Discrete Vernier tuning in terahertz quantum cascade lasers using coupled cavities

Iman Kundu,* Paul Dean, Alexander Valavanis, Li Chen, Lianhe H. Li, John E. Cunningham, Edmund H. Linfield, and A. Giles Davies

School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom
**el09ik@leeds.ac.uk*

1. Introduction

Terahertz-frequency quantum cascade lasers (THz QCLs) are compact solid-state sources of coherent radiation in the 1–5 THz region of the electromagnetic spectrum [1]. The emission spectra of THz QCLs typically exhibit multiple longitudinal modes characteristic of Fabry–Pérot (FP) cavities. However, widely-tunable (single-mode) THz QCLs would be ideally suited to many THz-sensing applications, such as trace gas detection, atmospheric observations [2], and security screening [3].

Here we demonstrate discrete Vernier tuning using a simple two-section coupled-cavity geometry. A monolithic THz QCL ridge cavity was etched using focused ion beam milling to create two coupled FP cavities separated by an air gap [Fig. 1 (a)]. In this scheme, one of the two sections (the '*lasing* section') is electrically driven above the lasing threshold, while the other is driven below threshold and acts as a '*tuning* section'. The lengths of the two sections and the air gap were designed such that the longitudinal FP modes of the respective sections coincide at a selected ('*resonant*') frequency. The dominant lasing mode of the coupled cavity occurs at this frequency owing to the reduction in threshold [4]. A small perturbation to the frequency of the modes in either section of the device will detune the resonance, causing the dominant mode of the coupled-cavity to 'hop' to a different frequency [Fig. 1 (b)], in a manner analogous to the Vernier effect. The longitudinal modes of the tuning section are controlled by perturbing its refractive index through current-induced heating.

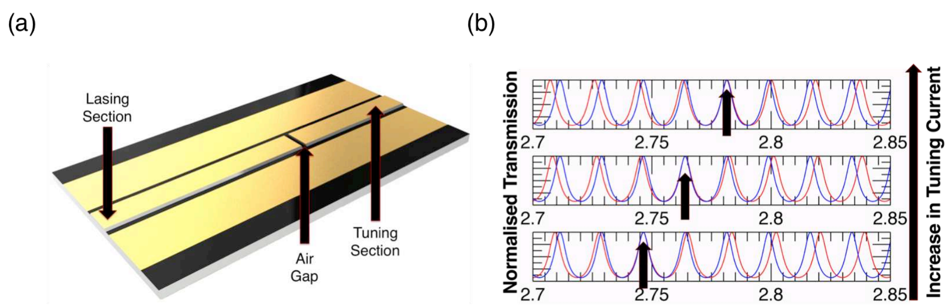

Fig. 1. (a) Illustration of a coupled cavity device. The two laser sections are separately biased enabling independent electrical control of the sections. (b) Simulated normalized transmission in the lasing section (blue) and tuning sections (red) of a device. Longitudinal modes coincide at a resonant frequency of 2.745 THz (bottom panel). Illustration of the shift in the resonant frequency as the refractive index of the tuning section is perturbed (middle and top panel).

2. Modeling using Scattering and Transmission Matrices

Propagation of the THz electric field through the coupled-cavity structure was simulated using scattering and transmission matrices representing the lasing, tuning and air gap sections, based on the approach described in Ref. [4]. A specific length of the tuning section was selected such that it exhibited maximum reflectivity at a frequency corresponding to that of a longitudinal FP mode of the lasing section. In order to predict how the emission of coupled-cavity devices varies with electrical input power delivered to the tuning section, a bulk thermal model was used. The steady-state temperature change during the tuning pulse can be estimated from $\Delta T = R_{Th} V_t I_t$ [5], where R_{Th} is the thermal resistance, and V_t and I_t are the voltage and current pulse amplitudes supplied to the tuning section, respectively.

Two coupled cavity designs were investigated. In the first instance (design 1), the lengths of the lasing and tuning sections differed by only a few half wavelengths, yielding very similar FP mode spacing in each section. The emission frequency of the coupled cavity device was then predicted to progressively hop between adjacent modes of the lasing section as the tuning section temperature changes [Fig. 2 (a)]. In the second design (design 2), the length of the lasing section was chosen to be almost twice that of the tuning section. Hence, the modes of the tuning section were designed to coincide with *alternate* modes of the lasing section as the electrical power delivered to the tuning section was varied [Fig. 2 (b)].

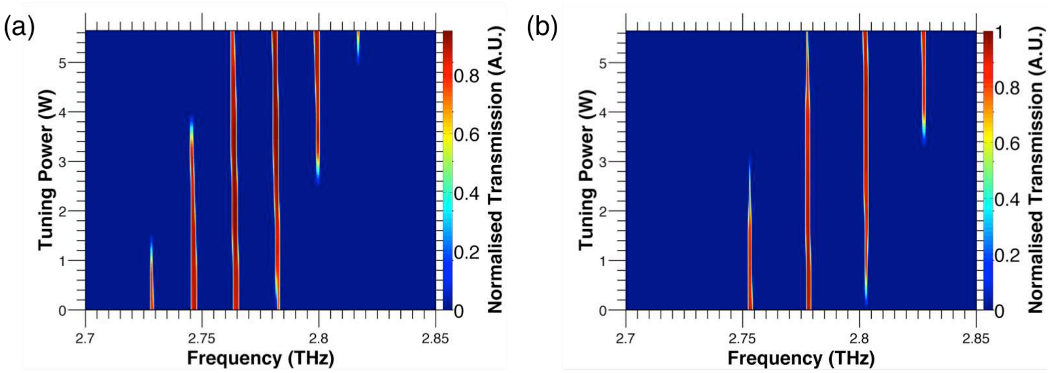

Fig. 2. Simulated transmission spectra of coupled-cavity devices as a function of heat dissipation power at tuning section. (a) design 1 and (b) design 2.

3. Experimental results

Samples based on a bound-to-continuum active region [6] were processed into single-plasmon waveguides. Devices were etched after packaging using a focused ion beam milling system to sculpt a 12-µm-deep gap to form the two-section cavity. The tuning section of the laser was heated below threshold using a train of 10–µs−long current pulses at a repetition rate of 8.21 kHz. This pulse train was gated using a 600-Hz reference frequency. The lasing section was driven by single 500–ns-long pulses above threshold, which were triggered using the same 600-Hz reference.

Discrete tuning with a blue shift in frequency was observed over bandwidths of 50 and 85 GHz from device 1 and 2 respectively [Fig. 3]. This observed hopping between modes was spaced by 15 GHz and 30 GHz in device 1 and 2. A red shift in frequency over 30 GHz was also observed in device 2 by swapping the function of the lasing and tuning sections [Fig. 3 (b) Inset]. Negligible degradation in output power was observed with tuning current.

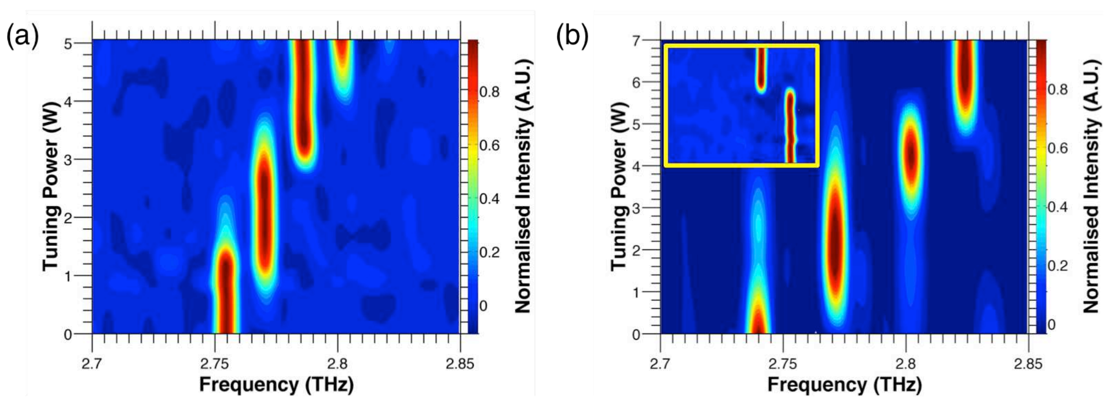

Fig. 3. Experimental data obtained from (a) device 1 and (b) device 2, with tuning power applied to the short tuning section. Inset: Red-shift in frequency observed over same frequency and tuning power by alternating between the lasing and tuning sections.

4. References

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