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High-Speed Modulation of a Terahertz Quantum Cascade Laser Using Coherent Acoustic Phonon Pulses

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***Abstract*—We demonstrate a new method for high-speed modulation of terahertz emission and electronic transport of a Ga(Al)As quantum cascade laser using coherent acoustic phonon pulses. The modulation, which is on the order of 6%, can be partially explained by a perturbation-theory analysis. The < 1 ns rise time of the modulation is dominated by parasitic device impedance in our experiment, however, the fast transit of phonons through the QCL heterostructure imply modulation rates > 100 GHz are possible.**

I. INTRODUCTION

TERAHERTZ (THz) frequency quantum cascade lasers (QCLs) are solid-state semiconductor sources, with applications in spectroscopy, imaging and communications. Conventional electronic modulation relies on direct modulation of the gain *via* the bias voltage [1], and is fundamentally limited in speed by parasitic impedance in the device.

Here we describe a new method to modulate the QCL emission using acoustic (strain) waves, which consist of coherent acoustic phonons with frequency ~100 GHz. Bulk acoustic waves have been shown to modulate the electron transport in resonant tunneling devices at high speed [2], inducing transient changes in the device bandstructure. Similar effects could be exploited to modulate the electronic transport in a QCL, effectively changing the injection of electrons into the active region. The fast transit of phonons through the QCL active region theoretically allows for modulation rates on the order of 100s of GHz [3].

II. THE EXPERIMENT

A GaAs/AlGaAs QCL structure, based on a 9-well structure designed to emit at a frequency of 2.5–2.75 THz [4], was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The 13.9-µm-thick heterostructure was processed into a surface-plasmon ridge-waveguide structure with dimensions (2000×150) µm^2. The substrate was thinned to ~150 µm to aid thermal dissipation, and a 100-nm-thick Al layer was deposited on the polished back surface to act as an acoustic transducer. The device was mounted in an optical cryostat, cooled to a temperature in the range of 10–20 K and was electrically pumped by 50-µs-duration current pulses with amplitudes of up to 1.8 A and a 5% duty cycle.

Single-cycle, bipolar, acoustic strain (coherent phonon) pulses, with an amplitude $\eta \leq 10^{-3}$ were generated in the Al-layer by optically exciting the transducer with ~40-fs, 800-nm pulses from a 1-kHz repetition rate Ti:Sapphire amplified laser system. These optical pulses ranged in average power from 1–10 mW and were synchronized to the QCL current pump pulses. The generated acoustic pulses propagated through the GaAs substrate and into the QCL stack, travelling vertically upwards through the structure to the top contact. The acoustic pulses were reflected upon incidence with the top contact and subsequently travelled back down through the QCL stack.

The acoustic-pulse-induced transient changes in the voltage across the QCL, $V(t)$, were extracted using a microwave bias tee to separate the high-frequency components from the quasi-dc bias, and measured on a 12.5-GHz sampling oscilloscope. Changes in the intensity of the QCL THz light emission, $L(t)$, were detected using the Schottky diode, and were also displayed on the oscilloscope.

III. RESULTS

Figure 1 shows $L(t)$ and $V(t)$ measured at a QCL pumping current of 1.64 A, where time $t = 0$ is the moment of impact of the optical pulse on the acoustic transducer. The first acoustic responses occur at $t = 32$ ns, corresponding to the transit time of the acoustic pulse through the GaAs to the underside of the QCL ridge. This modulation can be seen in both $L(t)$ (Fig. 1, black line) and $V(t)$ (Fig. 1, red line), and has a duration of approximately 6 ns, which is the time taken for the strain pulse to travel through the QCL ridge in each direction. These acoustic responses in both $L(t)$ and $V(t)$ exhibit rise times which

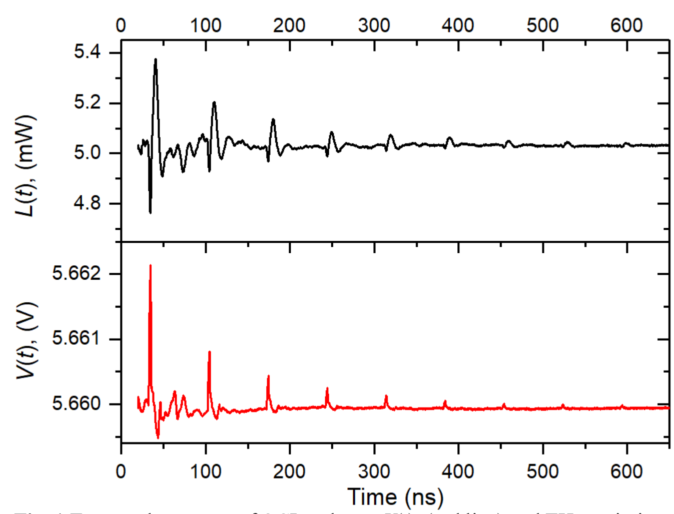

Fig. 1 Temporal response of QCL voltage, $V(t)$, (red line) and THz emission from QCL, $L(t)$, (black line) to incident strain pulses. The initial strain pulse arrives at 32 ns after being generated by laser impact in the Al transducer at t=0. Multiple reflections from the Al/substrate interface are seen every 70 ns.

are limited to ~0.8 ns by parasitic device impedance, rather than the timescales of the underlying acoustoelectric processes. Further acoustic responses, decaying in amplitude, are seen to occur with a period of 70 ns after the initial pulse which can be attributed to multiple reflections of the acoustic wave through the QCL ridge and substrate, with losses in the strain pulse amplitude at the top contact due to acoustic impedance mismatch between GaAs and Au.

The acoustic strain pulse is seen to result in a decrease in $L(t)$ and an increase in $V(t)$. The modulation in $L(t)$ [$V(t)$] is followed by a positive [negative] peak, which was attributed to ringing in the electrical circuit. The polarity of the modulation in $V(t)$ implies a transient increase in the resistance of the device as the strain pulse passes through the layered heterostructure whilst the polarity of the modulation in $L(t)$ shows a decrease in the THz emission from the device at this QCL pumping current. The modulation depth, *i.e.* a comparison of the modulation amplitude relative to the quasi-DC response of the Schottky detector, was found to have a maximum of 6% in our experiment and can be directly controlled by both the QCL drive current and the incident strain pulse amplitude. Preliminary investigations with increasing optical excitation power suggest it is possible to double the modulation depths with this QCL device before optical damage to the Al-layer will occur.

IV. 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 based on time-dependent perturbation theory [5], looking at the interaction of the acoustic pulse with the electronic band structure within one period of the QCL. In this model we consider the acoustic pulse as a propagating potential distortion of the band structure with an amplitude $\eta\Xi_D$, where Ξ_D is the deformation potential constant (~10 eV in GaAs). As this distortion passes from one period of the QCL structure to another it detunes the resonant injection of electrons into the upper laser level, affecting both the electronic transport and the THz emission from the QCL period. This perturbation model predicts a net decrease in tunnelling, regardless of QCL pump current, leading to a net increase in the device resistance which is consistent with experimental data. It was found, however, that this model provided a qualitative description of the experimental results but underestimated the modulation effect of the acoustic pulse on the THz emission. By considering the cumulative effect of the acoustic pulse on multiple periods of the QCL heterostructure, or other effects such as electric-field-domain formation, this model could be improved further.

V. Conclusions

We have demonstrated that coherent acoustic phonon (strain) pulses can perturb the band structure of a THz QCL, modulating both the electronic transport and THz power emission from the device. This can be partially explained by the proposed theoretical model. Modulation depths of 6% were obtained in our experiments, with measured rise times of 0.8 ns, limited by the parasitic device impedance. The theoretical modulation speed of the underlying physical processes are expected to be > 100 GHz.

Acknowledgements

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