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Time-resolved analysis of Vernier selection dynamics in coupled-cavity terahertz quantum-cascade lasers

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1. Introduction

Vernier selection is used extensively to design electrically tunable diode lasers [1], as well as quantum cascade lasers (QCLs) operating at both mid-infrared (mid-IR) [2] and terahertz (THz) frequencies [3]. In such lasers, the emission frequency is determined by a resonant mode that corresponds to a Vernier alignment between two slightly different reflectivity combs, each arising from a different waveguide section. Such a resonant mode experiences the largest feedback and hence the lowest lasing threshold. As a result, lasing is selectively favored at this mode. Furthermore, a controlled index perturbation applied to either of the two combs can shift the resonance to an adjacent mode, resulting both in discrete mode hops and continuous frequency shifts.

Whereas steady-state single mode emission with high spectral purity has been reported from such Vernier lasers [1], most characterization techniques are steady-state time averaged, and gaining an understanding of the dynamic processes in such multi-section lasers remains a technological challenge.

In this work, we study the lasing dynamic and Vernier selection processes in coupled-cavity THz QCLs using a THz time-domain spectroscopy (TDS) technique. This method has been used extensively to study injection seeded THz QCLs [4], and allows coherent dynamic probing of the THz field on ps timescales.

2. Methods

A THz QCL with a bound-to-continuum active region [5] was grown using molecular beam epitaxy. Alternating layers of $Al_{0.15}Ga_{0.85}As$/GaAs were grown in the following sequence, starting from the injection barrier: 3.8/11.6/3.5/11.3/2.7/<u>11.4</u>/2/<u>12</u>/2/12.2/1.8/12.8/1.5/15.8/0.6/ 9/0.6/14 nm (barriers in italics). The 11.4-nm and 12-nm-wide wells were n-doped with Si at 3.2×10^{16} cm^{-3}. A sample was processed into a laser ridge with a semi-insulating surface plasmon waveguide. A coupled-cavity device with a 3.446-mm-long passive tuning cavity and a 1.371-mm-long active lasing cavity, separated by an air gap of 14.3 µm, was processed following the procedures described in ref. [3]. The lasing section was driven with a quasi-direct current (DC) by a 5-µs-wide 10-kHz pulse train, and the tuning cavity was driven with a 10-µs-wide quasi-DC pulse train with a sub-threshold current amplitude (< 2.1 A). The lasing dynamics in the coupled cavity QCL were studied using the TDS system described in ref. [4]. Broadband THz pulses emitted from a photoconductive antenna were synchronized with an electrical pulse to drive the lasing section above lasing threshold and were used to injection seed the lasing section. The seed pulse is amplified with each round trip until gain saturation is reached. The field emitted from the facet of the tuning section was detected using an electro-optic sampling arrangement. A schematic of the device and the injection seeding scheme is shown in Fig. 1(a)

3. Results and discussion

Initially, the time-averaged spectra from the coupled cavity device were acquired using an incoherent detection system comprising a commercial Fourier transform infrared spectrometer and bolometric detector. The emission frequency was recorded at a laser section drive current of 0.75 A for different current amplitudes in the tuning cavity. Discrete mode hopping with a red-shift from 2.825 THz to 2.765 THz was observed. Subsequently, the electric field from the coupled cavity QCL was sampled as a function of time using the TDS system, initially with the tuning section switched off [Fig. 1(b)]. The temporal evolution of the emission spectrum was studied by performing a fast Fourier transformation (FFT) of the electric field within a time window of ~150 ps (1.3× roundtrip time ~115 ps), which was shifted incrementally by ~11 ps. The spectral power density (SPD) was calculated as a function of the round trip (RT) time by integrating the power contained at each of the Fabry–Pérot modes [Fig. 1(c)]. Multi-mode emission was observed at the start of injection and this evolved into a single mode emission at

2.825 THz after ~10 round trips (~1000 ps) as a steady-state condition was attained by Vernier selection. Furthermore, as a current pulse was applied to the tuning section, a change in the spectral distribution was observed, along with an increase in the number of RTs required to select the dominant mode, indicating a change in Vernier selection conditions.

The experimentally observed laser dynamics were compared with those obtained from a simulation of the coupled-cavity system. The reduced rate equation (RRE) model of a THz QCL, described in ref. [6], was modified to describe multi-mode emission. The coupled rate equations were solved using a fifth-order Runge–Kutta method. The simulated temporal variation of the spectral power distribution between the Fabry–Pérot modes, shown in Fig. 1(d), agrees well with the experimental results. Whereas, the number of RTs required to select the dominant mode was simulated to increase as the tuning current is increased, after a mode hop this was simulated to decrease; and agreed well with the experimental data [Fig. 1(e)]. This indicates that the time required for mode selection in the coupled cavity depends on the resonance of the reflectivity combs.

In conclusion, inter-mode competition and time-dependent Vernier selection of a dominant mode in a coupled-cavity QCL were measured using a TDS system, and were simulated using a RRE model.

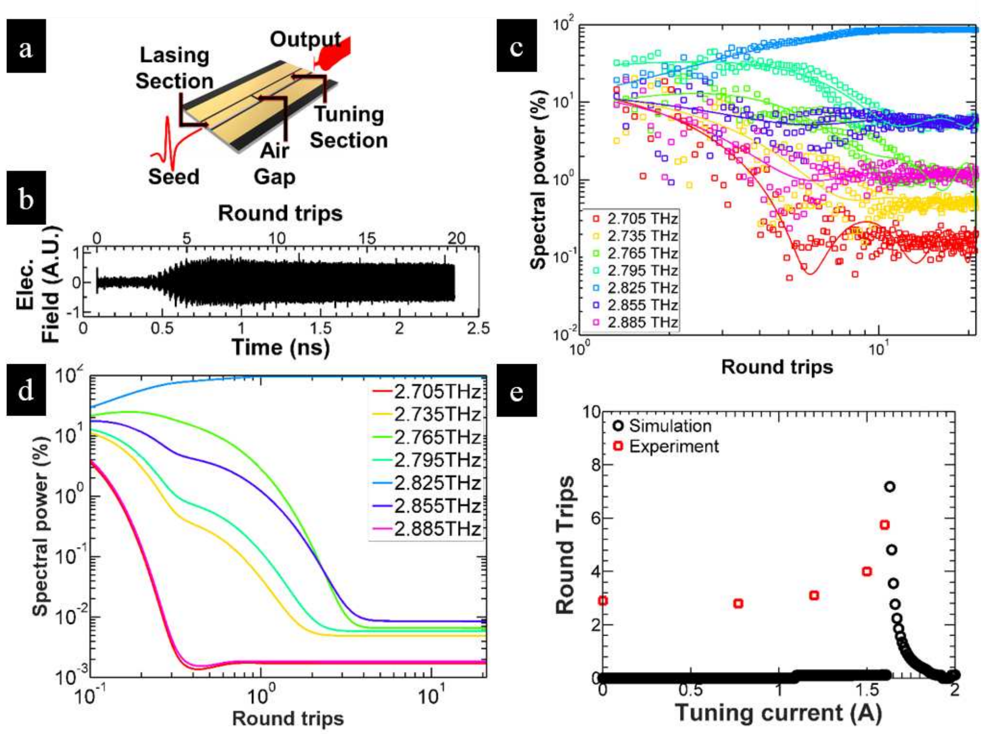

Fig. 1 (a) Schematic of coupled cavity THz QCL and the injection seeding arrangement. (b) Experimental data: emitted electric field measured as a function of time using TDS with the tuning cavity switched off. (c) Experimental data: SPD amongst the Fabry Pérot modes, calculated from the FFT spectra, as a function of the RT. (d) SPD amongst the Fabry-Pérot modes calculated from a multi-mode RRE model. (e) Simulated and experimental data: increase in the RTs to select the dominant mode in the coupled cavity device, as a function of the current amplitude in the tuning cavity.

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