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Spectral Characterisation of a Terahertz QCL through Self-Mixing

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The use of a single terahertz (THz) quantum cascade laser (QCL) device as both emitter and detector in a self-mixing (SM) scheme allows for the development of fast, sensitive and compact coherent systems for imaging and interferometry [1]. In this scheme, radiation re-injected to the laser cavity interferes ('mixes') with the intra-cavity electric field, causing small variations in the fundamental laser parameters, as described in the seminal paper by Lang and Kobashi (L–K) [2]. In particular, the voltage perturbation induced by optical feedback is described by a sinusoidal variation dependent on both the external cavity length L_{Ext} and the emission frequency under feedback ν, and is given by $\Delta V_{SM} \propto \cos\left(\frac{2\pi L_{Ext}\nu}{c}\right)$. As such, interferometric fringes can be acquired in a SM system by simply changing the external cavity length and concurrently monitoring the terminal voltage of the device. In this work we demonstrate the use of SM interferometry for performing spectral characterisation of a multi-mode THz QCL in a scheme that offers much reduced experimental complexity when compared with typical Fourier Transform infrared spectroscopy (FTIR) systems. In addition, we report the first direct measurements of the perturbation of the lasing frequency under feedback, and compare the results with predictions from the L–K model.

Methodology and results

The THz QCL used in this work consisted of a 14 µm-thick bound-to-continuum (BTC) active region emitting at ~2.24 THz ($\lambda \approx 134$ µm), which was processed into a SISP ridge waveguide with dimensions of 2.2 mm×200 µm. The device was mounted on a copper carrier such that both facets of the laser could be accessed optically. The device was cooled using a continuous-flow helium cryostat and maintained at a heat-sink temperature of 25 K.

Using the experimental set-up shown in Fig. 1, SM interferometric fringes were measured on the QCL terminal voltage through an extension of the SM external cavity (purple) using the left-hand facet of the QCL. For direct comparison, a spectral characterisation measurement of the QCL emission was performed subsequently using the right-hand facet of the device, which was coupled to an FTIR system (green).

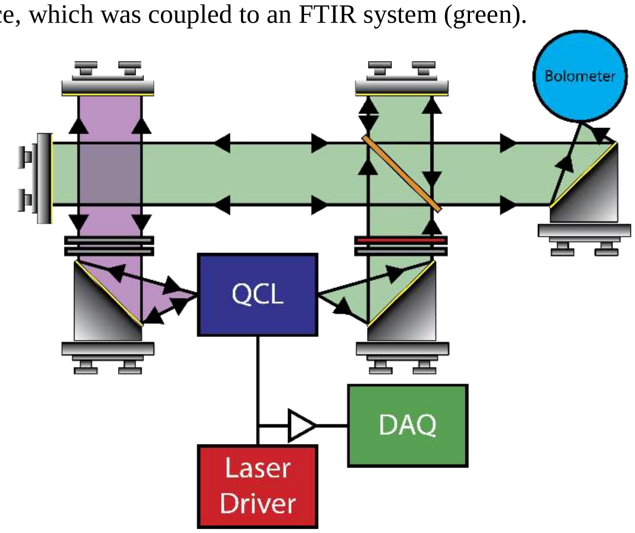

Figure 1. Schematic experimental set-up to directly compare the SM system to an FTIR. Emission from one facet (left) is coupled onto an external reflector used for SM interferometry, while emission from the other facet is directed into an FTIR system. This allows both systems to be run consecutively for direct comparison.

Optical polarisers (grey) were used to isolate the two systems, with a polariser in each system in cross-polarisation to the other. Through the use of a third polariser, the feedback into the QCL from the SM external cavity could be controlled by varying its angle in relation to the paired polariser. Finally, a quarter-wave plate (red) was used to prevent optical feedback in the FTIR system. A data acquisition (DAQ) board was utilised to measure the terminal voltage of the QCL for detection of SM interferometric fringes, and a thermal bolometer was used for detection of the FTIR interferograms.

After acquiring interferometric fringes on both systems, the same FFT analysis was performed on each measurement. Through comparison of the emission spectra acquired from both the SM and FTIR systems, good agreement can be observed for both single- and multi-mode emission regimes, as shown in Fig. 2. In addition the sensitivity of the SM system made it possible to resolve extra Fabry–Pérot modes not recovered in the FTIR system.

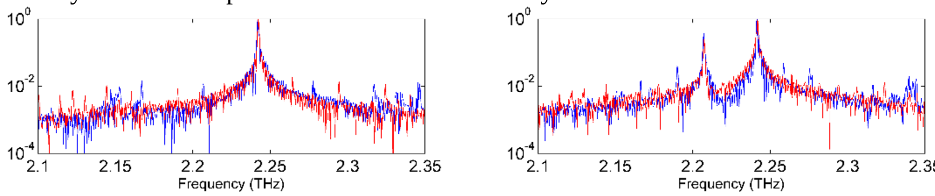

Figure 2. Exemplar spectra recovered from both SM (blue) and FTIR (red) systems for two driving currents (800 and 900 mA).

Further to this, the perturbation of the emission frequency of individual lasing modes under feedback, which is dependent on both the round-trip phase in the external cavity and the level of feedback, as predicted by the SM excess phase equation (EPE) [2], was observed experimentally for the first time. This was achieved by incrementally stepping the SM external cavity length L_{Ext} and measuring the resulting emission frequency using the FTIR system. Figure 3 shows an exemplar measurement, which reveals a frequency perturbation of up to ~80 MHz. Also shown is a fit to the EPE, which shows good agreement with experimental data. From this fit the feedback parameter C (=1.4), could be extracted. Similar measurements have been performed under varying levels of feedback and have revealed the evolution of this effect consistent with predictions of the EPE.

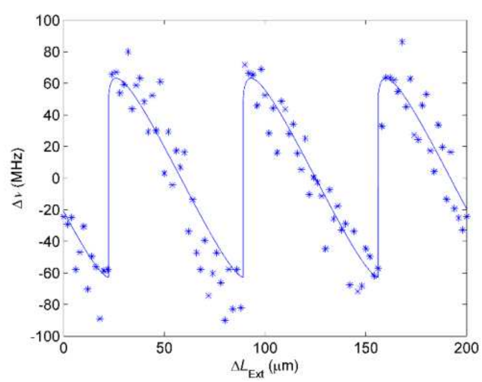

Figure 3. Change in frequency under feedback as a function of L_{Ext}. A self-mixing model was fitted to extract the fitted value of C = 1.4.

Summary

In the presented work, spectral characterisation of a THz QCL has been performed through self-mixing interferometry, offering a greatly reduced experimental complexity compared to typical methods such as FTIR. Furthermore, the frequency perturbation caused by feedback into the device has been observed experimentally for the first time in a THz QCL, and compared with predictions from the excess phase equation of the Lang-Kobashi model for lasers under optical feedback.

[1] P. Dean, A. Valavanis, J. Keeley, et al., "Terahertz imaging using quantum cascade lasers-a review of systems and applications," J. Phys. D. Appl. Phys., vol. 47, p. 374008, 2014.
[2] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," IEEE J. Quantum Electron., vol. 16, pp. 347-355, 1980.
[3] R. Kliese, T. Taimre, A. A. A. Bakar, et al., "Solving self-mixing equations for arbitrary feedback levels: a concise algorithm," Appl. Opt., vol. 53, p. 3723, 2014.