High-speed modulation of a terahertz-frequency quantum-cascade laser using coherent acoustic phonon pulses

Aniela Dunn[1], Caroline Poyser[2], Aleksandar Demić[1], Paul Dean[1], Alexander Valavanis[1*], Dragan Indjin[1], Mohammed Salih[1], Iman Kundu[1], Lianhe Li[1], Andrey Akimov[2], Giles Davies[1], Edmund Linfield[1], John Cunningham[1] and Anthony Kent[2]

[1] School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK
[2] School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK
*Contact Email: a.valavanis@leeds.ac.uk

Short Abstract We demonstrate a new method for high-speed modulation of the electron transport and photon generation within a terahertz-frequency quantum-cascade laser (THz QCL). An amplified femtosecond laser is used to generate coherent acoustic-phonon pulses, which are injected into the device, resulting in an electronic bandstructure perturbation, with ~1-ns rise-time. The corresponding change in optical gain allows up to ~6% amplitude modulation, with results explained accurately using a perturbation-theory model.

1. Introduction

The high-speed modulation of terahertz-frequency quantum-cascade lasers (THz QCLs) is a fundamental requirement for their potential applications in optical communications, high-resolution spectroscopy and metrology. However, conventional approaches, based on direct electronic modulation of the QCL bias [1] are limited fundamentally by the parasitic impedance of the QCL and its driving electronics. Although modulation bandwidths up to 35-GHz have been achieved using double-metal QCLs integrated with microstrip-lines, this approach is not well-suited to single-metal QCLs, which exhibit superior beam quality. Other approaches, e.g., using graphene-based modulators, allow > 100-MHz modulation [2], but this is still limited by the parasitic capacitance of the modulating element. As such, it is desirable to exploit alternative physical processes to control the QCL gain or cavity loss.

We present an entirely new and unexplored approach, in which coherent acoustic-phonon pulses modulate the electronic bandstructure, and hence optical gain in a QCL. Acoustoelectric effects are well established in microwave filters, delay-lines and modulators, and have been shown to allow ~100-GHz modulation of electrical properties in semiconductor heterostructures [3]. Through a similar methodology, we have modulated the gain of a QCL without the frequency limitations imposed by parasitic electronic effects. Here, coherent acoustic pulses have been generated within a 2.6-THz GaAs/AlGaAs QCL using an amplified femtosecond laser (800 nm, 1 kHz). The QCL was processed into a single-metal surface-plasmon ridge waveguide geometry (150×2000-mm^2), and a 100-nm-thick aluminum acousto-optic transducer film was deposited on the device substrate. The QCL was mounted within a helium cryostat at 10–20 K and driven using a pulsed current source (0–1.8 A, 50 µs length, 5% duty-cycle). The pump laser pulses were synchronized with the QCL current pulses, and directed onto the aluminum transducer, via a cylindrical lens. A 12.5-GHz-sampling oscilloscope was used to record the resulting time-domain variation in the QCL terminal voltage, and in the THz power measured via a Schottky-diode mixer.

2. Results

Fig. 1 shows the QCL voltage, V(t) and THz detector signal, L(t), measured following an initial photoexcitation pulse (not shown) at t = 0 ns. The first voltage perturbation is observed at t = 32 ns, and with a duration of 6 ns, which correspond respectively to the times taken for the acoustic pulse to traverse the QCL substrate and undergo a round-trip within its active region. Further acoustic responses, decaying in amplitude occur at 70-ns intervals, corresponding to repeated echoes between the top of the device and the bottom of the substrate. The polarity of the voltage shift indicates an increase in device resistance in response to the acoustic pulse perturbing carrier injection within its active region. A corresponding reduction in L(t) is observed, with a modulation depth of up to 6% of the unperturbed value, followed by a positive shift, owing to electrical ringing in the measurement electronics. The relative size and the polarity of the voltage perturbations are in good agreement with a time-dependent perturbation model [4], and the modulation in THz power can be explained simply using a phenomenological study of the effect of perturbing the device voltage around its d.c. operating point.

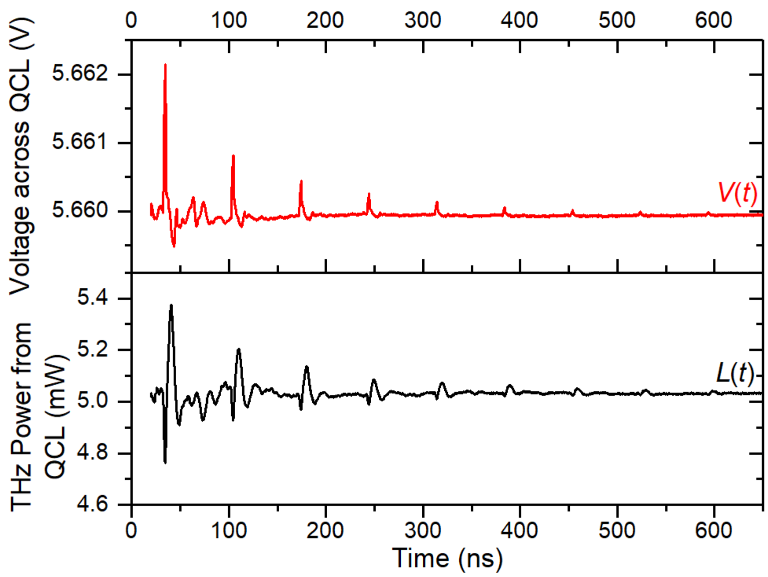

Figure 1: Time-domain response of QCL to acoustic pulses. (Top) Instantaneous change in voltage measured across the QCL, (Bottom) Corresponding change in measured THz power.

References

[1] S. Barbieri et al., '13GHz direct modulation of terahertz quantum cascade lasers', Applied Physics Letters, vol. 91, no. 14, p. 143510, Oct. 2007.

[2] D. S. Jessop et al., 'Graphene based plasmonic terahertz amplitude modulator operating above 100 MHz', Applied Physics Letters, vol. 108, no. 17, p. 171101, Apr. 2016.

[3] E. S. K. Young, A. V. Akimov, M. Henini, L. Eaves, and A. J. Kent, 'Subterahertz Acoustical Pumping of Electronic Charge in a Resonant Tunneling Device', Phys. Rev. Lett., vol. 108, no. 22, p. 226601, May 2012.

[4] C. Jirauschek and T. Kubis, 'Modeling techniques for quantum cascade lasers', Applied Physics Reviews, vol. 1, no. 1, p. 011307, Feb. 2014.