Dynamics of Photon-driven Electron Transport in InGaAs/InAlAs Quantum Cascade Lasers

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***Abstract*—Femtosecond time-resolved pump-probe experiments are used to investigate gain recovery dynamics and electron transport processes in quantum cascade lasers below and above threshold. The gain recovery has three contributions: the upper and lower lasing state lifetimes, and the superlattice transport time. The upper state lifetime dramatically reduces as a function of bias as the laser threshold is approached from below, due to the onset of quantum stimulated emission. Thus the electronic transport in the device is driven by the intracavity photon density. The transport and lasing in cascade lasers are coupled, and the gain recovery is qualitatively different from that in atomic, molecular, or interband semiconductor lasers.**

I. Introduction

The nature of transport in the presence of oscillating electromagnetic fields (at optical or terahertz frequencies) has been the subject of a number of experiments in the context of superconducting junctions [1], [2] and teraherz-induced tunneling in multi-quantum well structures [3], [4]. In those experiments, the presence of a strong external classical field opened up a new channel, increasing the transport across the device. This phenomenon has been referred to as "photon-assisted transport," although classical fields were used.

In this work, we investigate the transport of electrons through a quantum cascade laser (QCL) below and above threshold. In QCL's, electrons injected into the heterostructure cascade through each stage of the device, ideally emitting one photon via stimulated emission in each active region [5]. Thus QC operation results from a coupling of the perpendicular transport with the intra-cavity optical intensity. By investigating the transport via the gain recovery dynamics in detail near threshold, we have observed the transport of electrons in a QCL driven by the intracavity photon density. Just below threshold, the transport is driven by quantum stimulated emission, with only on the order of 100 photons present in the cavity. Thus the electron transport across the QCL device is "photon driven" through stimulated emission.

II. Experiment and Discussion

The QCL's used in our experiment are based on a 'diagonal transition' where the lasing transition is controlled by tuning oscillator strength through the linear Stark effect [6]. Two QCL's (N-432 and N-433) processed with different

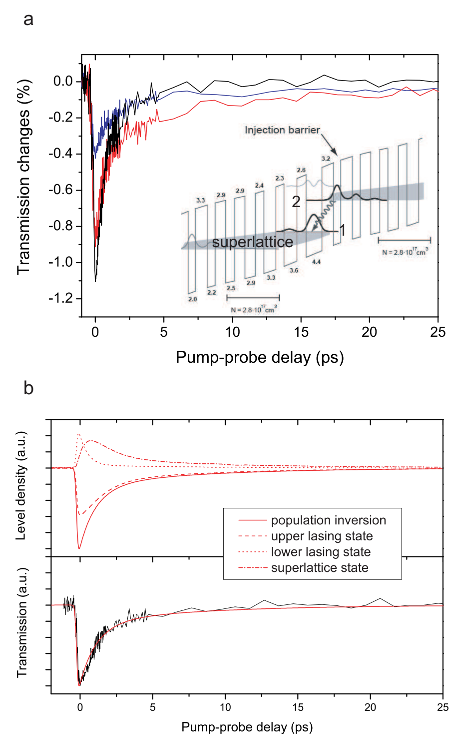

Fig. 1. (**a**) Pump-probe signals measured at 0.4 A (blue), 0.625 A (red), and 0.645 A (black) at 30 K. Threshold currents were 0.637 A for N-432 and 0.763 A for N-433, respectively. Inset: a calculated bandstructure of the QCL used in this study. (**b**) Upper panel: rate-equation analysis for the upper-lasing state (dashed), lower-lasing state (dotted), superlattice state (dash-dot), and population inversion (solid). Lower panel: measured DT signal at 0.635 A (black solid) and rate-equation analysis on the population inversion (red solid) are compared.

cavity length and width were studied. The lasers operated in continuous-wave mode during the experiments. The emission wavelength near threshold and the pump-probe wavelengths were around 5.2 μm. In the superdiagonal laser there is no resonant tunneling injection process for achieving population inversion, and the superlattice connecting adjacent active regions is directly connected to the upper-lasing state.

Our approach to studying the coupling of transport and laser dynamics in QCL is to use time-resolved pump-probe differential transmission (DT) to observe the dynamics of the gain recovery following an impulsive perturbation of the oscillating intra-cavity field. The gain recovery dynamics of operating QCL's are explored below and above threshold, concentrating on the near-threshold region to see the onset of stimulated emission, and the measured dynamics are used to develop a model incorporating rate equations for the QCL level populations coupled to the cavity photon density rate equation. This model is then used to calculate the steady-state light-current-voltage relationships, thus leading to a self-consistent picture of the laser oscillation and transport of electrons.

In Fig. 1(a), selected bias-dependent DT results at 30 K are displayed. For positive pump-probe delay, the DT is negative due to gain saturation induced by the pump. The resulting dynamics show the gain recovery determined by the electron transport through the cascade structure. A three-level rate equation including a coupling to the optical field provides an excellent fit to the measured DT signals (Fig. 1(b)).

The main result of this report is contained in Fig. 2, showing the upper-state lifetime τ_2, obtained from the rate-equation fits of the DT as a function of bias current. Well below threshold τ_2 is determined by the phonon-assisted relaxation to the lower state. As the bias approaches threshold from below, quantum stimulated emission begins to drive the diagonal lasing transition. Since the current through any level in the QC structure is $J = qn_j/\tau_j$, where n_j is the density in level j and τ_j is the state lifetime, we see that as the stimulated emission turns on, the current through the QC structure is driven by the photon emission, and τ_2 becomes the stimulated emission lifetime. The strong variation of the upper state lifetime in the vicinity of the threshold appearing in the gain recovery is due to two factors unique to QCL's. First, unlike traditional lasers, the gain recovery is not determined just by the upper-state lifetime but also by a transport delay through the superlattice which is of the same order of magnitude. Secondly, below threshold the upper state lifetime is almost entirely nonradiative. Due to the large spontaneous emission factor of 10^{-3} measured for these lasers, the stimulated emission rate speeds up rapidly just below threshold; application of the rate equation model to the steady-state L-I characteristics shows that the stimulated lifetime becomes of the order of the nonradiative lifetime (40 ps) with only of the order of 100 photons in the cavity.

In addition to τ_2, two other components are observed in the gain recovery dynamics; results are shown in Fig. 3. The fastest component, τ_1, is approximately 0.7 ps, and corresponds to the decay of lower-lasing state (level-1) due to tunneling across the barrier into the superlattice. This relaxation is bias-independent since the final density of states through the barrier down-stream is always high and nearly independent of bias.

The final component in the DT gain recovery is on the time scale of 1.5 ps and shows a characteristic inverse dependence on the bias current; this component is attributed to the superlattice transport. When electrons tunnel from the lower lasing state into the superlattice following pump-pulse-induced stimulated transitions, a perturbation is induced on

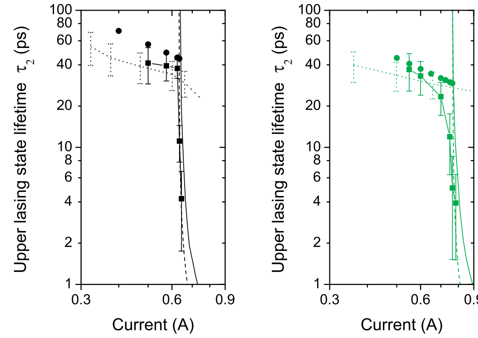

Fig. 2. Bias dependent upper-lasing state lifetime τ_2 for N-432 (left panel) and for N-433 (right panel). Filled squares are DT results from the rate-equation fit. Dotted lines are calculated phonon-assisted lifetime with error bars from monolayer fluctuations. The phonon-assisted lifetime was also calculated from the current continuity relation using the doping density for the population inversion (filled circles). The stimulated emission lifetime was estimated either from a steady-state rate-equation analysis (dash) or measured L-I curve (solid).

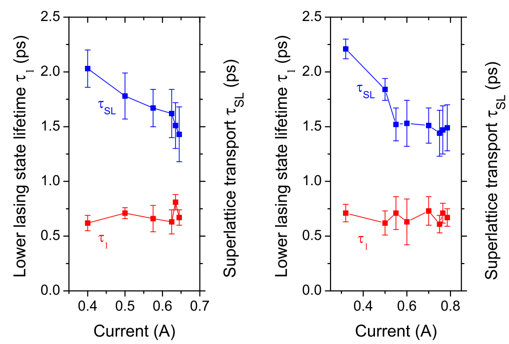

Fig. 3. Gain recovery time constants for QCL N-432 (left panel) and N-433 (right panel). τ_1 (red) is the phonon-assisted tunneling from level-1 into superlattice state and τ_{SL} (blue) is due to the relaxation in superlattice.

the equilibrium electron density profile in the superlattice. The equilibrium carrier density profile is restored in the superlattice in a manner analogous to dielectric relaxation.

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