Modelling of mode competition characteristics in coupled-cavity terahertz quantum cascade lasers using multi-mode reduced rate equations

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1. Introduction

Single-mode Terahertz (THz) emission with broad frequency tuning is highly desired for a wide range of spectroscopic sensing and imaging applications. In single cavity distributed feedback (DFB) QCLs, the intrinsic frequency tuning range by injection current and temperature are limited on the order of 0.1cm^{-1} (3GHz) [1]. Coupled-cavity (CC) THz QCLs can offer tunable emission over a wide spectral range as a function of localized electrical heating an optically coupled passive cavity[2,3], provided proper phase and amplitude relationships among the cavity lengths, the total loss and the gain spectra.

Unlike the interband CC lasers, the typical effective mirror loss in a CC-THz QCL is much smaller than the material peak gain due to longer lasing cavity lengths, which result in multiple longitudinal modes with their individual gain above the threshold. As such, stronger mode competition is favored and the cavity lengths relationship for wide tunability of the single-mode CC-THz QCL will be different from that in CC interband lasers [4]. In spite of the recognized importance of the mode competition dynamics and the wide tunablity condition in CC-THz QCLs, the related theoretical investigation has not been reported yet.

In this work, we studied the wide tunable condition in CC-THz QCLs with an emphasis on the effect of the total loss. The mode competition characteristics are investigated using a coupled cavity resonator analysis below threshold and multi-mode reduced rate equations (RREs) above threshold. The mode tuning process is simulated in the model by controlling the tuning current, yielding a good agreement with the experimental data.

2. Dynamical mode competition modelling

In order to accurately describe the performance of the CC-THz QCLs, the eigen longitudinal mode frequency deviations due to the coupled cavity scheme need to be dynamically updated before solving the multi-mode rate equations, especially for studying the tunablity as a function of refractive index for different passive cavity lengths. In the first instance, transfer matrix approach (S-matrix) was used to calculate the threshold gain at potential modes. Subsequently, the multi-mode three-level RREs in CC-THz QCLs were established as shown below (the photon lifetime τ_{pm} for mode m is modified by the coupled cavity parameters[4]):

$$\frac{dN_3(t)}{dt} = \frac{\eta_3 I(t)}{q} - \big(N_3(t) - N_2(t)\big)\sum_m G_m S_m(t) - \frac{N_3(t)}{\tau_3} \tag{1}$$

$$\frac{dN_2(t)}{dt} = \frac{\eta_2 I(t)}{q} + (N_3(t) - N_2(t))\sum_m G_m S_m(t) + \frac{N_3(t)}{\tau_{32}} + \frac{N_3(t)}{\tau_{sp}} - \frac{N_2(t)}{\tau_{21}} \tag{2}$$

$$\frac{dS_m(t)}{dt} = M\big(N_3(t) - N_2(t)\big)G_m S_m(t) - \frac{S_m(t)}{\tau_{pm}} + \frac{M\beta_{sp}}{\tau_{sp}} N_3(t) \qquad \text{For mode } m \tag{3}$$

where $N_3(t)$ and $N_2(t)$ are carrier populations in the upper and lower laser levels, respectively. $S_m(t)$ is the photon population in mode m, all the other parameters are defined in [5]. The multi-mode RRE can be solved by fifth-order Runge-Kutta method. The output emission power is calculated by $P_m(t) = \eta_0 \hbar v S_m(t)/\tau_{pm}$, where v is the frequency of each eigen mode. The dynamical mode competition process was described by the temporal spectral power density distribution (SPD) among the modes. We focus on a device with a lasing cavity length L_a=1.371 mm and an air gap length L_g=14.3µm, which are the dimensions of a fabricated device we used to verify our theoretical model. The wide tunability condition was obtained from comprehensive simulations with varying waveguide loss and the length of the passive cavity L_p in CC-THz QCL for three different cases of $L_a \gg L_p$, $L_a \sim L_p$ and $L_a < L_p$.

3. Results and discussion

The threshold gain and the temporal output power for each mode with L_a=1.371 mm, L_p=0.2285 mm and L_g=14.3um are plotted in Fig.1 (a) and (b), respectively. The blue crosses in Fig.1(a) represent the calculated eigen mode frequencies, which are between 2.706 THz and 2.976THz with a mode spacing of 30GHz. It is observed that the peak material gain g_p (2049 cm^{-1}) at 2.766THz of the Lorenzian gain spectrum (green broken curve) is larger than the modulation amplitude of the threshold gain g_{th} (red solid curve), thus 9 FP modes have their net gain above zero. Only the modes between 2.7 THz and 2.9 THz are considered since the full-width-half-maximum (FWHM) of the gain is 180 GHz. A single-mode emission at mode 3(2.766 THz) with a steady-state SMSR of 25.4dB was calculated. A comprehensive simulation reveals that the waveguide loss of the passive cavity plays an important role to decide the wide tunablity condition: the CC-QCLs with a relatively high passive waveguide loss (g_p>g_{th}) are more tunable with the power transitions between more modes, as such less stable when L_a>>L_p. While its mode tunability level reduces with the decreasing loss but that for the case of L_a~L_p is improving, the mode tunablity for L_a<L_p is in between but an SMSR above 30dB is generally not possible due to the small net gain differences between the adjacent modes. The mode tunability conditions above are verified by the steady-state SPD with varying L_p for (a) L_a>>L_p (b) L_a~L_p and (c) L_a<L_p in Fig.2, where the waveguide loss in the lasing and tuning section are both 9cm^{-1}.

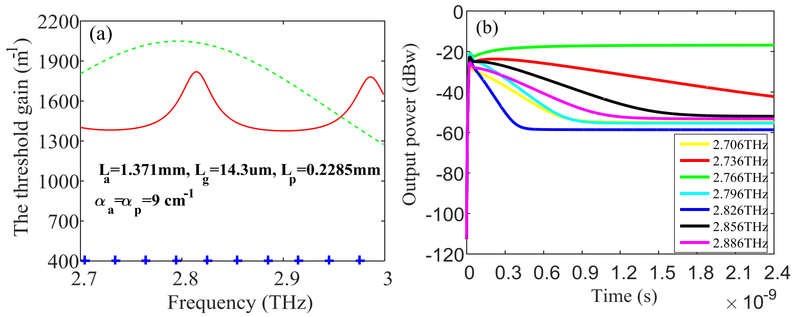

Fig.1The threshold gain and the output power for multi-mode in CC-QCL with L_a=1.371mm, L_g=14.3μm and L_p=0.2285mm: (a) The threshold gain (solid red line) and the Lorenzian gain (green broken line), the blue crosses represent the calculated eigen mode frequencies, which are between 2.706 THz and 2.976THz with a mode spacing of 30 GHz. (b) The temporal variation in output power of the 7 modes between 2.7GHz and 2.9GHz

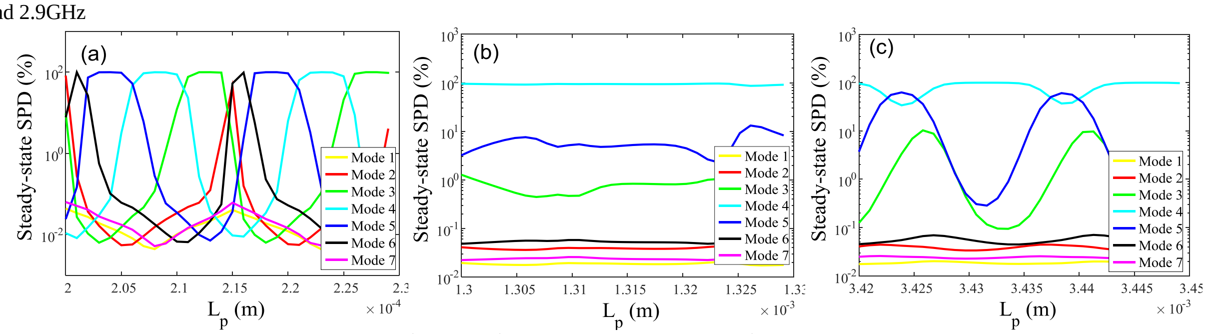

Fig.2 The steady state SPD as a function of the passive cavity length L_p for (a) L_a>>L_p (b) L_a~L_p, and (c) L_a<L_p

The model described above was used to simulate the mode transition with the tuning current I_p for a CC-QCLwith L_p=3.446 mm. Mode switching between mode 5 (2.825 THz) and mode 3 (2.765 THz) was observed with I_p tuning from 0 A to 2.0 A. The simulation results were compared with the experimental data obtained from the fabricated device with the same dimensions and operating conditions and they were in good agreement.

In conclusion, the complete modelling of mode competition characteristics in CC-THz QCLs based on transfer matrix method and multi-mode reduced rate equations was conducted. It was found that increased tunability is obtained when L_a>>L_p for CC-THz QCLs with higher total loss, which is in contrast to a CC interband laser that is more tunable when L_a~L_p. The accuracy of the modelling approach was verified by experiment.

4. References

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