# Cavity-induced slow gain recovery in pump-probe experiments of quantum cascade lasers

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**Abstract:** We show that the Fabry-Perot cavity dynamics of quantum cascade lasers(QCLs) play an important role in the gain recovery observed in a pump-probe experiment. Due to the residual pump power in the cavity after the pump pulse is reflected from the facet, the probed gain recovers at a slower rate.

Pump-probe measurements—based on time-resolved spectroscopy techniques—are an experimental approach that has been used to investigate the complex carrier transport and gain dynamics of quantum cascade lasers (QCLs). The results of pump-probe experiments on mid-infrared QCLs show a very fast initial gain recovery on the order of few hundred femtoseconds, followed by a relatively slow recovery on the order of few picoseconds [1, 2]. The fast recovery in the beginning is attributed to the fast depopulation of the lower lasing level by emitting longitudinal optical phonons and the coherent resonant tunnelling of carriers to the upper lasing level. The following slow recovery tail is attributed to the incoherent scattering transport through the quantum layers, which extracts carriers from the ground level of one period and populates the upper lasing level of the next period. Surprisingly, the slow recovery tail depends significantly on the pump pulse intensity [1]. Liu et al. [1] found that when the pump intensity increases, the gain does not recover to the equilibrium value even on the timescale of tens of picoseconds, and the difference between the recovered gain and the equilibrium value increases as the pump intensity increases. The long recovery tail on the order of tens of picoseconds and the pump intensity-dependent partially-recovered gain cannot be explained merely by the electronic dynamics.

In this work, we show that the Fabry-Perot cavity dynamics of QCLs contribute to the ultra-slow gain recovery or the partially-recovered gain observed in pump-probe experiments. Using a simulation approach similar to a pump-probe experiment, we find that due to a significant reflection of the pump pulse from the facet after a single pass, the probed gain recovers rather slowly, which also depends on the intensity of the pump. In our simulation approach, the QCL is electrically pumped by an external direct current source. The pump and probe pulses are coupled into the QCL cavity through one of the facets. The probe pulse is recorded at the output of the other facet after a single pass. The pump and probe pulses are resonant to the gain medium and are given by

$$E_{\text{pump}} = mE_p \operatorname{sech}\left(\frac{t}{\tau}\right), \qquad E_{\text{probe}} = m\frac{E_p}{M} \operatorname{sech}\left(\frac{t-t_d}{\tau}\right), \tag{1}$$

where m is a variable describing the peak field, Ep is the peak field of the pump pulse when m = 1, M is the ratio of the peak fields of the pump and probe pulses, $\tau$ is the full-width at half-maximum/1.763 pulse duration, and td is the delay of the probe pulse with respect to the pump pulse. In this work, we assume Ep = 3:66× 106 V/m, $\tau$ = 100 fs, and M = 30. We vary m to study the effects of the pump pulse energy on the gain recovery dynamics.

The interaction of the propagating pump and probe pulses with the gain medium can be described by the coupled Maxwell-Bloch equations in an open two-level system approximation given by [3]

$$\frac{n}{c}\frac{\partial E,e_\pm}{\partial t} = \mp\frac{\partial E,e_\pm}{\partial z} - i\frac{N\Gamma dk}{\varepsilon_0 n^2}\eta_{E,e\pm} - lE,e_\pm, \tag{2a}$$

$$\frac{\partial \eta_{E,e\pm}}{\partial t} = \frac{id}{2\hbar}(\Delta_0 E,e_\pm + \Delta_2^\mp E,e_\mp) - \frac{\eta_{E,e\pm}}{T_2}, \tag{2b}$$

$$\frac{\partial \Delta_0}{\partial t} = \lambda + \frac{id}{\hbar}(E_+^*\eta_{E+} + e_+^*\eta_{e+} + E_-^*\eta_{E-} + e_-^*\eta_{e-} - \text{c.c.}) - \frac{\Delta_0}{T_1}, \tag{2c}$$

$$\frac{\partial \Delta_2^\pm}{\partial t} = \frac{id}{\hbar}(E_\pm^*\eta_{E\mp} + e_\pm^*\eta_{e\mp} - E_\mp\eta_{E\pm}^* - e_\mp\eta_{e\pm}^*) - \left(\frac{1}{T_1} + 4k^2 D\right)\Delta_2^\pm, \tag{2d}$$

where E and e denote the envelopes of the electric fields of the pump and probe pulses, respectively, $\eta_E$ and $\eta_e$ denote the dielectric polarizations due to the pump and probe pulses, respectively, Δ0 denotes the population inversion, and Δ2 denotes the inversion grating. The quantities with a +(–) subscript or superscript represent fields that are propagating in the positive (negative) z-direction. The parameter T1 denotes the gain recovery time,

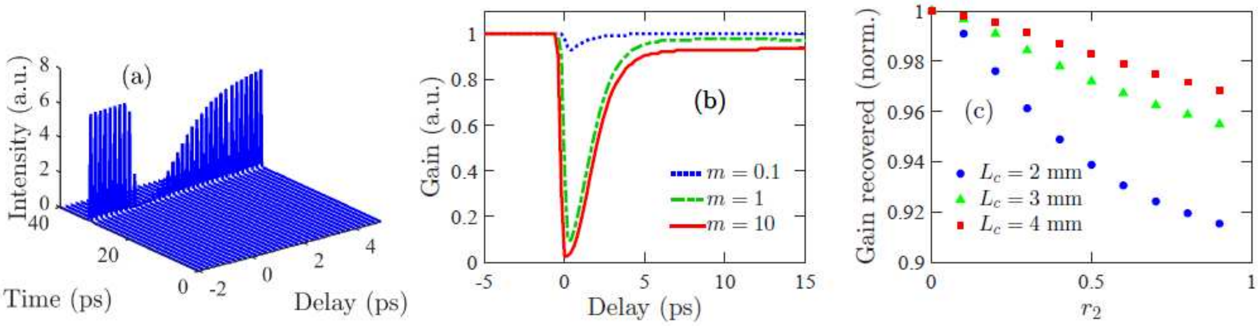


Fig. 1. (a) A sequence of probe pulses at the output as the delay, td , varies. We assume m = 10. (b) Gain recovery dynamics with different intensities of the pump pulse. (c) Recovered gain at td = 25 ps normalized by the equilibrium value with different reflectivities of the output facet for different cavity lengths. In all cases, we assume T1 = 1 ps and s = 1.

T2 denotes the coherence time, l denotes the linear cavity loss per unit length not including mirror losses, and λdenotes the pump parameter. The other parameters have been described in Ref. [3]. The threshold pumping required to overcome the linear loss in the cavity and the losses in the two facets is

$$\lambda_{\text{th}} = \frac{2\varepsilon_0 n^2 \hbar}{N\Gamma d^2 k T_1 T_2 L_c}\left[lL_c + \frac{1}{2}\ln\left(\frac{1}{r_1}\right) + \frac{1}{2}\ln\left(\frac{1}{r_2}\right)\right], \tag{3}$$

where Lc is the length of the cavity, and r1 and r2 are the reflection coefficients of the two facets. The current pumping to the medium can be expressed as λ = sλth, where s represents the strength of the current pumping. We keep s = 1, so that the QCL is operating at threshold.

Now, we solve Maxwell-Bloch equations with the pump and probe pulses injected such that the electric fields are allowed to propagate in both forward and backward directions and reflect from the facets. If the pump pulse is intense and the input current is close to or above the lasing threshold, the reflected pump pulse after a single pass will be intense enough to deplete the gain medium while propagating in the backward direction. In Fig. 1(a), we show the probe pulses at the output after a single pass when the delay of probe pulse varies from −2 ps to 5 ps. The probe pulse experiences the equilibrium gain of the QCL when it leads the pump pulse by more than the duration of the pump pulse. The intensity of the probe pulse decreases sharply when it overlaps with the pump pulse and is minimum when td = 0. With td > 0, the probe pulse experiences a recovering gain medium and the intensity of the probe pulse at the output increases as td increases. The intensity of the probe pulse reaches a steady-state after few picoseconds, although the gain is not fully recovered to the equilibrium value.

In Fig. 1(b), we plot the peak intensity of the probe pulse after a single pass with a variable delay of the probe pulse to the pump pulse, for different values of the pump pulse intensity. While the gain initially recovers exponentially with a time constant T1, the time-resolved spectroscopy also shows a slow recovery tail and a trend of reaching a steady-state less than the equilibrium value. The deviation of the steady-state gain from the equilibrium increases as the pump intensity increases. The decrease of the partially-recovered gain with the increase of the injected pump intensity can be explained from the increase of the reflected and backward propagating residual pump intensity. In Fig. 1(c), we plot the recovered gain normalized by the equilibrium value with a variable reflectivity of the output facet for different lengths of the cavity. We note that the recovered gain decreases when r2 increases, i.e., when the reflected pump intensity is stronger. We also note that the recovered gain decreases for a smaller cavity as the reflectivity makes a more significant part of the total loss in a smaller cavity.

In conclusion, we have shown that the Fabry-P´erot cavity dynamics play an important role in the slow gain recovery of QCLs in a pump probe experiment with intense pump pulses. The pump pulse depletes the gain as it propagates in the forward direction. Furthermore, the pump pulse reflected from the facet may also significantly deplete the gain medium as it propagates in the backward direction. If the gain depletion caused by the reflected and backward propagating pump pulse is significant, the probe pulse experiences a depleted gain medium even it is delayed by tens of picoseconds from the pump pulse. The two-level model used in this work is appropriate to investigate the effects of the cavity in a pump-probe experiment due to the reflection of the pump pulse from the device facets. However, to find a better understanding of the gain recovery immediately after the pump pulsedepletes the gain medium, the QCL should be modelled with a greater number of levels as in Ref. [4].

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**References**

1. S. Liu, E. Lalanne, P. Q. Liu, X.Wang, C. F. Gmachl, and A. M. Johnson, IEEE J. Sel. Topics in Quant. Electron. 18, 92 (2012).
2. H. Choi, L. Diehl, Z.-K. Wu, M. Giovannini, J. Faist, F. Capasso, and T. Norris, Phys. Rev. Lett. 100, 167401 (2008).
3. M. A. Talukder and C. R. Menyuk, Opt. Express 22, 15608 (2014).
4. M. A. Talukder, J. Appl. Phys. 109, 033104 (2011).