Modulation of the THz Emission by a Quantum Cascade Laser using Coherent Acoustic Phonon Pulses

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Abstract

We use laser-generated coherent acoustic phonon (strain) pulses to modulate the electronic transport and THz emission of a 2.6 THz Ga(Al)As quantum cascade laser. The modulation amplitude is of the order of a few % and the rise time, limited by the measurement system response, is less than 1 nanosecond.

1. Introduction

As compact sources of intense THz radiation, quantum cascade lasers (QCLs) have applications in spectroscopy, imaging and communications. For a number of applications, it is essential to be able to modulate the THz emission, e.g.: for superimposing information, or to generate pulsed emission or tunable sidebands.

One way of modulating the QCL emission is to change the electrical pumping current [1]. A large modulation depth is possible and it is theoretically fast due to the ps electron dynamics of the QCL. However, the practical speed is limited by the ability to drive fast current changes in a highly reactive load. Another method is to use an electrically gated graphene-based modulator layer at the output of the QCL [2]. Depths of modulation up to 100% are possible with this method, but maximum modulation speeds have been limited to ~ 100 MHz, again due to the difficulty of driving reactive loads at high speed.

Here we describe an alternative method of QCL emission modulation using bulk acoustic (strain) waves consisting of coherent acoustic phonons with frequency ~ 100 GHz. Previously it was shown that short strain pulses could be used to modulate the electron transport in resonant tunneling devices at high speed [3]. This was due to transient changes to the device bandstructure, via the deformation potential electron–phonon interaction, as the strain pulse propagated through the device. Similar effects could be exploited to modulate a QCL, e.g. by changing the injection of electrons into the active region. The theoretical limit to the speed is the time it takes for the acoustic wave, travelling at the speed of sound, to travel through the resonant tunneling region, which is ~10 ps.

2. The experiment

The Ga(Al)As QCL structure designed to emit at about 2.6 THz was grown by molecular beam epitaxy on a semi-insulating GaAs substrate, and consisted of 88 repeat periods of the injector and active regions. The total thickness of the structure was about 14 microns. A QCL ridge, 2 mm long by 150 μm wide, was formed by etching and electrical contacts made to the top and back. The substrate was thinned to 150 μm and then polished, and a 100 nm aluminium thin film acoustic transducer deposited opposite the QCL ridge. The device was mounted in an optical cryostat, cooled to a temperature in the range 10 – 20 K and was pumped by 50-μs-duration current pulses of amplitude of up to I = 1.8 A and with a duty cycle 5%. The QCL emission was detected using a THz Schottky diode.

Single-cycle, bipolar, acoustic strain pulses, with an amplitude $\eta \leq 10^{-3}$ and duration ≈15 ps, were generated by exciting the transducer with ~100-fs-duration pulses from an amplified Ti:Sapphire laser, of 800 nm wavelength, with a repetition rate of 1 kHz (synchronized to the QCL pump current pulses), and average power in the range 1 – 10 mW. The generated acoustic pulses propagated across the substrate and entered the QCL stack, travelling vertically up through the structure to the top contact, whereupon they were reflected and travelled back down through the QCL stack. The acoustic-pulse-induced transient changes in the voltage across the QCL, $V(t)$, were extracted by using a bias tee in the DC pumping line and measured on a 12.5 GHz sampling oscilloscope. Changes in the intensity of the QCL THz light emission, $L(t)$, detected using the Schottky diode, were also displayed on the oscilloscope.

3. Results

Fig. 1 shows $V(t)$ and $L(t)$ measured for a QCL pumping current of 1.64 A. Time t = 0 is the moment of impact of the laser pulse on the acoustic transducer, the first acoustic responses occur at t = 32 ns, which is the time taken for the strain pulse to reach the QCL ridge. Further acoustic responses, decaying in amplitude, are seen to repeat with a period of 64 ns. These are due to multiple reflections of the acoustic wave back and forth across the substrate. A closer look at the $V(t)$ response (inset to Fig. 1) shows that the duration of the signal is about 6 ns. This is the time it takes for the strain pulse to travel through the QCL ridge in each direction, before and after reflection at the gold top contact. The polarity of the QCL contact voltage response implies an increase in the resistance of the device as the strain pulse propagates through the device. The rise time of the $V(t)$ response is 0.8 ns, but this is apparently limited by the temporal response of the measurement system.

The corresponding $L(t)$ shows a fast negative spike (reduction of THz emission) during the propagation of the strain pulse through the device. This is followed by a recovery and electrical ringing due to the parasitic reactances of the setup. Comparing the amplitude of the initial negative spike with the quasi-DC response of the Schottky detector, we find the modulation depth is 6%.

4. Discussion

We observed that the acoustic pulse increases the electrical resistance and reduces the THz output of the QCL as it propagates through the device. We have developed a theoretical model of the interaction of the acoustic pulse with the QCL: in essence, the acoustic strain pulse can be considered as a propagating potential distortion of the band structure with amplitude $\eta \Xi_D$, where Ξ_D is the deformation potential constant (~ 10 eV in GaAs). As this passes through each period of the QCL structure, it detunes the resonant injection of electrons into the upper lasing level, thus affecting the transport and the THz emission. More detailed calculations show that the THz emission from the QCL may increase or decrease, depending on whether the QCL is biased at a current below or above the peak in the steady-state *L-I* curve as we have observed experimentally.

5. Conclusions

We have used laser generated picosecond acoustic (strain) pulses to modulate the THz emission from a QCL. The modulation depth obtained in our device was 6%, and the measured rise time of the QCL voltage response was 0.8 ns. However, the theoretical modulation speed is expected to be much higher: ~ 10 ps.

Acknowledgements

The authors acknowledge the support of this work by the UK Engineering and Physical Sciences Research Council, grant references: EP/M016161/1, EP/M01598X/1, and EP/P021859/1. We also acknowledge support of the Royal Society and the Wolfson Foundation.

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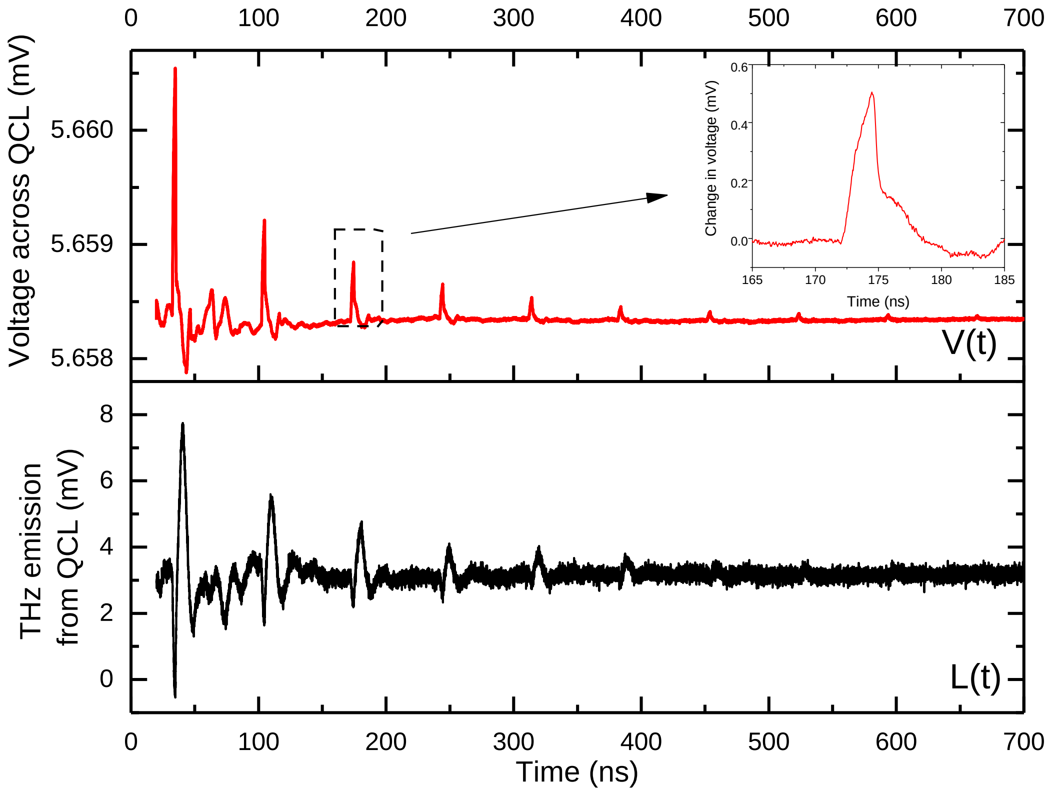

Figure 1: Temporal response of QCL voltage, $V(t)$, (red trace) and Schottky detector signal, ~ $L(t)$, (black trace) to incident strain pulses. The initial strain pulse, arriving at 32 ns, is generated by laser impact on the Al transducer at $t = 0$ and the following pulses are due to multiple reflections in the sample. The inset shows the detail of the $V(t)$ response to an incident acoustic pulse.