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Amplitude Stabilization of a THz Quantum-Cascade Laser using a Photonic Integrated Circuit

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***Abstract* — We demonstrate a method to stabilize the output power of a ~3.3-THz quantum-cascade laser (QCL) using a photonic integrated circuit, consisting of a racetrack resonator (RTR) coupled to a QCL ridge waveguide. Amplitude stabilization was achieved for >300 seconds, without perturbation to the emission spectrum, by dynamically adjusting the electrical bias to the RTR, and hence the coupling between the QCL and RTR.**

I. INTRODUCTION

TERAHERTZ-frequency quantum-cascade lasers (THz QCLs) are compact, electrically efficient, yet powerful semiconductor sources of narrowband radiation in the ~2–5-THz range [1]. These properties make them attractive for use in a range of sensing and imaging applications. One such example is their use as THz local oscillators (THz-LO) for atmospheric or deep-space radiometry [2], [3]. However, these measurements require long integration times, and therefore a stable THz source power is required to achieve a high signal to noise ratio. The output power of QCLs is susceptible to drifts in the thermal and mechanical environment, optical feedback, spontaneous quantum noise, and instability in the driving electronics.

To date, amplitude stabilization has required the use of external modulation elements (e.g., mechanical actuators, graphene modulators, or external laser sources), resulting in an increase in system size and complexity [4]–[6]. In this work, we demonstrate a fully integrated approach, based on a photonic integrated circuit (PIC) structure consisting of a lossy racetrack resonator (RTR) [7], coupled with a 3.3-THz QCL ridge waveguide. By varying the electrical bias on the RTR, the optical resonances, and hence the coupling between the QCL and RTR can be adjusted. The net gain in the THz field can therefore be adjusted dynamically, resulting in THz amplitude modulation.

II. RESULTS

The device consists of a ~3.3-THz QCL active region, grown epitaxially on a GaAs substrate. The gain medium was processed into a PIC structure (Fig. 1), consisting of a 4-mm-long gold–gold QCL ridge waveguide, adjacent to an RTR element. The two sections of the device were electrically isolated, but optically coupled, via a 2.5-µm air gap. Gold wire-bonds were attached to each section of the device, enabling independent biasing of the QCL and RTR.

The device was operated inside a Janis ST-100 helium cryostat, with the temperature stabilized at 40 K. The QCL was driven in continuous-wave mode at its peak emission power, using a d.c. power supply, and the emitted THz beam was modulated using an optical chopper. The output power was detected using a silicon bolometer, with the magnitude determined using a lock-in amplifier referenced to the chopper frequency.

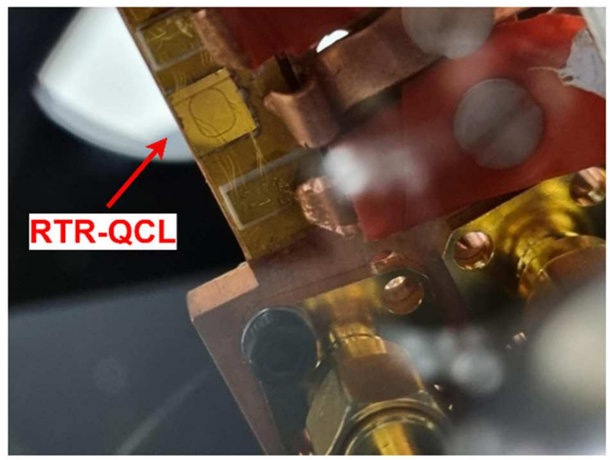

Fig. 1. QCL/RTR integrated circuit mounted on the cold-finger of a Janis ST-100 liquid-helium cryostat

The emission spectrum of the device was obtained using a Bruker IFS/66 Fourier-Transform Infrared (FTIR) spectrometer, as shown in Fig. 2, as the bias to the RTR modulator element was adjusted. In all cases, four identical principal modes were observed at ~3.277, 3.285, 3.372, and 3.392 THz. However, the output power was reduced as a function of RTR bias. This demonstrates that the output power can be controlled independently from the laser emission frequency.

An amplitude stabilization system was developed by using a proportional–integral (PI) controller to lock the magnitude of the QCL power from the lock-in amplifier to a predetermined reference level. The control output from the PI controller was used to adjust the bias current on the RTR modulator. The long-term drift in output power was successfully stabilized over a >300-second period, as shown in Fig.3, with a drift reduction to around 0.1%.

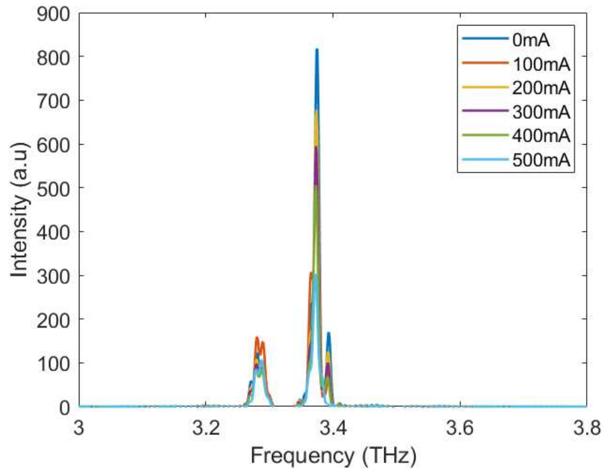

Fig. 2. Emission spectra of the QCL/modulator device obtained using a Fourier Transform Infrared spectrometer with the QCL at a fixed bias of 9.71 V and the ring-modulator driven at a range of currents.

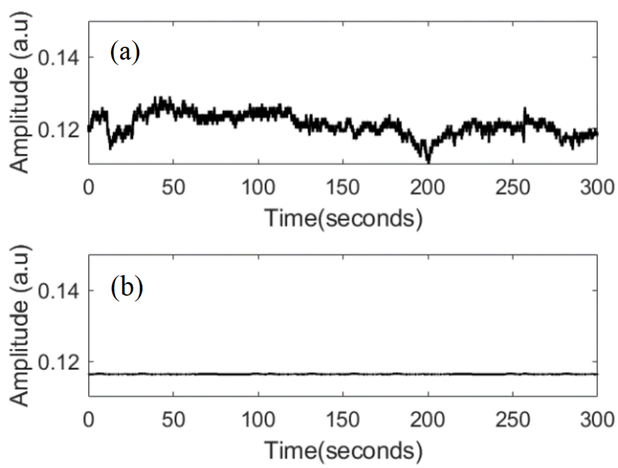

Fig. 3. (a)Free-running QCL output power with respected to time, detected by the lock-in amplifier. (b) QCL output amplitude stabilized with respect to time.

III. Summary

Amplitude stabilization of a THz QCL using an integrated photonic controller was successfully demonstrated. This approach eliminated the need for external THz optical modulators.

Output power was controlled through the modulator driving current in order to confine the THz field. A long integration power-lock of >300 seconds was achieved which is suitable for THz LO. This work could play a vital role in improving the performance of high-resolution spectroscopic systems useful in satellite integration for detecting gas species in the atmosphere.

Acknowledgments

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Data Availability

The data associated with this paper are openly available from the University of Leeds Data Repository http://doi.org/10.5518/1319.

Author Declarations

Conflict of interest

The authors have no conflicts to disclose.

Author contributions

S. S. Kondawar: writing — original draft preparation; investigation (lead); methodology (equal). N. K. North: investigation (supporting). Y. Han: investigation (supporting); D. Pardo: investigation (supporting). N. Brewster: investigation (supporting). M. Salih: investigation (supporting). M. D. Horbury: investigation (supporting). L. H. Li: investigation (supporting). P. Dean: supervision (supporting). B. N. Ellison: methodology (equal); supervision (equal); funding acquisition (supporting); conceptualization (supporting). I. Kundu: conceptualization (equal); methodology (equal); funding acquisition (supporting). A. Valavanis: conceptualization (equal); supervision (lead); methodology (lead); funding acquisition (lead); writing — reviewing & editing (lead).

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