Photothermoelastic response of zincblende crystals to radiation from a THz-frequency quantum cascade laser

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***Abstract*—We investigate the photothermoelastic response of ZnTe and GaP crystals irradiated by THz-frequency radiation from a quantum cascade laser. We present a full theoretical description of this interaction that agrees well with the measured response.**

I. Introduction And Background

The use of optically-sampled crystals for the detection of terahertz (THz) frequency radiation has become widespread within applications such as THz time-domain spectroscopy. The most commonly adopted detection scheme exploits the linear electro-optic (EO) (or 'Pockels') effect in noncentrosymmetric crystals whereby the THz field induces a birefringence in the crystal (typically ZnTe) that can be probed optically. Electro-optic crystals have also been applied to incoherent and coherent sampling of THz fields generated using a quantum cascade laser (QCL) source. Interestingly, an incoherent interaction mechanism of thermal origin has recently been identified using a standard EO sampling arrangement with a ZnTe crystal and a THz QCL source [1].

In this paper we further investigate this interaction in ZnTe and GaP crystals illuminated by a QCL source emitting at 2.2 THz. Our results indicate a photothermoelastic origin of the interaction, whereby the stress distribution established through localised heating of the crystal induces a change in optical birefringence via the photoelastic response of the crystal. We have developed a comprehensive model of this previously unexplored mechanism, which shows good agreement with experimental data.

II. Experiment and Results

The photothermoelastic response of (110)-orientated ZnTe and GaP crystals with thicknesses L=1.9 mm and 1 mm, respectively, were investigated experimentally using a QCL source emitting at 2.2 THz. Radiation from the QCL was focused onto each crystal, and a 778 nm probe beam was employed to sample the induced birefringence optically using a balanced sampling arrangement [2]. Both the THz beam and the probe beam were linearly polarized parallel to the [-1,1,0] direction of the crystal, which in turn was oriented parallel to the polarisation axis of the Wollaston prism. The QCL device was operated in pulsed mode, emitting an average power ~845 μW. The pulse trains were electrically modulated in the frequency range 10 Hz–3 kHz, with lock-in detection of the photodiode response being employed.

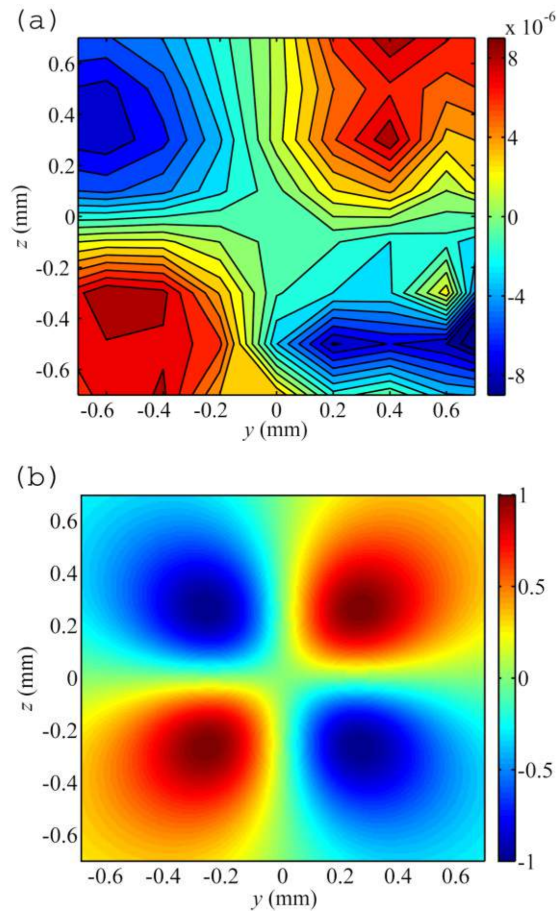

Fig. 1. (a) Contour plot showing the spatial variation of the photodiode signal measured across the y−z plane (the (110) plane) of the ZnTe crystal. The origin (0,0) corresponds to the centre of the THz beam. (b) Spatial variation of the (normalized) photodiode signal calculated using the photothermoelastic model for the same experimental conditions.

By translating the focusing lens in our apparatus, the probe beam could be scanned across the crystal surface in two dimensions. Using this approach the spatial variation of the measured response, relative to the position of the focussed THz beam, was investigated. Figure 1(a) shows a contour plot of the photodiode signal measured across an area of 1.4 mm ×

1.4 mm on the surface of the ZnTe crystal (defined as the y−z plane), for a laser modulation frequency of 40 Hz. As can be seen, the sign of the signal alternates in adjacent quadrants of the crystal surface and reaches a maximum magnitude at a critical radius along the ±45º diagonals. The intensity is also seen to vanish towards zero at the centre of the THz beam.

The absolute value of the phase delay between orthogonal components of the probe beam can be obtained from the photodiode response. Fig. 2 shows the optical phase delays measured as a function of laser modulation frequency, at the positions of maximum response (see Fig. 1), for the ZnTe and GaP crystals. As can be seen, the measured response decreases with modulation frequency ω and tends towards an inverse relationship at higher frequencies. A similar behavior has been observed previously [1] using a 3.2 THz QCL, and is symptomatic of a thermal response.

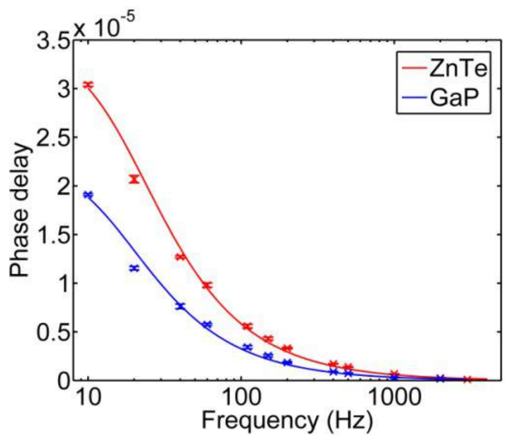

Fig. 2. Optical phase delay measured as a function of pulse modulation frequency for ZnTe and GaP crystals using a 2.2 THz QCL.

III. Theoretical Model and Discussion

We have developed a theoretical description of the measured response based on a photoelastic modulation of the optical birefringence arising from the stress distribution that is thermally-induced in the crystal upon localised THz irradiation. Our model predicts a modulation of the birefringence given by the relationship

$$\Delta n = \frac{-n^3}{2}\left[\frac{\left(\Delta B_2 - \Delta B_3\right)^2}{2\Delta B_4} + 2\Delta B_4\right]\sin\left(2\alpha\right), \qquad (1)$$

in which n is the refractive index and α is the angle between the [-1,1,0] direction of the crystal (the y−axis) and the major axis of the index ellipsoid induced through the photothermoelastic mechanism. The tensor components of the perturbation to the optical indicatrix, expressed in single-suffix (matrix) notation, are given by

$$\Delta B_i = p_{ij} s_{jk} \sigma_k, \qquad (2)$$

where p_{ij} are the components of the forth order photoelastic tensor and s_{jk} are the components of the fourth order elastic compliance tensor. The components of the second rank stress tensor σ_k are obtained by modeling the crystal as an isotropic thin disk subject to a radial temperature distribution determined by the Gaussian profile of the THz beam [3]. As such, Δn, ΔB_i and σ_k vary in three dimensions by virtue of attenuation of the THz power as the beam propagates through the crystal, as well as through the spatial distribution of the stress field in the y−z plane (the (110) plane of the crystal).

Figure 1(b) shows the spatial variation of the photodiode signal predicted using our model for the ZnTe crystal. The prediction is seen to agree well with the experimentally-determined spatial variation shown in Fig. 1(a). It should be noted that such a spatial variation is dependent upon the establishment of a radially-varying stress field in the (110) plane of the anisotropic crystal, and would not arise through a simple temperature-dependence of the refractive indices.

The measured response depends not only on the photoelastic properties of the crystal but also on the magnitude of the temperature modulation induced by the incident THz radiation. Our model also allows us to define a figure-of-merit for the response, at the position corresponding to the maximum signal, that depends on crystal properties including the elastic constant s_{44}, the photoelastic constant p_{44}, the volumetric heat capacity ρC, the thermal expansion coefficient α_{th}, the THz absorption coefficient α and Young's modulus Y:

$$FOM = \frac{\alpha_{th} Y n^3 p_{44} s_{44}\left(1-e^{-\alpha L}\right)}{\rho C} \qquad (3)$$

For ZnTe and GaP we obtain values for the FOM of 6.9×10^{12} $J^{-1}m^3$ and 3.0×10^{-12} $J^{-1}m^3$ at 2.2 THz, respectively (see Fig. 1). By comparison, the measured phase delays for these crystals are $\delta = 6.7 \times 10^{-7}$ and 3.0×10^{-7} at $\omega = 1$ kHz, in good agreement with the ratio of figures of merit.

IV. Conclusion

We have investigated the photothermoelastic response of ZnTe and GaP crystals to QCL radiation at a frequency 2.2 THz, and developed a theoretical description of this mechanism that models the experimental data well.

Acknowledgments

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Coherent imaging and sensing using the self-mixing effect in THz quantum cascade lasers

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We present recent advancements in the development of coherent THz imaging and sensing systems that exploit the self-mixing (SM) effect in quantum cascade lasers (QCLs). 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 the inter-cavity field, producing variations in the emitted power and terminal voltage [1]. Thus, by combining the local oscillator, mixer, and the detector all in a single laser, this technique allows the development of simple, self-aligned systems that can sense both the phase and amplitude of the THz field reflected from samples. We demonstrate the coherent nature of this sensing technique for depth-resolved reflection imaging, whereby the phase-shift induced upon reflection is interpreted in terms of surface morphology of the sample. We will also present an alternative, novel sensing modality based on this self-mixing approach.

The THz QCL consisted of a 10-µm-thick GaAs-AlGaAs bound-to-continuum active-region, emitting at ~2.6 THz, that was processed into a semi-insulating surface-plasmon ridge waveguide. Radiation from the QCL was collimated and focused at normal incidence onto the sample using a second identical reflector [2]. The sample was raster-scanned in two dimensions, and the self-mixing signal monitored at each pixel via the voltage across the QCL terminals.

For depth-resolved imaging the QCL was operated in continuous-wave, just above the lasing threshold, where the laser is most sensitive to the feedback of radiation. At each pixel the sample was scanned longitudinally and the SM interferometric waveform recorded over several periods. Each of these waveforms was then fitted to a three-mirror model [3, 4] that describes the laser system under feedback, as shown in Fig. 1. The phase parameter in this model can be equated to the distance travelled by the THz radiation in the external cavity, and hence to the depth of the surface of the sample. Figure 2 shows an exemplar cross-section of a stepped GaAs structure fabricated by wet chemical etching. As can be seen, the etched steps can be resolved, as well as the tilt of the sample, which is estimated to be ~0.4°. Figure 3 shows a three-dimensional profile of a similar structure.

[1] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," IEEE J. Quantum Electron. **QE-16**, 347 (1980).
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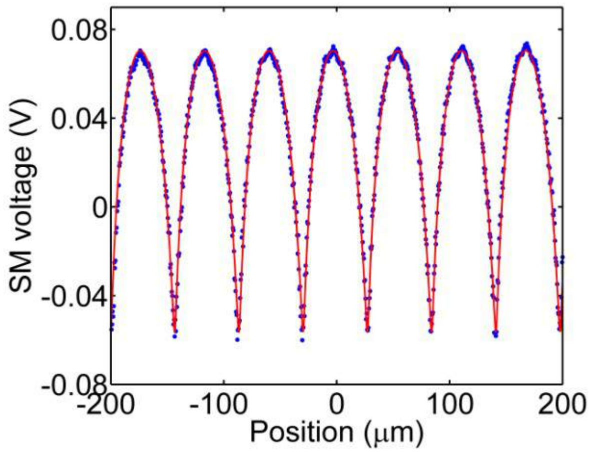

Fig. 1: Exemplar self-mixing waveform obtained by longitudual displacement of the target. The dots are data points, the solid line represents a fit to the data.

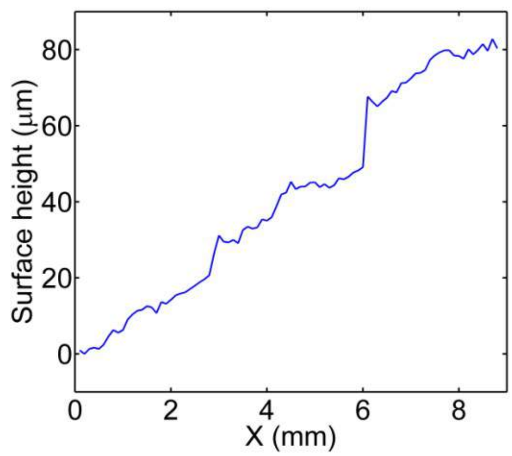

Fig. 2: Cross-section of a GaAs sample revealing etched steps and sample tilt.

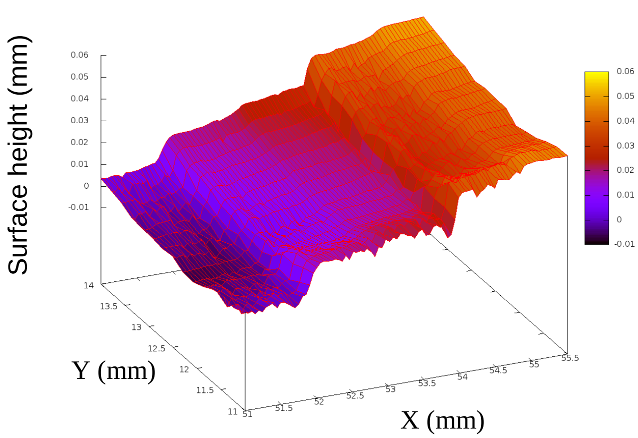

Fig. 3: Three-dimensional image of a stepped GaAs sample

International Conference on THz and Mid Infrared Radiation and Applications to Cancer Detection Using Laser Imaging

Workgroup Meetings
of COST ACTIONs MP1204 and BM1205

October 10 - 11, 2013

Sheffiled Hallam University
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Conference Programme

Thursday, October 10

time	Presentation title/ author	Chair
9:45 – 10:00	**Opening**	Mauro Pereira and Dragan Indjin
10:00 – 10:40	**Manijeh Razeghi - Women in Thz, Invited Keynote Talk** **Pushing the frontiers of monolithic integration:** **a compact THz revolution**	
10:40 – 11:10	**Maurizio Dabbicco - Invited Talk** Optical Feedback Interferometry in Semiconductor Lasers	
11:10 – 11:40 coffee break		
11:40 – 12:05	**Johanes Koeth - Invited Talk** Tunable single mode quantum cascade lasers with shallow-etched distributed Bragg reflector	Kamil Kosiel
12:05 – 12:30	**Santiago Royo - Invited Talk** Skin and laser imaging research activities at CD6	
12:30 – 12:55	**Janis Spigulis - Invited Talk** Multimodal skin imaging: concept and prototype device	
12:55 – 13:30	**Paul Dean - Invited Talk** Coherent imaging and sensing using the self-mixing effect in terahertz quantum cascade lasers	
13:30 – 15:00 lunch		
15:00 – 15:25	**Lukas Emmeneger - Invited Talk** Recent advances in QC laser spectroscopy for ambient air monitoring	Oleg Mitrofanov
15:25 – 15:50	**Thierry Bosch - Invited Talk** Blood flow measurements by self-mixing laser velocimetry	
15:50 – 16:15	**Francesco Mezzapesa - Invited Talk** QCLs based coherent imaging via optical feedback interferometry	
16:15 – 16:35	**Adonis Bogris** Noise properties of injection locked quantum cascade lasers	
16:35 – 18:00 Coffee and poster session		
18:00 – dinner		

Friday, October 11

time	Presentation title/ author	Chair
10:00 – 10:40	**Angela Dyson - Women in Thz, Invited Talk** **Mechanisms for THz Generation in GaN**	Manijeh Razeghi
10:40 – 11:20	**Renata Butkuté - Women in Thz, Invited Talk** **Bismides for Laser Diode Active Layers**	
11:20 – 11:40 coffee break		
11:40 – 12:20	**Martin Koch - Invited Talk** Devices to guide and manipulate THz waves	Angela Dyson
12:20 – 13:00	**Miriam Vitiello - Women in Thz, Invited Talk** **Nanowire and graphene FETs as powerful detection** **systems across the THz range**	
13:00 – 13:20	**Tomasz Ochalski** Optical emission of a strained direct band-gap Ge quantum well embedded inside InGaAs alloy layers	
13:20 – 13:40	**Anna Szerling - Women in THz** Epitaxy and device fabrication for AlGaAs/GaAs THz quantum-cascade lasers	
13:40 – 15:00 lunch		
15:00 – 15:40	**Irmantas Kašalynas - Invited Talk** Multispectral terahertz imaging with the compact THz detectors designed for room temperature operation	Miriam Vitiello
15:40 – 16:20	**Oleg Mitofanov - Invited Talk** High-spatial resolution THz near-field imaging using surface waves	
16:20 – 16:40	**Mauro Pereira** Recent progress in microscopic approaches to transport and optics of semiconductor TERA-MIR materials	
16:40 – 16:50	**Closing address**	
18:00 – dinner		

Coherent imaging and sensing using the self-mixing effect in terahertz quantum cascade lasers

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We present recent advancements in the development of coherent terahertz (THz) imaging and sensing systems that exploit the self-mixing (SM) effect in quantum cascade lasers (QCLs). 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 the inter-cavity field, producing variations in the emitted power and terminal voltage [1]. Thus, by combining the local oscillator, mixer, and the detector all in a single laser, this technique allows the development of simple, self-aligned systems that can sense both the phase and amplitude of the THz field reflected from samples. We demonstrate the coherent nature of this sensing technique in two distinct imaging modalities: Depth-resolved reflection imaging, whereby the phase-shift induced upon reflection is interpreted in terms of surface morphology of the sample; and a novel swept-frequency approach that enables extraction of target complex refractive indices with a high degree of accuracy.

For depth-resolved imaging the QCL was operated in continuous-wave, just above the lasing threshold, where the laser is most sensitive to the feedback of radiation. At each pixel the sample was scanned longitudinally and the SM interferometric waveform recorded over several periods. Each of these waveforms was then fitted to a three-mirror model [2] that describes the laser system under feedback. The phase parameter in this model can be equated to the distance travelled by the THz radiation in the external cavity, and hence to the depth of the surface of the sample.

In our second sensing approach, we employ a novel swept-frequency coherent imaging scheme that can be performed without mechanical modulation or longitudinal scanning of the sample. By fitting the acquired SM signals to the three-mirror model, both amplitude-like and phase-like images of the sample can be obtained. Different materials impose different phase-shifts on the incident THz wave according to their complex refractive index, dominated by its imaginary part. We can thus relate the operating parameters of the laser under feedback to the complex refractive index of the target.

References

[1] R. Lang and K. Kobayashi, IEEE J. Quantum Electron. QE 16, 347 (1980).

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Self-mixing effect in THz quantum cascade lasers: Applications in sensing and imaging

(Invited paper)

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***Abstract*— The paper introduces self-mixing interferometry in semiconductor lasers in general, and then discusses recent advancements in the coherent THz imaging and sensing systems based on the self-mixing effect in terahertz quantum cascade lasers. Two different imaging modalities are used to illustrate the coherent nature of this sensing technique and its applications to three-dimensional surface profiling and material identification.**

Keywords—Self-mixing; Optical feedback; QCL; THz imaging; THz Sensing

I. INTRODUCTION

Over the past decade the quantum cascade laser (QCL) has established itself as one of the most promising radiation sources for imaging applications at terahertz (THz) frequencies. The appeal of these semiconductor devices emanates from their compact size, broad spectral coverage (~1–5 THz), and high output powers. These attributes, coupled with their ability to generate coherent continuous-wave emission with quantum noise-limited linewidths, make THz QCLs particularly suited to the development of coherent THz sensing and imaging systems.

In this paper, we introduce the self-mixing (SM) technique in semiconductor lasers and then present recent advancements in the development of coherent THz imaging and sensing systems that exploit the SM effect in QCLs.

II. SELF-MIXING EFFECT

The SM effect occurs when light reflected from a target enters the laser cavity and is added coherently to the cavity field causing gain modulation, which can be observed as variation in the laser optical power and terminal voltage [1, 2]. Thus, this technique effectively combines the local oscillator, mixer, and the detector all in a single laser, allowing for the development of simple, self-aligned systems that can sense both the phase and amplitude of the field reflected from the target.

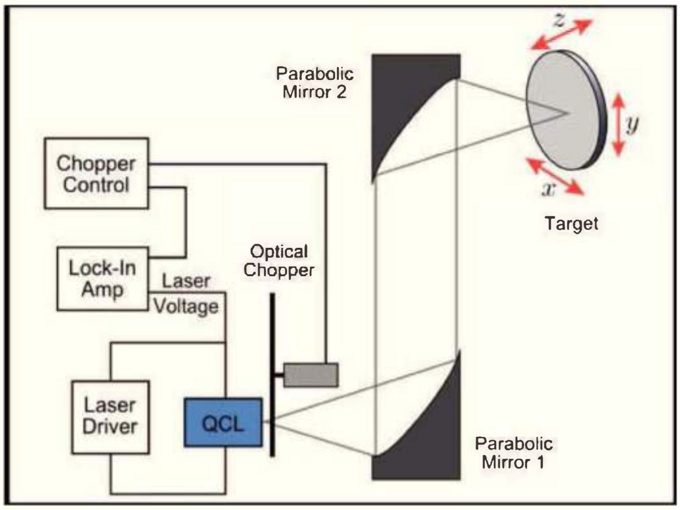

Fig. 1 Self-mixing setup for 3D imaging utilising a THz QCL. The self-mixing signal is accquired directly by monitoring the voltage variations across the QCL terminals.

III. EXPERIMENTS

Two distinct imaging modalities will be used to illustrate the coherent nature of this sensing technique: (1) Three-dimensional (3D) surface profiling, whereby the phase-shift induced upon reflection is interpreted in terms of surface morphology of the sample; and (2) a novel continuous-wave swept-frequency delayed self-homodyning approach that allows extraction of the optical constants of the target under test and therefore the target material identification [3].

Figure 1 shows the experimental setup used in our experiments. The THz QCL used in our experiments consisted of a 10-µm-thick GaAs-AlGaAs bound-to-continuum active-region that was processed into a semi-insulating surface-

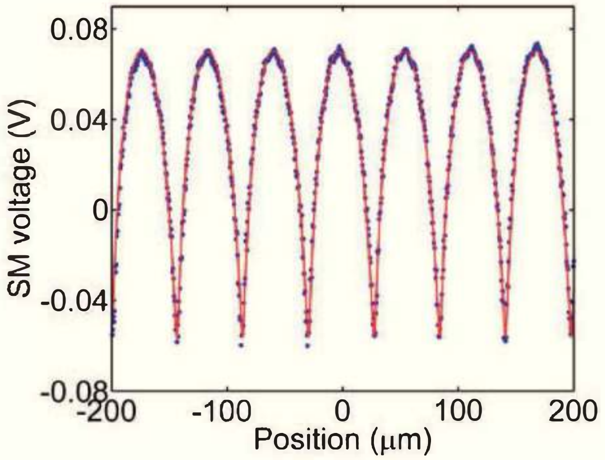

Fig. 3 Exemplar self-mixing waveform obtained by longitudual displace-ment of the target. The dots are data points, the solid line represents a fit to the data.

plasmon ridge waveguide. Radiation from the QCL was collimated and subsequently focused onto the target using a second identical reflector [4]. The target was raster-scanned in two dimensions, and the SM signal acquired at each pixel by monitoring the voltage across the QCL terminals.

For the 3D surface profiling, the QCL was operated in continuous-wave, just above the lasing threshold, where the laser is most sensitive to the feedback of radiation [4, 5]. At each pixel, the sample was scanned longitudinally and the SM interferometric waveform recorded over several periods. Each of these waveforms was then fitted to the excess-phase model [6, 7] that describes the laser system under feedback in steady-state. Experimental results and corresponding model fits are shown in Fig. 2 The fitted phase parameter for this model can be related to phase-shift on transmission in the external cavity, and hence to the depth of the surface of the sample. Figure 3 shows an exemplar 3D profile of a staircase GaAs structure, custom fabricated by wet chemical etching for this experiment.

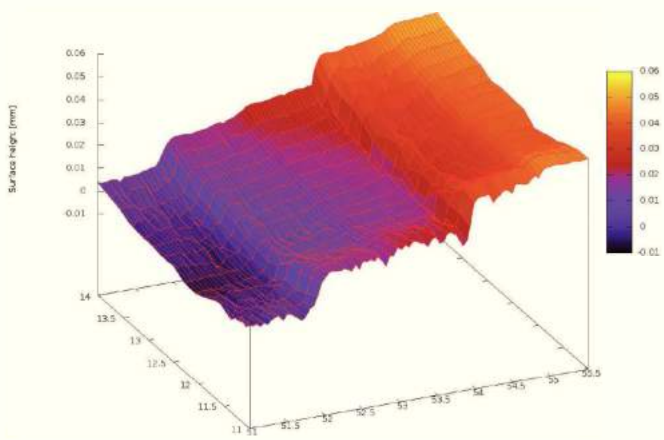

Fig. 4 Three-dimensional image of a stepped GaAs sample.

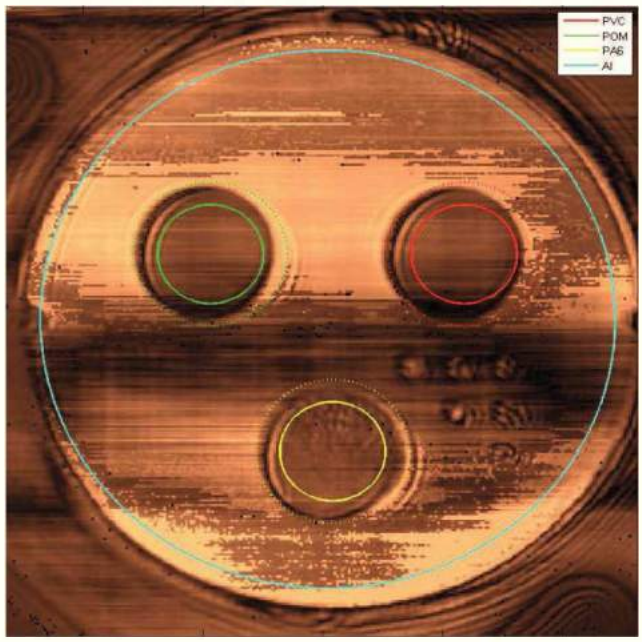

Fig. 2 Peak-to-peak image of an aluminium target containing three bores of different plastics. The array of six dots is for alignment purposes.

Our second technique [3] is based on the application of sawtooth modulation to the laser driving current, which has the effect of frequency-modulating the laser, and sweeping the system through a set of compound cavity resonances. In this way coherent imaging can be performed without mechanical modulation or longitudinal scanning of the sample. An image obtained by scanning a composite target containing three organic materials embedded in an aluminium holder is shown in Fig. 4. Using this simple, robust approach, both intensity- and phase-like images of materials can be acquired concurrently. This technique enables us to interrogate regions of the target and extract precise values for refractive index and absorption coefficient within these defined areas. Such characterisation of the optical properties of substances at THz frequencies will enhance the detection and discrimination in the materials science. Extension of this single-laser system to an array of QCLs will allow for material characterisation at a number of frequencies, and therefore material identification

Acknowledgment

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