How does Such Narrow Linewidth come out from a Quantum Cascade Laser?

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One of the most striking features of quantum cascade lasers is the extremely narrow linewidth of laser output. In fact, the linewidth was observed to be around 10 kHz by a current- and temperature-stabilized mid-infrared laser [1] and as a instantaneous linewidth, less than 30 kHz by a free-running THz laser [2], two or three orders of magnitude narrower than that of conventional bipolar lasers in communication band. However, physics behind the narrowness of the linewidth has not always been clarified so far. The aim of this presentation is to clarify the physical origin for the narrow linewidth.

We restricted the rate equation analysis to a three-level system that consists of the two states, levels 3 and 2, involved in optical transitions, which are characterized by relaxation times, $\tau_r$ ~ psec and $\tau_e$ and the ground state, level 1 which is viewed to be merged to the injector states. By solving the rate equations, one obtains an expression for the laser linewidth in a case where $\tau_e<<\tau_r$ being, as a result of usage of the Einstein relation, simply proportional to the effective coupling coefficient $\beta_{eff} = (\tau/r_e) \beta_i$.

$$\delta f = (F_e\beta_i)/(1+\alpha_e^2) (\tau/r_e) \frac{\beta_i \gamma (P_i/P_{th})}{1}$$

where $F_e$ is the spontaneous emission enhancement factor which is close to unity in a DFB laser cavity with a strong coupling $sL>2$, $\alpha_e$ the linewidth enhancement factor, $\tau_r$ the spontaneous emission life time (10 nsec at mid-infrared and 10 psec at THz), $\beta$ the coupling coefficient of spontaneous emission into a lasing mode (10$^{-3}$ at mid-infrared and 10$^{-1}$ at THz), $\gamma$ the photon decay rate in a cavity, $P_i$ the pump rate, and $P_{th}$ the threshold pump rate. Uses of reasonable numerical values for the physical parameters: $F_e = 1$, $\alpha_e = 0$, $\beta_{eff} = (\tau/r_e) \beta_i = 10^{-7}$, $\gamma = 5 \times 10^{11}$/sec, $P_i/P_{th} = 1.5$ in the expression, result in a very small number for the linewidth, $\delta f = 8$ kHz, which is very close to experimental values [1], [2]. Furthermore, the coupling coefficient $\beta$ is proportional to the optical lineshape function while as a result of the single lobe Lorentzian lineshape, $1+\alpha_e^2$ is proportional to the inverse of the lineshape function. Hence, the key factor, $(1+\alpha_e^2) \beta$ appearing in the above expression does not depend on photon energy. Namely, the linewidth of a QC laser is inherently very narrow, independent of the detuning between gain-peak and DFB-Bragg wavelengths. In other words, the null value of $\alpha_e$ is not necessarily responsible for the narrowness of the linewidth. The remarkably narrow linewidth originates from the extremely short nonradiative scattering time, $\tau_{nr} \sim$ psec, out of the upper state.