Terahertz time-domain spectroscopy has evolved in recent years from a laboratory technique to a technology that is rapidly reaching maturity and finding applications in chemical sensing, security applications, biomedical imaging and characterization of art works, to name just a few. The interest in THz radiation is fuelled by a unique combination of properties; non-ionising, transparency of plastics and sensitivity to polar molecules. Another emerging THz technology is the THz quantum cascade laser (QCL). These uni-polar semiconductor lasers emit THz radiation in 1-5THz range with powers of upto 100s of mW.

In this project we have combined these two promising THz technologies to exploit the coherent detection that is intrinsic to THz TDS to make coherent measurements of the radiation from THz QCLs. There are two motivations for this; firstly we aimed to gain a deeper understanding of the ultra-fast processes at work in THz QCLs and secondly to create tools that could be used for THz spectroscopy applications. The work in this project was divided in to three tasks, detailed below.

Pulse formation in THz QCLs

The aim of this task was to measure the formation of pulses in THz QCLs on an ultrafast time scale. The experimental arrangement used is shown in Figure 1. The experiment is based on a femtosecond laser; the pulses are split and one portion used to trigger a nanosecond electrical pulse, applied to the QCL and a second part is used to generate a single cycle THz pulse. The THz pulse is focused into the QCL cavity to phase lock the QCL and a third portion of the femtosecond pulse is used to detect the phase-locked emission. By scanning the delay of the probe pulse, using a mechanical delay line, we measure the signal shown in Figure 2(a), then, because the measurement is coherent, taking the Fourier transform reveals the spectrum of the emitted radiation, shown in Figure 2(b). The potential of this measurement is clear; in a single measurement we record both time-domain and frequency domain information. In addition the radiation is concentrated in a narrow frequency range from the spectrally pure QCL which cannot be generated with conventional TDS technique. It was also found in this task that a passive modelocking regime could be accessed by direct phase synchronisation [1].

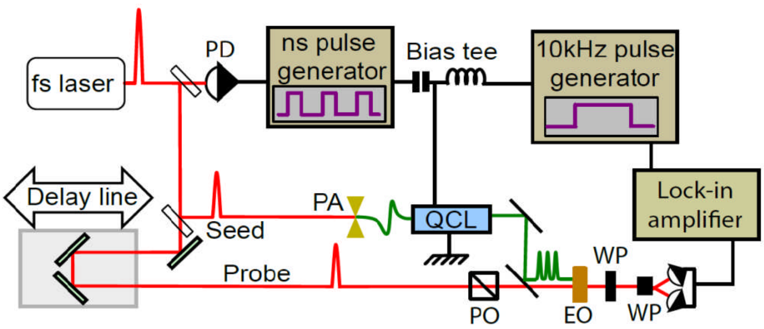
Task 2: Investigation of gain recovery time and Kerr effects

The second task of this project was concerned with studying the effects of gain recovery time and Kerr effects in THz QCLs. Both of these effects are important factors for pulse formation in QCLs and particularly modelocking, thus an understanding of these effects is important for the third task of the project. To investigate these effects simulations of pulse formation were performed using the coupled Maxwell-Bloch equations solved using the Finite-difference time-domain method [2]. By comparing results from task 1 with the simulations performed for different gain recovery times we were able to deduce a gain recovery time of 15ps for typical bound-to-continuum THz QCLs. The data was also investigated for Kerr effects, that is for a change of refractive index with intra-cavity intensity, however given the relative speed of the gain recovery time it is unlikely that Kerr effects could be useful. For this reason efforts were concentrated on active modelocking.

Task 3: Active mode-locking

Modelocking is an important technique for lasers, allowing short pulses to be produced. The third

Figure 1: Experimental arrangement for coherent detection of QCL.



task of this project was to perform active modelocking with THz QCLs. To perform active modelocking an Yttrium Iron Garnet tuneable band-pass filter was used to produce a signal at the QCL cavity round-trip frequency that was phase-locked to the femtosecond laser repetition rate. We first measured modelocked pulse formation in the QCL using a non-coherent method based on electro-optic detection [3]. This allowed us to measure modelocked pulses from the QCL when operated in a quasi-continuous-wave regime and in the pulsed regime. A following experiment made use of the coherent detection technique discussed in task 1. Some example data are shown in figure 2. In this work we demonstrated coherent detection of an actively modelocked QCL. As can be seen from figure 2(c), regular pulses are formed. When the Fourier transform is taken a broader spectrum is found due to the active modulation [4].

In conclusion, this project has demonstrated the integration of THz QCLs with THz TDS and made use of this technique to investigate modelocking and other pulsed regimes in QCLs. It was also found

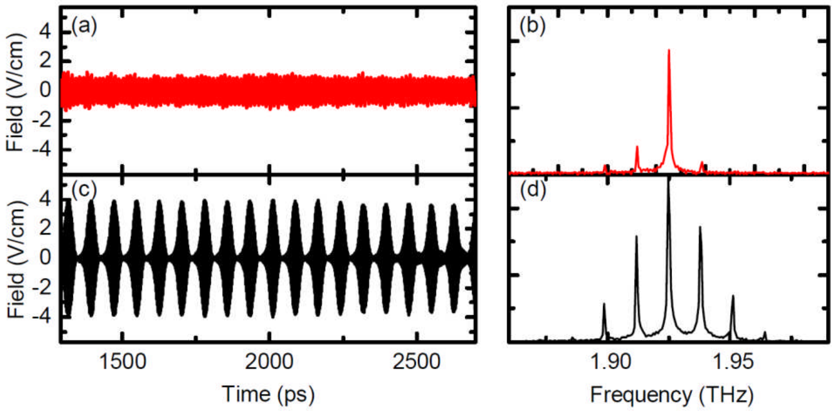


Figure 2: (a) Electric field of the THz QCL and (b) Fourier transform of this signal. (c) The same signal measured when an electrical signal at the QCL round-trip frequency is applied to modelock the QCL and (d) the Fourier transform of this signal.

from simulations that the gain recovery time in QCLs should be around 15ps suggesting that active modelocking is the best method for modelocking in QCLs. Further to the project aims the fellow was also involved with two other projects at the host laboratory that resulted in publications [5, 6]. Work on using THz QCLs with high performance metal-metal waveguides was also initiated during the project and a publication on this work is in preparation.

Impact

Besides the academic impact, demonstrated by the publications below, it is hoped that methods demonstrated will enable the TDS-QCL system to become more widely used. In particular, this system could be particularly useful when a narrow band THz pump beam is required in combination with a broadband THz probe.

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