Quasi-continuous tuning in coupled cavity terahertz quantum cascade lasers with an integrated photonic lattice

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1. Introduction

Terahertz (THz) frequency quantum cascade lasers (QCLs) typically emit multiple longitudinal modes characteristic of Fabry–Pérot (FP) cavities [1]. Whilst many potential THz sensing applications, such as trace gas detection, atmospheric observations and security screening [2], require a widely-tunable (single-mode) THz source, the current and temperature tuning of THz QCLs is only ~– 5 MHz/mA and –34 to –100 MHz/K, respectively [3].

We recently demonstrated discrete Vernier tuning in THz QCLs using a device consisting of two coupled cavities (CC) monolithically integrated on the same substrate, as illustrated in Fig. 1(a) [4]. In such CC lasers, the emission frequency is determined by a Vernier resonance between two slightly different Fabry–Pérot longitudinal combs, corresponding to the cavity lengths of the lasing and tuning sections. Lasing is selectively favoured in such a resonant mode, since it has the largest feedback and hence the lowest lasing threshold. In our previous demonstration, the active lasing cavity was electrically driven above the lasing threshold, while the passive tuning cavity was driven below threshold to induce localized Joule heating as a tuning mechanism. Whilst discrete mode hops were observed with controllable red-shift and blue-shift in frequency, continuous tuning was not observed.

In this work, we have designed a CC THz QCL to reduce the frequency separation between mode hops by increasing the comb spacing ratio (CSR) between the reflectivity combs associated with the lasing and tuning cavities. The cavity modes can be tuned in frequency by controlling the drive power in either the lasing or tuning cavities, as well as the pulse width in the tuning section to achieve quasi-continuous tuning of the emission frequency. Furthermore, we demonstrate the use of a one-dimensional photonic lattice (PL) integrated into the lasing cavity to improve the side-mode suppression ratio (SMSR).

2. Design 1: THz CC QCL with a large CSR

THz CC QCLs were designed to reduce the frequency separation between mode hops. Whilst this can be achieved by using longer cavities to reduce the free spectral range (FSR) in both the lasing and the tuning sections in a CC QCL with a CSR of 1:1, such designs risk spurious mode or two-peak emission. Instead, a THz CC QCL was designed with a high CSR > 1:2.5, which allows a frequency separation of CC modes that is lower than the FSR of each of the lasing and tuning cavities. Additionally, an index perturbation in the lasing cavity was introduced by varying the laser drive current and using wide tuning pulses to continuously frequency shift the emission modes. To this end, a CC QCL was designed comprising a 3.52-mm-long lasing cavity (FSR=12 GHz) and a 1.29-mm-long tuning cavity (FSR=32 GHz) separated by a 16.7-µm-wide air gap. The transfer matrix model, described in ref. [4], was used to simulate the CC modes as a function of the localized electrical Joule heating power supplied to the tuning cavity [Fig. 1(b)]. The high CSR results in two interleaved sets of CC modes, each with frequency spacing ~35 GHz (modes 1&2 and 3&4). Additionally, the model predicts that an index perturbation in the lasing cavity can quasi-continuously shift mode 1 to cover the frequencies between modes 1 and 4 (~11 GHz).

A THz QCL based on a bound-to-continuum active region [5] was grown in the $Al_{0.1}Ga_{0.9}As/GaAs$ material system using molecular beam epitaxy. Samples were processed into single-plasmon waveguides with 150-µm-wide and 14-µm-thick laser ridges. A 4.81-mm-long laser ridge was cleaved and mounted on a copper block. The ridge was divided into lasing and tuning cavities post-packaging using focused ion beam (FIB) milling. The device was mounted in a continuous-flow helium-cooled cryostat, and the lasing and tuning sections were driven with 2-µs and 20 or 95-µs-wide current pulses, respectively. Spectra were acquired using a Bruker Fourier transform infrared spectrometer with resolution 7.5 GHz.

Initially, spectra were acquired at a laser drive power (current) of ~4.10 W (0.95 A), and with varying electrical heating power supplied to the tuning cavity [Fig. 1(c)]. Discrete mode hops were observed between three CC modes, agreeing closely with the behaviour predicted in Fig. 1(b). The mode at ~2.25 THz [mode 4 in Fig. 1(c)] could be shifted continuously by ~5 GHz through variation of the tuning power (in the range ~3.5–5 W), before hopping by~−15 GHz at tuning powers >5 W, in close agreement with the frequency spacing between modes 1 and 4 in

Fig. 1(b). Furthermore, the device was also characterized by varying the drive current supplied to the lasing cavity, as well as the heating power and pulse width driving the tuning cavity, to obtain the full spectral coverage shown in Fig. 1(d). Emission frequencies from ~2.185 to 2.285 THz were observed with quasi-continuous shifts of ~5, 7 and 4 GHz centered at ~2.22, 2.25 and 2.285 THz, respectively.

3. THz CC QCL with integrated PL

In order to improve the SMSR, and gain further control over the emission frequency of these devices, a one-dimensional photonic lattice (PL) [6] was also integrated on the lasing cavity using FIB milling [Fig. 1(e)]. The transfer matrix model was modified to include the PL, and predicted a continuous mode shift of ~3 GHz (centered at ~2.215 THz) as a function of the electrical heating power in the tuning cavity [Fig. 1(f)]. Spectra were acquired with the lasing cavity driven at its peak output emission power, and as a function of the electrical peak power supplied to the tuning cavity. Single mode emission with an SMSR of 20 dB was observed at ~2.21 THz, close to the design frequency of 2.215 THz [Fig. 1(g)]. A continuous tuning of ~3 GHz was also observed as a function of the peak power supplied to the tuning cavity.

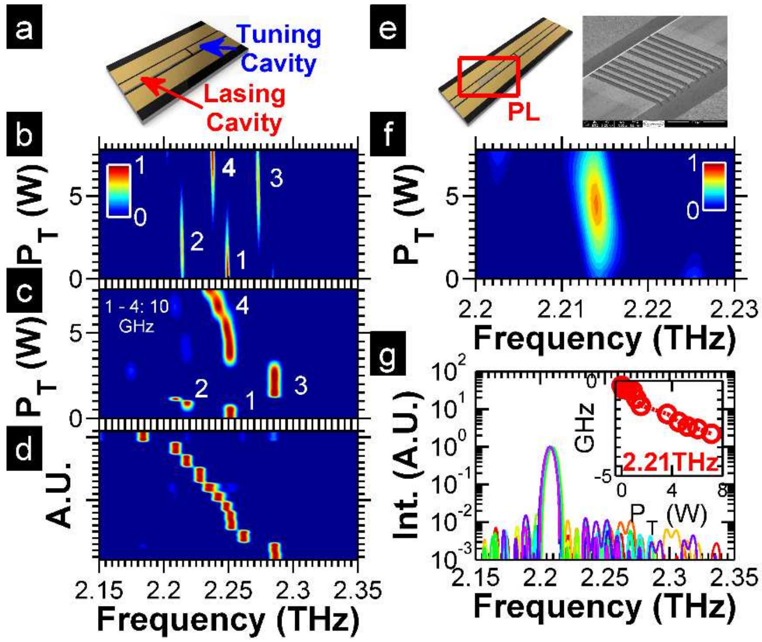

Fig. 1 (a) Schematic of a THz CC QCL. (b) Simulated normalized transmission spectral map as a function of the electrical heating power at the tuning cavity. (c) Experimentally observed contour of the spectra (at 6 K) as a function of the electrical heating power at the tuning cavity. The lasing cavity is driven with (4.10 W) 2-μs-wide pulse train, and the tuning cavity is driven with 95-μs-wide pulse train. (d) Single mode spectral coverage of the device with discrete mode hops extending from 2.185–2.285 THz. (e) Schematic of a THz CC QCL with PL. (f) Simulated normalized transmission spectral map as a function of the tuning power. (g) Experimentally observed spectra (at 6 K) with an improved SMSR of 20 dB. Inset: Red shift in emission frequency calculated from the weighted mean of the SPD at 2.21 THz, as a function of the power at the tuning cavity (95 μs-wide pulses).

In conclusion, continuous tuning of ~7 GHz and a spectral coverage of ~100 GHz has been demonstrated using a coupled-cavity THz QCL. We have also demonstrated the use of a one-dimensional photonic lattice integrated into the lasing cavity to achieve single-mode continuous tuning of ~3 GHz with no degradation in emission power.

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