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Frequency Tunability in Coupled-cavity Terahertz Quantum Cascade Lasers

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***Précis*-** **Based on scattering matrix theory and multi-mode reduced rate equations, we demonstrate the dependence of the frequency tunability on the passive to active cavity length ratio in coupled-cavity terahertz quantum cascade lasers. Mode hopping among five eigenmodes with continuous frequency tuning of each dominant mode of 2–5GHz is obtained.**

Tunable terahertz (THz) emission with the coherent radiation of 0.5–10 THz is highly desired for many spectroscopic sensing and imaging applications [1]. Large tuning range (> 20 GHz) THz emission has been realized by applying an external grating or MEMS in quantum cascade lasers (QCLs) [2,3], but suffers from slow tuning, operation difficulties, or system complexity. Coupled-cavity (CC) THz QCLs can provide fast frequency tuning by control of the passive cavity current [4] or the heat sink temperature of the device. However, the device parameters that determine the frequency tunability in CC THz QCLs have not been investigated. In this work, we studied the dependence of the frequency tunability of the device on the passive to active cavity length ratio (L_p / L_a). It is found that the larger the ratio L_p / L_a, mode hops among more eigenmodes that are covered by the gain spectrum bandwidth, but with less continuous frequency tuning within a certain heat sink temperature tuning range.

A CC THz QCL is composed of two cavities separated by an air gap; the active cavity is electrically driven above the lasing threshold while the passive cavity is operated below threshold to control the dominant mode [4]. The longitudinal eigenmodes are dynamically updated by the transmission coefficient of the device with varying device parameters. The spectral power density (SPD) of each mode is modelled next by the multi-mode reduced rate equations (RREs) and thermal equation as shown below:

$$\frac{dN_3(t)}{dt} = \frac{\eta_3 I_a(t)}{q} - (N_3(t) - N_2(t))\sum_{m=1}^{N} G_m S_m(t) - \frac{N_3(t)}{\tau_3}, \tag{1}$$

$$\frac{dN_2(t)}{dt} = \frac{\eta_2 I_a(t)}{q} + (N_3(t) - N_2(t))\sum_{m=1}^{N} G_m S_m(t) + \frac{N_3(t)}{\tau_{32}} + \frac{N_3(t)}{\tau_{sp}} - \frac{N_2(t)}{\tau_{21}}, \tag{2}$$

$$\frac{dS_m(t)}{dt} = M(N_3(t) - N_2(t))G_m S_m(t) - \frac{S_m(t)}{\tau_{pm}} + \frac{M\beta_{sp}N_3(t)}{\tau_{sp}}, \quad m = 1, 2, \cdots, N, \tag{3}$$

$$\frac{dT_e(t)}{dt} = \frac{1}{mc_p}\left[I_p(t)V_p(t) - \frac{T_e(t) - T_0}{R_{th}}\right]. \tag{4}$$

The multi-mode RREs are an extension of that for single-mode QCLs [5]. The frequency tunability achievable by control of the heat sink temperature in a CC THz QCL with L_a =1.5 mm and various L_p is simulated. It is found that the mode hopping times are proportional to the ratio of L_p / L_a. When L_p =3.4 mm, the eigenmode frequencies are at 2.713, 2.74, 2.768, 2.793, 2.819, 2.847, and 2.873 THz with ΔT_{HS} = -100 K, which are indicated as mode 1 to 7, respectively. As shown in Fig.1(a), successive mode hopping from mode 6 to 2 is achieved with ΔT_{HS} varying over a range of 200 K, which is potentially possible considering the THz QCL with the operation temperatures from 8 K to 200 K is now available [6]. Continuous frequency tuning of each dominant mode of 2–5 GHz is observed from Fig.1(b).

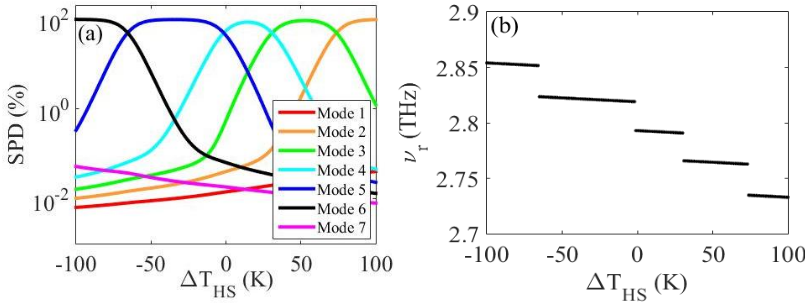

Fig. 1. The frequency tunability of a CC THz QCL with L_p =1.5mm, L_g =13μm, and L_p =3.4mm: (a) The steady state SPD and (b) the dominant mode frequency ν_r as a function of the heat sink temperature variation ΔT_{HS}.

[1] S.H. Wang, B. Ferguson, D. Abbott, X.-C. Zhang, "THz imaging and tomography," *J.Biol.Phys.,* **29**, 247 (2003)

[2] A.W.M. Lee, B. S. Williams, S. Kumar, Q. Hu and J. L. Reno, "Tunable terahertz quantum cascade lasers with external gratings," *Opt. Lett.,* **35**, 910 (2010)

[3] N. Han, A. D. Geofroy, D. P. Burghoff, et.al., "Broadband all-electronically tunable MEMS terahertz quantum cascade lasers", *Opt. Lett.*, **39**, 3480 (2014)

[4] I. Kundu, P. Dean, A. Valavanis, L. Chen, L. Li, J. E. Cunningham, E. H. Linfield, and A. G. Davies, "Discrete Vernier tuning in terahertz quantum cascade lasers using coupled cavities," *Opt. Express*, **22**, 16595 (2014)

[5] 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).

[6] S. Fathololoumi, E. Dupont, C. W. I. Chan, Z. R. Wasilewski, S. R. Laframboise, D. Ban, A. Mátyás, C. Jirauschek, Q. Hu, and H. C. Liu, "Terahertz quantum cascade lasers operating up to ~200 K with optimized oscillator strength and improved injection tunneling," *Opt. Express*, **20**, 3866 (2012)