A Density-Matrix Model for Photon-Assisted Electron Transport in Quantum Cascade Lasers

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Quantum cascade lasers (QCLs) are coherent sources of light that emit in the terahertz and infrared portions of the electromagnetic spectrum. Different theoretical models with varying levels of detail have been proposed to incorporate the effect of the optical field in the current–voltage-power characteristic of QCLs. Models based on the rate equations and density matrix (DM) often employ empirical or phenomenological parameters to incorporate radiative and nonradiative sources of scattering present in the active region of the QCL [1,2]. This limits their practicality as a modeling tool for the design and optimization of QCLs. The nonequilibrium Green's function (NEGF) technique allows for a methodical treatment of nonradiative scattering mechanisms and the optical field [3]. However, the NEGF method involves numerous matrix products and inversions, which, for a highly resolved (large matrices) calculation, can easily require modern supercomputers [4]. Therefore, there is a need for a numerically efficient quantum-transport model in QCLs that incorporates the effect of the optical field and does not require phenomenologically introduced parameters.

In this paper, we present a quantum-mechanical model for electron transport in QCLs that is computationally efficient, requires no phenomenological parameters, and incorporates the effect of the optical field nonperturbatively [5]. The model is based on a positivity-preserving Markovian master equation of motion for the DM. We use it to obtain the steady-state and frequency-dependent characteristics of a QCL. We show that the photon resonances arising with the inclusion of optical field have a pronounced effect on electron transport around and above the lasing threshold, which leads to better above-threshold agreement between the computed and experimental current densities. The model allows for the inclusion of the lasing field beyond linear response and the calculation of the output power. The calculated power is in close agreement with experiment.

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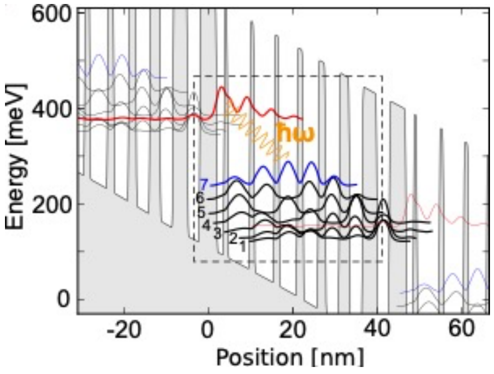

Fig.1: Conduction-band edge and probability densities for the eight eigenstates used in calculations (bold curves) at an above-threshold electric field bias of 50 kV/cm. The states that belong to neighboring periods are denoted by thin gray curves and the dashed box indicates a single stage, starting with the injection barrier. The states are numbered in the order of increasing energy, starting with the ground state; the radiative transition occurs from 8 to 7. (Reprinted from [5])

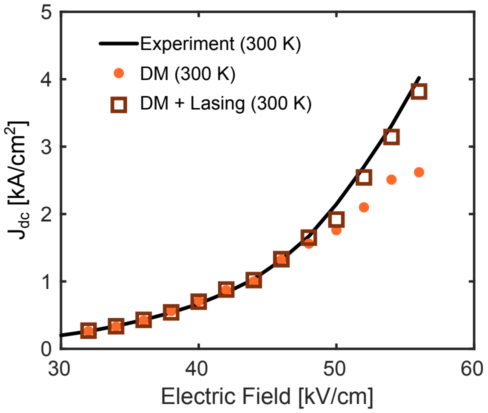

Fig.2: Calculated current density as a function of the applied bias electric field at 300 K, with (open squares) and without (solid circles) the influence of optical field. Experimental data is from Ref. [1]. (Reprinted from [5])

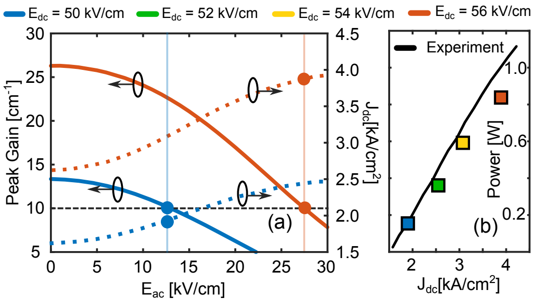

Fig.1: (a) Gain (solid lines) and current density (dotted lines) vs. optical field for E_{dc}= 50 kV/cm (blue) and E_{dc}= 56 kV/cm (red). The horizontal dashed line marks the threshold gain $G_{th} \approx 10cm^{-1}$. At each bias, the intercept of the gain vs. E_{ac} curve with the threshold-gain line determines the ac field where gain and losses compensate, i.e., the operational field. (b) Measured and calculated output power as a function of the current density. Data points are color-coded to indicate the corresponding bias field in the legend (top). Experimental data is from Ref. [1]. (Reprinted from [5])