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Interferometry via Thermal Modulation in Low Duty Cycle Pulsed Terahertz QCLs

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The terahertz (THz) gap is being rapidly filled by a variety of new THz technologies, foremost of which is the quantum cascade laser (QCL). Modelling is a vital component in the development of new THz QCL applications, with modelling efforts tending to be technology (rather than application) centric. As such, the focus is on specific aspects of QCL operation such as laser dynamics, heat transfer and dissipation, and emission frequency control in order to optimize the devices themselves. To advance THz QCL applications, however, modelling requires an approach that considers aspects of device behaviour that are important from an application standpoint. Our work aims to demonstrate how we can achieve this, by modelling a real 2.59 THz bound-to-continuum QCL under pulsed operation and optical feedback. The foundation of our model is an accurate large-signal representation of the free-running QCL capable of predicting optical output power at arbitrary lattice temperature and terminal voltage [1]. In addition to the free-running QCL, our complete model includes the effects of self-heating thermal transients due to pulsed operation, and optical feedback, providing a realistic tool for predicting THz bound-to-continuum QCL behaviour in future applications involving pulsed QCL operation.

Frequency modulated QCLs can be effectively used in interferometric applications for imaging and materials analysis [2,3]. To date we have extensively used adiabatic modulation in our interferometric work [2–5]. Adiabatic modulation is achieved by sweeping or switching the laser's drive current – change in optical cavity refractive index as a result of changing carrier density then alters the laser's emission frequency. The aim of this work is to demonstrate, using our QCL model with optical feedback, that thermal modulation (emission frequency change) is an alternative way for creating the interferometric signal. Figure 1 illustrates the self-mixing [6] behaviour of our exemplar 2.59 THz bound-to-continuum QCL in an interferometric application employing adiabatic modulation [3]. In contrast, thermal modulation relies on change in optical cavity length and refractive index with temperature to alter the laser's emission frequency. The simplest method of invoking this mechanism is with short, low duty cycle rectangular (constant current) drive pulses. Each pulse both turns the laser on and, via self-heating, induces a thermal transient that sweeps the laser's emission frequency sufficiently for interferometric application.

To illustrate the potential for pulsed operation of laser feedback interferometers, we used the model to simulate optical output power for an external cavity length $L = 1.42$ m, target reflectivity of 0.7, and re-injection loss factor of 0.01, giving an Acket's characteristic parameter $C = 2.41$. The drive current pulse used is shown in Fig. 2 (a) and the self-mixing response under the given conditions in Fig. 2 (b). With appropriate signal processing [7], such self-mixing fringes captured in the laboratory can yield a wealth of information about the target material [3, 8]. A noteworthy feature of Fig. 2 (b) is the uneven spacing of self-mixing fringes due to the active region's approximately exponential thermal response. In comparison, the adiabatic fringes seen in Fig. 1 are close to equally spaced. We are currently working on an experimental setup for interferometric measurement of real target properties using thermal modulation via low duty cycle pulsing.

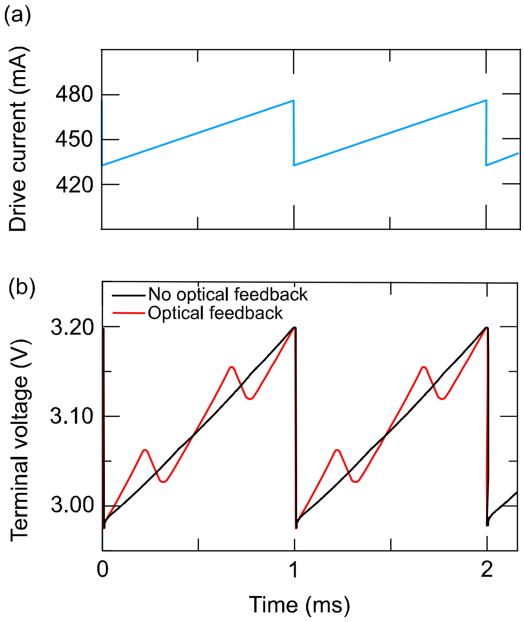

Figure 1. **Self-mixing response to adiabatic modulation. Part (a) shows drive current to the laser and part (b) the laser terminal voltage with and without optical feedback present. Laser terminal voltage and optical output power due to self-mixing are proportional under small signal conditions, making part (b) comparable with Fig. 2(b).**

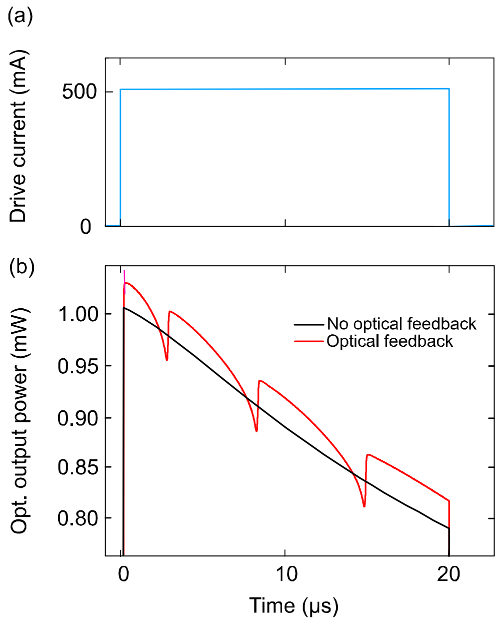

Figure 2. **Self-mixing response to thermal modulation. Part (a) shows drive current to the laser and part (b) the optical output power with and without feedback present.**

4. References

[1] G. Agnew, A. Grier, T. Taimre, Y. L. Lim, M. Nikolić, A. Valavanis, J. Cooper, P. Dean, S. P. Khanna, M. Lachab, E. H. Linfield, A. G. Davies, P. Harrison, Z. Ikonić, D. Indjin, and A. D. Rakić, "Efficient prediction of terahertz quantum cascade laser dynamics from steady-state simulations," Appl. Phys. Lett. **106**, 161105 (2015).

[2] P. Dean, A. Valavanis, J. Keeley, K. Bertling, Y. L. Lim, R. Alhathlool, A. D. Burnett, L. H. Li, S. P. Khanna, D. Indjin, T. Taimre, A. D. Rakić, E. H. Linfield, and A. G. Davies, "Terahertz imaging using quantum cascade lasers - a review of systems and applications," J. Phys. D: Appl. Phys. **47**, 374008 (2014).

[3] A. D. Rakić, T. Taimre, K. Bertling, Y. L. Lim, P. Dean, D. Indjin, Z. Ikoni´c, P. Harrison, A. Valavanis, S. P. Khanna, M. Lachab, S. J. Wilson, E. H. Linfield, and A. G. Davies, "Swept-frequency feedback interferometry using terahertz frequency QCLs: A method for imaging and materials analysis," Opt. Express **21**, 22194–22205 (2013).

[4] K. Bertling, T. Taimre, G. Agnew, Y. L. Lim, P. Dean, D. Indjin, S. Höfling, R.Weih, M. Kamp, M. von Edlinger, J. Koeth, and A. D. Rakić, "Simple electrical modulation scheme for laser feedback imaging," IEEE Sens. J. **16**, 1937–1942 (2016).

[5] T. Taimre, M. Nikolić, K. Bertling, Y. L. Lim, T. Bosch, and A. D. Rakić, "Laser feedback interferometry: a tutorial on the self-mixing effect for coherent sensing," Adv. Opt. Photon. **7**, 570–631 (2015).

[6] A. Valavanis, P. Dean, Y. L. Lim, R. Alhathlool, M. Nikolić, M., R. Kliese, S. P. Khanna, D. Indjin, S. J. Wilson, A. D. Rakić, E. H. Linfield, and A. G. Davies, "Self-mixing interferometry with terahertz quantum cascade lasers," IEEE Sens. J. **13**, 37–43 (2013).

[7] T. Taimre, K. Bertling, Y. L. Lim, P. Dean, D. Indjin, and A. D. Rakić, "Methodology for materials analysis using swept-frequency feedback interferometry with terahertz frequency quantum cascade lasers," Opt. Express **22**, 18633–18647 (2014).

[8] S. Han, K. Bertling, P. Dean, J. Keeley, A. D. Burnett, Y. L. Lim, S. P. Khanna, A. Valavanis, E. H. Linfield, A. G. Davies, D. Indjin, T. Taimre, and A. D. Rakić, "Laser feedback interferometry as a tool for analysis of granular materials at terahertz frequencies: Towards imaging and identification of plastic explosives," Sensors **16**, 1–9 (2016).