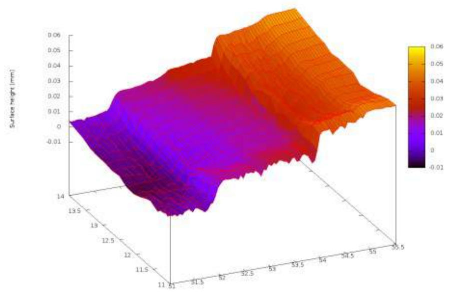

Figure 1 Exemplar three-dimensional image of a GaAs stepped sample.

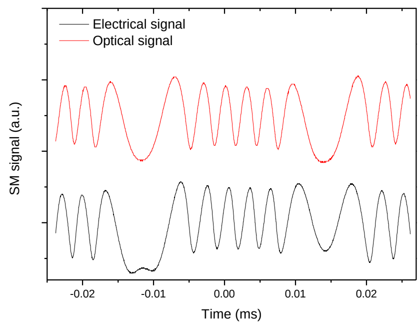

Figure 2 Exemplar electrical and optical SM signals obtained in response to a moving target.

1. R. Kohler et al., Nature **417**, 156 (2002).
2. R. Lang and K. Kobayashi, IEEE J. Quant. Electron. **16**, 347 (1980).
3. Y. L. Lim et al., Appl. Phys. Lett. **99**, 081108 (2011).
4. P. Dean et al., Opt. Lett. **36**, 2587 (2011).

Detection of concealed weapons and characterisation of crystalline powders using 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], D. Indjin[1], S. J. Wilson[2], A. D. Rakić[2], A. G. Davies[1], and E. H. Linfield[1]

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Terahertz (THz)-frequency radiation (located between the microwave and infrared parts of the electromagnetic spectrum) offers many potential benefits for security sensing. In particular, it propagates through many common packaging materials, and excites material-specific resonances in crystalline compounds.[1] However, THz sources are typically too large, expensive or low-powered for many applications. We present two imaging techniques that exploit THz quantum cascade lasers (QCLs)—compact semiconductor sources of intense coherent 1–5 THz radiation.

Self-mixing-interferometry imaging of concealed objects: When THz radiation is partially reflected from objects back into a QCL, intra-cavity interference (self-mixing) causes measurable changes in terminal voltage, depending on the amplitude and phase of the reflections.[2] This removes the need for an external detector and allows imaging of metallic objects (Fig. 1a) at up to 21 m round-trip distances. The 3D surface-profile may then be inferred from the phase of the interference.

Spectroscopic diffuse-reflectance imaging: We measure backscattered radiation from powders illuminated by a tuneable 3–3.4 THz QCL. Unlike transmittance imaging, this technique does not require precise detector alignment, and arbitrarily-thick samples may be scanned.[3] Diffuse reflectance measurements reproduce THz spectral features accurately and we show that material-specific resonances may be obtained for a range of materials (Fig. 1b).

This work was funded by the ERC Advanced Grants '*TOSCA*', EPSRC (UK), the Innovative Research Call in Explosives and Weapons Detection (2007), a cross-government programme sponsored by a number of government departments and agencies under the CONTEST strategy, and the Australian Research Council's Discovery Projects funding scheme (DP120103703).

1. M. Tonouchi, Nat. Photonics **1**, 97 (2007).
2. P. Dean, et al., Opt. Lett. **36**, 2587 (2011).
3. P. Dean, et al., Opt. Express **16**, 5997 (2008).

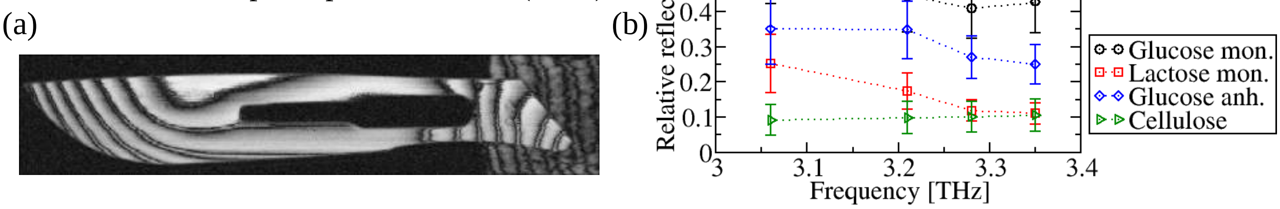

Fig. 1 (a) 2.6 THz self-mixing interferometry image of a scalpel blade at 10.5 m scanning-range. (b) Diffuse-reflectance spectra of a range of powders, at 3–3.4 THz.

Thermo-optic detection of quantum cascade laser radiation in the range ~2.2−2.9 THz using a ZnTe crystal

A.H. Awang[a], P. Dean, R. Alhathlool, I. Kundu, S.P. Khanna, L.H. Li, E.H. Linfield, and A.G. Davies

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It has recently been reported that the radiation emitted from a terahertz (THz) quantum cascade laser (QCL) can be detected through the thermo-optic (TO) response of a ZnTe crystal [1]. However, a full quantitative analysis of this response has yet to be undertaken. We have measured the TO response of a ZnTe crystal to QCL radiation in the frequency range ~2.2−2.9 THz, and developed a full analytical description of the TO mechanism in ZnTe. We have found that the anisotropy of the TO coefficients must be considered in order to correctly reproduce the experimental results.

Radiation from a THz QCL was focused onto a wedged ZnTe crystal, and the TO response measured using a probe beam from a 778.3 nm diode laser in a balanced sampling arrangement [1] (Fig. 1 (inset)). The TO response was investigated for variations in driving current and pulse modulation frequency for THz QCLs emitting at ~2.2 THz, ~2.6 THz and ~2.9 THz. Fig. 1(a) shows the TO response as a function of bias current for a ~2.2 THz QCL. For comparison, the response obtained using a helium-cooled germanium bolometer is also shown. They exhibit a similar functional form, which demonstrates that the sampling technique is sensitive to the THz radiation intensity. Fig. 1(b) shows the thermo-optically-induced change in birefringence of ZnTe, measured as a function of pulse modulation frequency. We find that the TO response can be understood using a thermal model [2] that incorporates the absorbed THz power and accounts for the anisotropic thermo-optic coefficients of ZnTe.

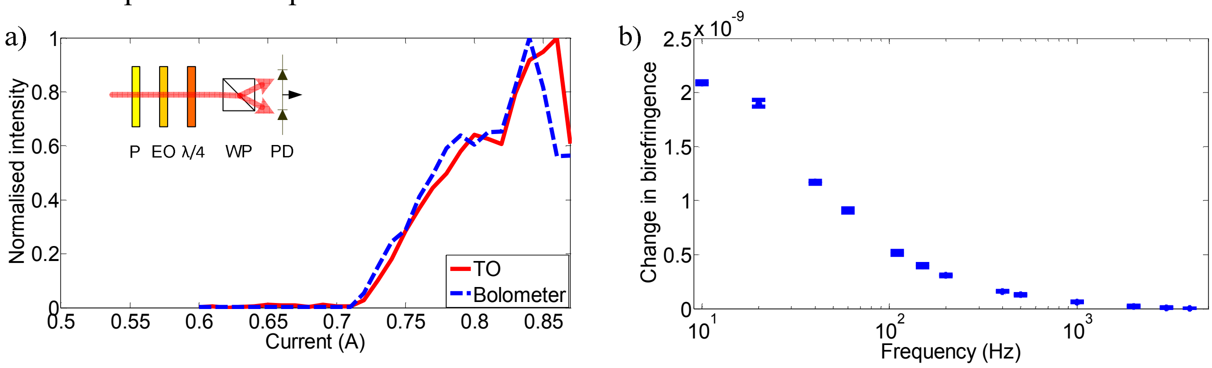

Fig.1. a) Intensity-current characteristic of a ~2.2 THz QCL obtained from the TO response (solid line) and a bolometer (dashed line). (Inset) Detection setup comprising a grid polariser (P), ZnTe EO crystal, quarter-wave plate (λ/4), Wollaston prism (WP) and a pair of balanced photodetectors (PD). b) Change in birefringence as a function of pulse modulation frequency for a ~2.2 THz QCL.

References
[1] A. van Kolck *et al, Appl. Phys. Lett.* **97**, 251103 (2010).
[2] J. C. Brasunas *et al, Infrared Physics & Technology* **38**, 69 (1997).

Oral Session, July 4 (Wednesday)

** presented by member of JSPS Core-to-Core Program*

4A-01 *Multi-THz Nonlinear Optics: Four-wave mixing, transient spin order, and ultrastrong light-matter coupling*

9:30-10:10 (Invited) O. Schubert, M. Porer, R. Huber (Univ. of Konstanz, Univ. of Regensburg), F. Junginger, B. Mayer, C. Schmidt, A. Pashkin, K. Kim, J. Demsar, A. Leitenstorfer (Univ. of Konstanz), J. M. Menard (Univ. of Regensburg)

4A-02 *Terahertz and Infrared Dynamics in Graphene and Carbon Nanotubes*

10:10-10:50 (Invited) L. Ren, L. G. Booshehri, Q. Zhang, E. H. Haroz, S. Nanot, J. Kono, C. L. Pint, R. H. Hauge, M. Wang, R. Vajtai, P. M. Ajayan, J. Yao, Z. Sun, Z. Yan, Z. Jin, J. M. Tour (Rice Univ.), R. Kaneko, I. Kawayama, M. Tonouchi (Osaka Univ.)

4A-03 *Quantitative Characterization of Rust in Coated Steel Plates using Terahertz Waves*

11:00-11:20 (Invited) N. Fuse T. Fukuchi, T. Takahashi and T. Okamoto (Central Research Inst. Electric Power Industry), M. Mizuno and K. Fukunaga (NICT)

4A-04 *Terahertz Coherent Control of a Landau-quantized Two-dimensional Electron Gas*

11:20-11:40 (Invited) T. Arikawa (Kyoto Univ.), Q. Zhang, X. Wang and J. Kono (Rice Univ.), D. J. Hilton (Univ. of Alabama), J. L. Reno, W. Pan (Sandia National Laboratories)

4A-05* *Pair-breaking in Superconducting Thin Films induced by Intense Terahertz Pulses*

11:40-12:00 C. H. Zhang, I. Kawayama, H. Murakami, M. Tonouchi (Osaka Univ.), B. B. Jin, J. Chen (Nanjing Univ.), A. Glossner (Osaka Univ., Univ. Erlangen-Nurnberg), P. Muller (Univ. Erlangen-Nurnberg)

4P-01 *THz Photon-assisted Tunneling in Single Quantum Dot Transistors*

13:00-13:30 (Invited) K. Hirakawa, K. M. Cha (Univ. of Tokyo, CREST-JST), K. Shibata, Y. Zhang (The Univ. of Tokyo)

4P-02 *Carbon Nanotube Field Effect Transistors with End-contact Geometry*

13:30-14:00 (Invited) K. Sueoka and A. Subagyo (Hokkaido Univ.)

4P-03* *Carrier Scattering and Flux Cancellation in Multi-walled Carbon Nanotubes*

14:00-14:20 (Invited) M. Kida, A. Seino,Y. Asano, N. Aoki, and Y. Ochiai (Chiba Univ.), T. Nakanishi (AIST), and J. P. Bird (SUNY Buffalo)

4P-04 *Nanoscale THz Sensing and Imaging with Nano-Carbon Devices*

14:20-14:40 (Invited) Y. Kawano (Tokyo Inst. of Tech.)

4P-05 *Self-Mixing Interferometry with Terahertz Quantum Cascade Lasers*

14:40-15:00 (Invited) P. Dean, A. Valavanis, R. Alhathlool, S. P. Khanna, D. Indjin, E. H. Linfield and A. G. Davies (Univ. of Leeds), Y. L. Lim, M. Nikolic, R. Kliese, S. J. Wilson and A. D. Rakic (The Univ. of Queensland)

4P-06* *Laser Induced Polymerization of Fullerene Thin-Films and Nano-Whiskers*

15:15-15:30 T. Doi, X. Wei, D. Momiyama, M. Toriumi, K. Miyamoto, T. Omatsu, N. Aoki and Y. Ochiai (Chiba Univ.), J. P. Bird (SUNY Buffalo)

4P-07* *Simulation of Terahertz Plasmons in Graphene and Heterostructure Two-dimensional Electron Gas*

15:30-15:45 A. Satou, H. Shida, V. Ryzhii and T. Otsuji (Tohoku Univ.), V. V. Popov (Russian Academy of Sciences)

4P-08*
15:45-16:00
Dynamically-generated Pure Spin Current in Single Layer Graphene
Z. Y. Tang, E. Shikoh, Y. Ando, T. Shinjo and M. Shiraishi (Osaka Univ.), H. Ago (Kyushu Univ.)

4P-09
16:00-16:15
GaN-based Two-Well Terahertz Quantum Cascade Laser
H. Yasuda (NICT)

Oral Session,July 5 (Thursday)

* *presented by member of JSPS Core-to-Core Program*

5A-01
9:30-10:10
(Invited)
Nanoscale Engineering with Carbon
P. M. Ajayan (Rice Univ.)

5A-02*
10:10-10:50
(Invited)
CVD Growth Control of Single-walled Carbon Nanotubes
S. Maruyama (The Univ. of Tokyo)

5A-03*
11:00-11:20
(Invited)
THz Coherent Phonons in Graphene on Silicon
M. Suemitsu, M. H. Jung and H. Fukidome (Tohoku Univ.), I. Katayama, J. Takeda (Yokohama National Univ.), M. Kitajima (National Defense Academy)

5A-04*
11:20-11:40
(Invited)
Toward the Creation of Terahertz Graphene Lasers: Injection vs. Optical Pumping
T. Otsuji, A. Satou and V. Ryzhii (Tohoku Univ.), M. Ryzhii (Univ. of Aizu)

5A-05
11:40-12:00
Vibrational Spectroscopy of Nylon Samples in Terahertz Frequency Region
H. Hoshina, H. Suzuki and C. Otani (RIKEN), S. Ishii, T. Uchiyama (Miyagi Univ.), H. Sato, S. Yamamoto, Y. Ozaki (Kwansei Gakuin Univ.), Y. Morisawa (Kinki Univ.)

5P-01
13:00-13:30
(Invited)
Terahertz Spectroscopy of Silicon Nanowire Films
M. Lim, G.S. Lee, Y. Do and H. Han (Postech), SJ. Choi, M.L. Seol and Y.K. Choi (KAIST)

5P-02
13:30-14:00
(Invited)
Relativistic Ultrafast Dynamics of an Electron-Hole Plasma in Graphene
K. M. Dani (OIST), J. Lee, A. D. Mohite, A. M. Dattelbaum, H. Htoon, A. J. Taylor (Los Alamos National Laboratory), R. Sharma (TRIUMF), C. C. Galande, P. M. Ajayan (Rice Univ.)

5P-03
14:00-14:20
(Invited)
Optical Pulse Sources for Terahertz Measurement
N. Sekine, I. Morohashi, J. Hamazaki and I. Hosako (NICT)

5P-04
14:20-14:40
(Invited)
Ultrafast Terahertz Dynamics of Graphene Nanostructures and Devices
I. Maeng and H. Choi (Yonsei Univ.), S. Lim, S. J. Chae, and Y. H. Lee (Sungkyunkwan Univ.), J. H. Son (Univ. of Seoul)

5P-05
14:40-15:00
(Invited)
Sensing the Heartbeat in the sub-THz Region of the Spectrum
P. B. Ishai (The Hebrew Univ. of Jerusalem, Nagoya Univ.), M. Brodski, Y. Segev, A. Polsman and Y. Feldman (The Hebrew Univ. of Jerusalem)

5P-06*
15:15-15:30
Scanning Laser Terahertz Near-field Imaging System
K. Serita, H. Murakami, I. Kawayama, Y. Takahashi, M. Yoshimura, Y. Mori, M. Tonouchi (Osaka Univ.), J. Darmo (Osaka Univ., Vienna Univ. of Tech.)

5P-07
Carrier Transport in Conducting Polymer PEDOT:PSS investigated by THz and IR-UV Spectroscopy
15:30-15:45
M. Yamashita, Y. Yamada, C. Otani (RIKEN), Y. Mochizuki, H. Okuzaki (Univ. of Yamanashi), T. Sasaki (Tohoku Univ.)

5P-08 *Visualization of the Catalytic Reactions of Hydrogen Gas using the Terahertz Chemical Microscope*

15:45-16:00 T. Kiwa, T. Hagiwara, K. Omura, K. Sakai and K. Tsukada (Okayama Univ.)

5P-09 *Development of a Terahertz Imaging System for the Analysis of a Solar Cell*

16:00-16:15 H. Nakanishi, A. Ito (Dainippon Screen Mfg.), K. A. Salek, K. Takayama, I. Kawayama, H. Murakami and M. Tonouchi (Osaka Univ.)

Poster Session, July 4 (Wednesday), 16:30-17:45

** presented by member of JSPS Core-to-Core Program*

P-01* *CVD Growth of Mono- and Bi-layer Graphene from Ethanol*

X. Chen, P. Zhao, B. Hou, S. Chiashi, S. Maruyama (The Univ. of Tokyo)

P-02* *Characterization of Single-walled Carbon Nanotubes and Graphene-based Field-effect Transistors*

S. Kim, S. Aikawa, P. Zhao, E. Einarsson, S. Chiashi, S. Maruyama (The Univ. of Tokyo)

P-03* *Instability-driven Terahertz Emission and Injection Locking Behavior in an Asymmetric Dual-grating Gate HEMT with a Vertical Cavity Structure*

T. Watanabe, T. Fukushima, Y. Kurita, A. Satou, T. Otsuji (Tohoku Univ.)

P-04* *Resonant Detection of Terahertz Radiation at Low Temperature by Asymmetric Dual-grating-Gate HEMT*

T. Fukushima, Y. Tanimoto, S. Boubanga-Tombet, T. Watanabe, T. Otsuji (Tohoku Univ.), Y. Wang, H. Minamide, H. Itou (RIKEN), D. Fateev, V. Popov (Kotelnikov Inst. of Radio Eng. and Electronics), D. Coquillat, W. Knap (Univ. Montpellier 2 & CNRS)

P-05* *Relationship between Momentum Relaxation Time and Negative Dynamic Conductivity in Optically Pumped Graphene*

Y. Kurita, T. Watanabe, T. Fukushima, S. B. Tombet, A. Satou, V. Ryzhii, T. Otsuji (Tohoku Univ.) S. Chan (Nano-Japan Rice Univ., Tohoku Univ., Univ. of Pennsylvania)

P-06* *THz Detection Device using Graphene FET*

A. M. Mahjoub, T. Abe, Y. Iso, T. Ohuchi, N. Aoki, K. Miyamoto, T. Omatsu,, Y. Ochiai (Chiba Univ.), J. P. Bird (SUNY), D. K. Ferry (Arizona State Univ.),, K. Ishibashi (RIKEN)

P-07* *High Performance Field-Effect Transistor composed of Network of Metallic/Semiconducting SWNTs*

X. Wei, N. Aoki, T. Yahagi, K. Maeda, M. Matsunaga, Y. Ochiai (Chiba Univ.), J. P. Bird (SUNY), K. Ishibashi (RIKEN)

P-08* *Band-Gap Engineering of Bilayer Graphene with Ionic-Liquid Gate*

Y. Ohno, Y. Yamashiro, T. Ikuta, K. Maehashi, K. Inoue and K. Matsumoto (Osaka Univ.)

P-09 *Generation of Wide Range THz Waves using a Semiconductor Laser Chaos and a He-Ne Laser*

F. Kuwashima, T. Shirao (Fukui Univ. of Tech.), M. Tani, K. Kurihara, K. Yamamoto, H. Iwasawa (Univ. of Fukui), M. Hangyo, T. Nagashima (Osaka Univ.)

P-10 *Detection of Additives Localization in Rubber Vulcanizates by Terahertz Spectroscopy*

Y. Saita, Y. Hirakawa, Y. Ohno, T. Gondoh, T. Mori (Kurume Nat. College. of Tech.), M. Tonouchi (Osaka Univ.)

P-11 *Time-domain Spectroscopy using Ultra-Compact THz Probe based on EO Sampling*

Y. Imajo, H. Noguchi (Stack Electronics Co., Ltd.), I. Morohashi, N. Sekine, I. Hosako (NICT)

P-12 *Terahertz Wave Reflection Measurement with Mental and Physical Stimulus*

M. Yamaguchi, L. Rang, S. Katori, H. Ogura (Nagoya Univ.), S.R. Tripathi, K. Kawase(Nagoya Univ., RIKEN)

P-13 *Measurement of Various Types of Solar Cells using Laser Terahertz Emission Microscopy*

A. Ito, H. Nakanishi (Dainippon Screen Co.), K. A. Salek, K. Takayama, I. Kawayama, H. Murakami, M. Tonouchi (Osaka Univ.)

P-14* *Dielectric Responses of (Ba, Sr)TiO_3 Thin Films observed by Terahertz Time Domain Spectroscopy*

I. Kawayama, K. Kotani, M. Misra, R. Kinjo, H. Murakami, M. Tonouchi (Osaka Univ.)

Surface-profiling through self-mixing in a THz quantum cascade laser

R. Alhathlool[1,a], P. Dean[1], A. Valavanis[1], Y. L. Lim[2], R. Kliese[2], M. Nikolić[2], S. P. Khanna[1], L. H. Li[1], D. Indjin[1], J. Cunningham[1], S. J. Wilson[2], A. D. Rakić[2], A. G. Davies[1] and E. H. Linfield[1]

[1]*School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK*
[2]*School of IT and Electrical Engineering, The University of Queensland, QLD 4072, Australia*
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Terahertz frequency quantum cascade lasers (THz QCLs) are semiconductor sources of coherent THz radiation, and have numerous potential applications in chemical sensing and industrial inspection, as well as security and biomedical imaging [1]. However, these applications require a compact and sensitive detection system. We address this by using a THz QCL as both the radiation source and as an interferometric detector.

Self-mixing (SM) occurs when radiation is reflected from an external object back into the QCL cavity. The resulting interference modulates the emitted power and QCL voltage [2], depending on the amplitude and phase of the reflection. This allows simple, ‘detector-free’, sensing of displacement and reflectivity, with high-sensitivity owing to its coherent nature [3, 4]. We demonstrate 3D imaging using SM in a THz QCL. Fig. 1(a) shows a 3D image of a stepped GaAs structure fabricated by wet chemical etching, in which the surface height has been extracted from the phase of the SM signal. Although the SM signals in [3, 4] were obtained from changes to the laser voltage, we show that SM signals can also be obtained from the THz emission from the back laser-facet. Fig. 1(b) shows the equivalence of electrical and optical SM signals, resulting from reflections from an oscillating object. Owing to the high SM sensitivity, we have been able to demonstrate stand-off imaging at round-trip distances of up to 20 m through air.

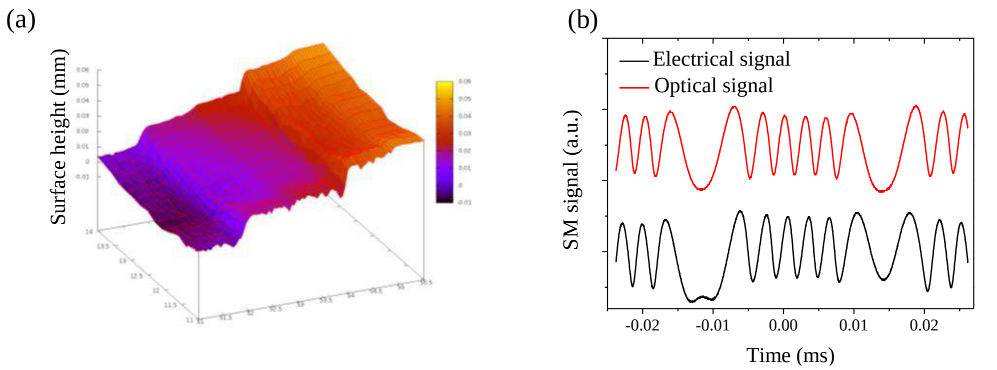

Fig. 1: (a) Exemplar 3D image of steps etched in GaAs. (b) Electrical and optical SM signals obtained in response to a moving target.

1. R. Kohler *et al.*, Nature **417**, 156 (2002).
2. R. Lang and K. Kobayashi, IEEE J. Quant. Electron. **16**, 347 (1980).
3. Y. L. Lim *et al.*, Appl. Phys. Lett. **99**, 081108 (2011).
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Thermo-optic detection of quantum cascade laser radiation in the range ~2.2−2.9 THz using a ZnTe crystal

A.H. Awang[a], P. Dean, R. Alhathlool, I. Kundu, S.P. Khanna, L.H. Li, E.H. Linfield, and A.G. Davies

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It has recently been reported that the radiation emitted from a terahertz (THz) quantum cascade laser (QCL) can be detected through the thermo-optic (TO) response of a ZnTe crystal [1]. However, a full quantitative analysis of this response has yet to be undertaken. We have measured the TO response of a ZnTe crystal to QCL radiation in the frequency range ~2.2−2.9 THz, and developed a full analytical description of the TO mechanism in ZnTe. We have found that the anisotropy of the TO coefficients must be considered in order to correctly reproduce the experimental results.

Radiation from a THz QCL was focused onto a wedged ZnTe crystal, and the TO response measured using a probe beam from a 778.3 nm diode laser in a balanced sampling arrangement [1] (Fig. 1 (inset)). The TO response was investigated for variations in driving current and pulse modulation frequency for THz QCLs emitting at ~2.2 THz, ~2.6 THz and ~2.9 THz. Fig. 1(a) shows the TO response as a function of bias current for a ~2.2 THz QCL. For comparison, the response obtained using a helium-cooled germanium bolometer is also shown. They exhibit a similar functional form, which demonstrates that the sampling technique is sensitive to the THz radiation intensity. Fig. 1(b) shows the thermo-optically-induced change in birefringence of ZnTe, measured as a function of pulse modulation frequency. We find that the TO response can be understood using a thermal model [2] that incorporates the absorbed THz power and accounts for the anisotropic thermo-optic coefficients of ZnTe.

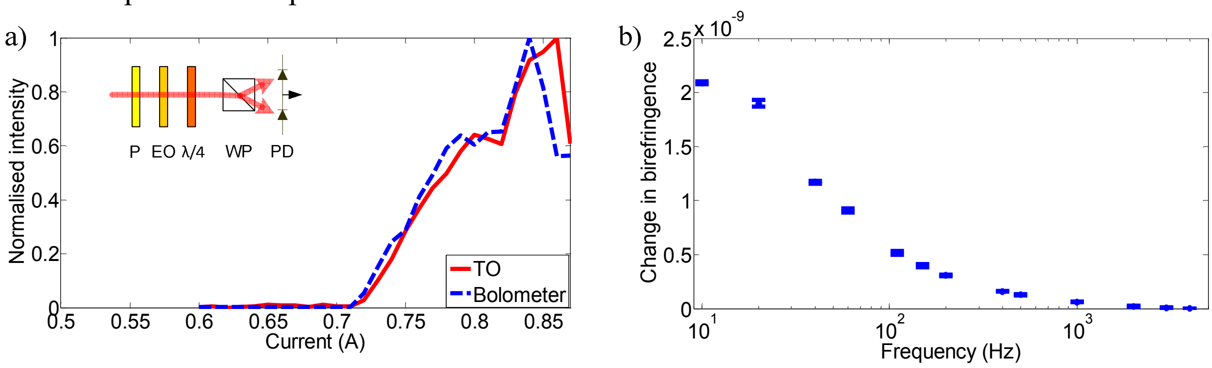

Fig.1. a) Intensity-current characteristic of a ~2.2 THz QCL obtained from the TO response (solid line) and a bolometer (dashed line). (Inset) Detection setup comprising a grid polariser (P), ZnTe EO crystal, quarter-wave plate (λ/4), Wollaston prism (WP) and a pair of balanced photodetectors (PD). b) Change in birefringence as a function of pulse modulation frequency for a ~2.2 THz QCL.

References
[1] A. van Kolck *et al, Appl. Phys. Lett.* **97**, 251103 (2010).
[2] J. C. Brasunas *et al, Infrared Physics & Technology* **38**, 69 (1997).

Thermo-optic detection of quantum cascade laser radiation in the range ~2.2−2.9THz using a ZnTe crystal

P. Dean*, A. H. Awang, R. Alhathlool, I. Kundu, S.P. Khanna, L.H. Li, E.H. Linfield, and A.G. Davies
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Email: *p.dean@leeds.ac.uk

***Abstract*—We have investigated the thermo-optical (TO) response of a ZnTe crystal to THz QCL radiation in the frequency range ~2.2-2.9 THz. The TO response was investigated for variations in driving current, QCL polarisation direction and pulse modulation frequency. We show that the anisotropy of the TO coefficients should be taken into account to correctly describe the experimental response.**

I. Introduction and Background

It has recently been reported that the radiation emitted from a terahertz (THz) quantum cascade laser (QCL) can be detected via the thermo-optic (TO) response of a ZnTe crystal [1]. However, a full quantitative analysis of this response has yet to be undertaken. We have measured the TO response of a ZnTe crystal to QCL radiation in the frequency range ~2.2−2.9 THz, and developed a full analytical description of the TO mechanism in ZnTe. We have found that the anisotropy of the TO coefficients must be considered in order to correctly reproduce the experimental result.

II. Methodolgy and Thermo-optic Model

Radiation from a THz QCL was focused onto a wedged <110> ZnTe crystal with average thickness L=1.8mm, and the TO response measured in a balanced sampling arrangement [1] using two collinear probe beams from diode lasers with wavelength λ=778.3 nm and combined power ~20 mW (see inset Fig. 1). Devices were driven either in continuous wave, with mechanical modulation and lock-in detection being employed to improve the detection sensitivity, or in pulsed mode with the pulse trains being electrically modulated. In this scheme the detected signal is expected to vary approximately linearly with the thermally-induced change in birefringence of the ZnTe crystal Δn, which in turn is determined by the temperature change ΔT induced by the absorbed QCL radiation, according to the relation [2,3]

$$\Delta I = I_0 \sin\left(\frac{2\pi L \Delta n}{\lambda}\right) \approx \frac{2\pi L \Delta T}{\lambda}\left(\frac{\kappa_2}{n_2} - \frac{\kappa_1}{n_1}\right). \quad (1)$$

Here κ_1 and κ_2 are constants describing the anisotropic thermo-optic coefficients of the crystal with natural birefringence (n_2-n_1). The temperature change ΔT is expected to depend on the absorbed THz power, the QCL pulse modulation frequency and the thermal properties of the ZnTe crystal.

The TO response was investigated for variations in driving current, QCL polarisation direction and pulse modulation frequency for THz QCLs emitting at ~2.2 THz, ~2.6 THz and ~2.9 THz.

III. Results

Fig. 1 shows the TO response as a function of bias current for a ~2.2 THz QCL driven in continuous wave. For comparison, the response obtained using a helium-cooled germanium bolometer is also shown. They exhibit a similar functional form, which demonstrates that the sampling technique is sensitive to the THz radiation intensity, with the linear dependence predicted from Eq. (1).

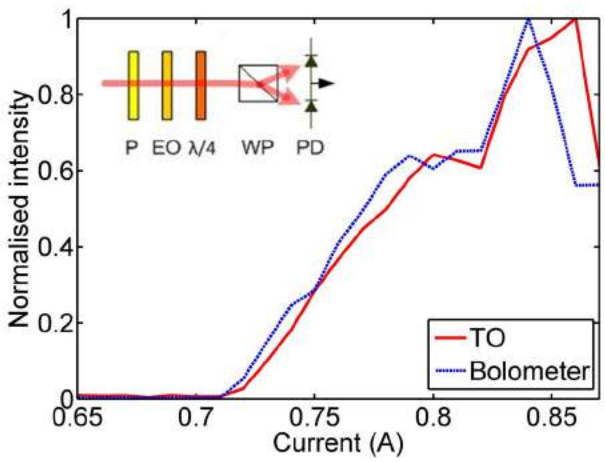

Fig. 1. The intensity-current characteristic of a ~2.2 THz QCL obtained from the TO response (red, solid line) and a germanium bolometer (blue, dashed line). (Inset) Schematic of the detection setup comprising a grid polariser (P), ZnTe EO crystal, quarter-wave plate (λ/4), Wollaston prism (WP) and a pair of balanced photodetectors (PD).

The response to variations in the polarisation direction of the QCL field relative to the [-1,1,0] direction of the ZnTe crystal was investigated by rotating a wire grid polariser in the QCL beam. Fig. 2 shows the angular dependence of the thermo-optically-induced change in birefringence Δn, obtained using Eq. (1), for a ~2.6 THz QCL mechanically modulated at

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a frequency of 40 Hz. Also shown is the corresponding angular variation of QCL power, measured using a germanium bolometer, which arises from the transmission of the elliptically polarised QCL field through the wire grid polariser. The TO response reproduces the variation of QCL power well, which confirms the expected insensitivity of the TO mechanism to the polarisation direction of the THz field.

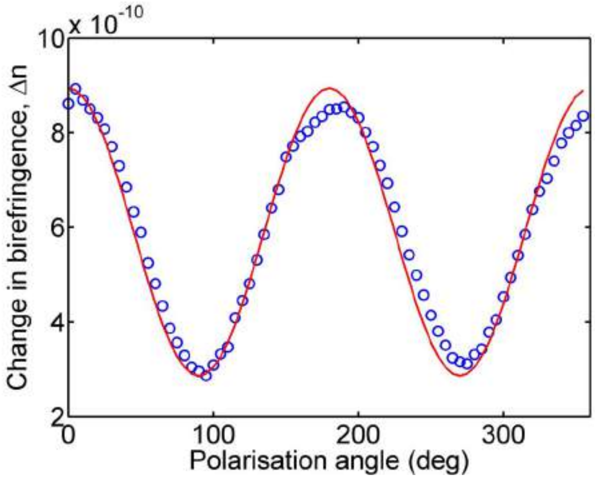

Fig. 2. Thermo-optically-induced change in birefringence as a function of the polarization angle relative to the [-1,1,0] direction of a ZnTe crystal (blue data points). Also shown is the variation of QCL power (red solid line).

Fig. 3 shows Δn measured as a function of electrical modulation frequency for a ~2.2 THz QCL. As expected for a slow thermal response, the change in birefringence decreases with increasing modulation frequency in this range. We find that the TO response can be understood using a thermal model [4] for the temperature change ΔT that accounts for the absorbed THz power, the modulation frequency, and the thermal conductance and heat capacity of the irradiated crystal volume. Using this model in conjunction with Eq. (1), and by fitting to the data in Fig. 3, the TO response can be fully quantified. We find that TO-induced temperature changes of the order ΔT~0.01 K are achieved at low modulation frequencies.

The thermal response of the ZnTe crystal can be further quantified through measurement of the crystal's natural birefringence using the balanced detection scheme in the absence of THz radiation. From the small value obtained (n_2-n_1~10^{-6}) and by inspection of Eq. (1) we find that the anisotropy of the thermo-optic coefficients plays an important role in determining the magnitude of the TO response.

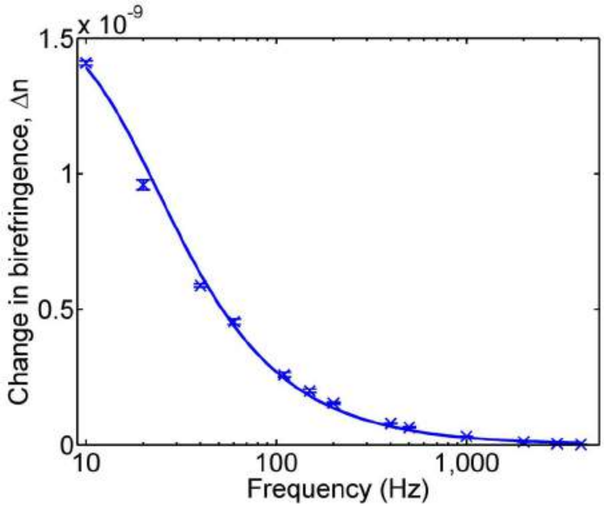

Fig. 3. Thermo-optically induced change in birefringence of a ZnTe crystal, measured as a function of pulse modulation frequency for a ~2.2 THz QCL.

IV. CONCLUSION

The thermo-optic response of a ZnTe crystal to THz QCL radiation in the frequency range ~2.2-2.9 THz has been studied. A quantitative description has been developed that accounts for the anisotropy of the thermo-optic coefficients in ZnTe. This anisotropy is found to strongly influence the magnitude of the TO response.

ACKNOWLEDGMENT

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Feedback interferometry and diffuse reflectance imaging with terahertz quantum cascade lasers

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***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.

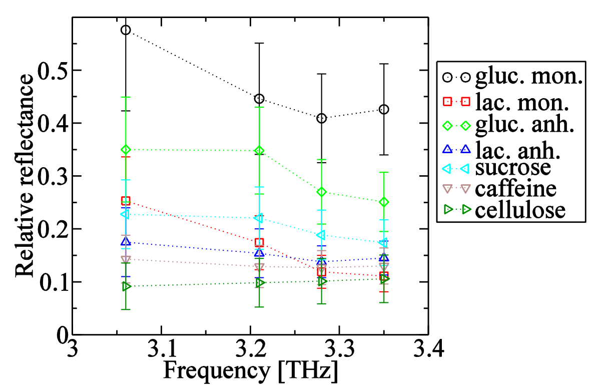

Figure 1. Diffuse reflectance of a range of powdered solids at 3.05, 3.21, 3.28 and 3.35 THz, relative to that of a PTFE reference powder.

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.

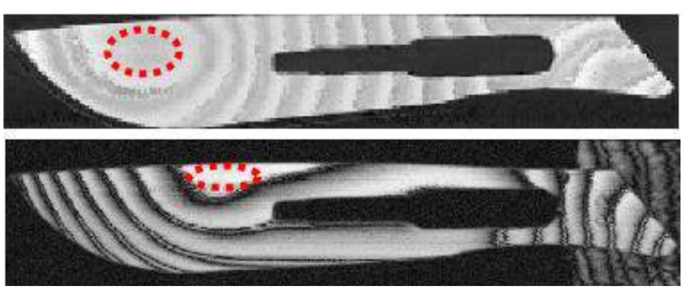

Figure 2: 2.6 THz feedback interferometry images of scalpel blades obtained at ranges of 50 cm (top) and at 10.5 m (bottom). The flat part of the blade used for calculating the figure-of-merit in each image is indicated by a dashed ellipse.

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.

V. ACKNOWLEDGEMENTS

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Self-mixing signals in terahertz lasers

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Abstract: Recently demonstrated self-mixing effect in terahertz quantum cascade lasers (QCL) opens new possibilities for detectorless sensing in this range of electromagnetic spectrum. In this paper we compare self-mixing signals obtained from variations in QCL terminal voltage against the signals obtained from variations in QCL radiated power monitored using a bolometer. We show that these two signals are equivalent allowing for the disposal of a conventional bulky and slow thermal detector.

1 Introduction: Terahertz (THz) radiation offers many potential sensing opportunities in a variety of fields including astronomy, biomedicine, security and non-destructive material testing applications [1]. THz quantum cascade lasers (THz QCLs) offer an attractive compact and high power solution for these sensing applications. However most conventional THz sensing schemes employ thermal based detection (helium-cooled bolometers, pyroelectric sensors, Golay cells) which are typically bulky or slow. One solution to this problem is to adapt self-mixing (SM) interferometry with THz QCLs [2,3]. The homodyne nature of this scheme provides high sensitivity and noise-rejection [4].

In this paper we compare the SM signal obtained as variation in the QCL terminal voltage to that observed as variation on emitted power collected from the QCL back facet using a bolometer. Relationship between the two signals has been investigated for a number of SM feedback levels.

2 Experimental Setup: The device investigated was a single mode 2.6 THz QCL (10 μm-thick bound-to-continuum active-region [5], formed into a 3 mm × 140 μm surface-plasmon ridge waveguide) operated in CW, just above threshold (0.9 A) in a liquid-helium-cooled continuous-flow cryostat (at 25 K). Emitted radiation was collimated (using a 2” diameter, *f*/2, 90° gold-plated mirror) onto a 3” plate mounted on the cone of a loudspeaker. The loudspeaker was driven by an AC signal to create a sinusoidal displacement of the target (estimated amplitude ~150 μm, $f = 20$ Hz) (Fig. 1).

Displacement SM interferograms were observed via two methods, one employing the measurements of the laser terminal voltage through an AC coupled 100X amplifier (electrical signal) and via monitoring variation in emitted power from the QCL back facet using a bolometer (optical signal). The feedback level for

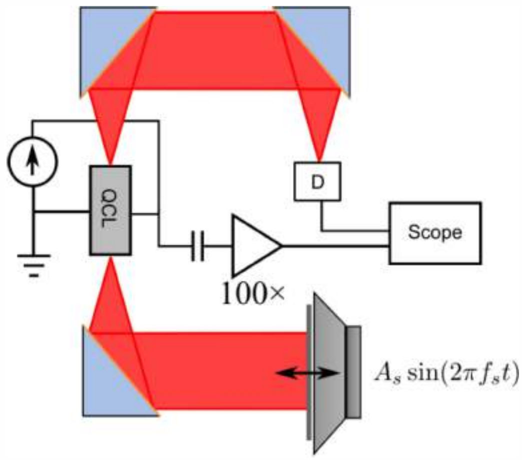

Fig. 1. Schematic diagram of the THz-SM experimental setup. The collimated THz beam is reflected by a aluminium plate attached to the cone of a loudspeaker, which is driven by a sinusoidal waveform. In this system, SM signals are accquired in two ways: - by measuring the voltage perturbations across the laser terminals, and by observing the THz emission from the back facet of the QCL using using a helium-cooled bolometer, *D*.

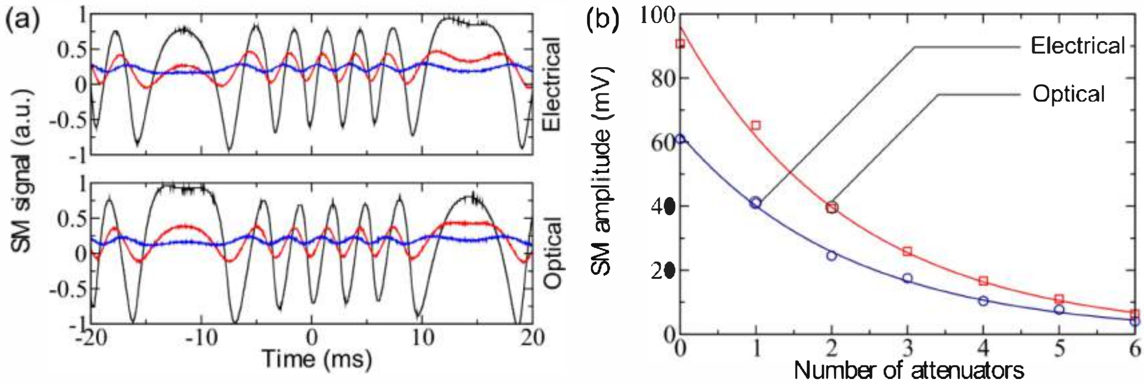

Fig. 2. Comparison between SM signals from the 150 µm 20 Hz loudspeaker motion, obtained via laser terminal voltage (Electrical) and via the back facet emission using the bolometer (Optical). (a) shows the SM interferogram from each method for a number of attenuations (*N*=0 **black**, *N*=3 **red**, *N*=6 **blue**). (b) shows decay of SM signal amplitude vs. number of attenuators with solid lines showing the regression for exponential decay.

the SM signal power was varied in amplitude by using a number of attenuators (*N*) (3 mm thick polytetrafluoroethylene (PTFE) sheets ($\alpha_{\mathrm{PTFE}} \sim 2$ cm^{-1} [6]) between the target and the QCL.

3 Results:

Figure 2 shows the results from both SM signal acquisition techniques, for various attenuations (and thus feedback levels). Both techniques yield almost identical signals (Fig. 2(a)) and calculation of the displacement from each set of signals estimated the speaker displacement to 170 and 171 µm for the electrical and optical signals respectively. These match almost exactly and are very close to the estimated displacement of the loudspeaker mounted target.

The SM signal amplitudes for both sets of measurements decay exponentially with increasing number of attenuators (shown in Fig. 2(b)). Fitting this gives a decay of the signal proportional to $e^{-0.442N}$ and $e^{-0.443N}$ for the electrical and optical signals respectively. This along with the almost identical recovered loudspeaker displacement suggests that using either terminal voltage or back facet optical power monitoring of SM signals should yield equivalent results.

In addition, from the exponential fittings it is possible to determine absorption coefficient of the PTFE at this frequency which, $\alpha_{\mathrm{PTFE}} = 1.47$ cm^{-1}, which is close to the value reported in the literature [6].

Acknowledgements

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Terahertz interferometry and imaging using self-mixing in a quantum cascade laser

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1. Background

The terahertz (THz) frequency quantum cascade laser (QCL) is a high power (>100 mW) semiconductor source of narrowband, coherent THz radiation, which is well-suited for applications [1] in two-dimensional (2D) and three-dimensional (3D) THz imaging. However, exploitation of THz QCLs, to date, has been limited by the need to use cryogenically-cooled bolometers to achieve high sensitivity detection. We have addressed this through the design of a compact and simplified imaging system, based on a self-mixing (SM) scheme [2] in which the QCL is not only used as the THz source, but also as an interferometric detector. In this SM arrangement, the radiation emitted from the laser is coupled back into the emitting facet after being reflected off an external object. This leads to a perturbation in the QCL threshold gain, emitted power, lasing spectrum and terminal voltage [3], each of which can be monitored. Importantly, unlike when using bolometers, the detection is coherent. This opens up the possibility of sensing displacement, surface morphology and reflectivity with high precision [4, 5].

2. 2D and 3D imaging using self mixing

In our self-mixing experiments, THz radiation is focused onto the sample, which is itself raster-scanned transverse to the beam. At each position, perturbation of the QCL voltage through optical feedback from the target is recorded. Fig. 1 illustrates 2D imaging of a scalpel blade, with adjacent fringes corresponding to a change of $\lambda/2$ in the depth of the surface. To acquire a 3D image, the sample was also scanned longitudinally. The phase of the resulting fringes was used to extract the relative displacement of the sample surface, enabling a 3D image to be reconstructed. Exemplar fringes and a fitted SM function [6] for phase and amplitude extraction are demonstrated in Fig. 2.

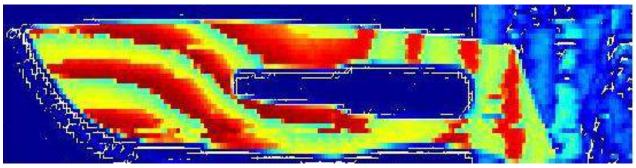

Fig. 1 2D image of a scalpel blade at 2.6 THz

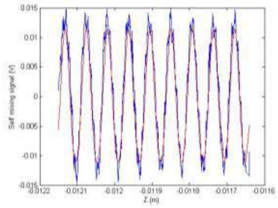

Fig. 2 Data from one pixel of a 3D image, with a fitted curve for phase and amplitude extraction

We acknowledge support from the ESPRC (UK), the Royal Society, the Wolfson Foundation, and the ERC programmes 'NOTES' and 'TOSCA'.

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