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HIGH K-SPACE LASING IN EXCITED STATE QUANTUM CASCADE LASERS

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Population inversion is a fundamental property of practically all laser systems. In semiconductor laser devices, charge carrier dynamics are dominated by ultra-fast non-radiative scattering; the fastest of these processes is phonon-mediated scattering within a single energy subband. For semiconductor lasers, the consequence of such ultra-fast intrasubband scattering is that only electron distributions having small wavevectors near $k \approx 0$ are able to achieve relaxation lifetimes sufficient to attain population inversion. Here, we present a quantum cascade (QC) laser structure that achieves population inversion at high k-space values. The laser exhibits two optical transitions that have anti-correlated output power behavior.

The device herein reported is an excited state QC laser, a special class of QC lasers whose optical transitions are composed completely of quantum well excited states [1]. For our QC active region made from two coupled quantum wells, the primary optical transition is between the fifth and fourth active region energy states, while a typical two well active region QC laser would have the optical transition between the third and second energy states. We observe two dominant and distinct optical transitions in spontaneous emission: one at 9.5 μm and one at 8.2 μm. Furthermore, we find these transitions are able to lase simultaneously under appropriate conditions. We identify the 9.5 μm light (transition 1) as originating from the transition between the fifth and fourth active region energy states. The 8.2 μm light (transition 2) originates from a transition between the fourth and second active region energy states.

Transition 1 has properties consistent with a characteristic QC laser transition; the highest output powers and lowest threshold currents are achieved at low temperatures. In contrast, the behavior of transition 2 significantly diverges from this standard behavior. Most strikingly, transition 2 lases with higher power and lower threshold at elevated temperatures (near 100 K), while performance is diminished at lower temperatures. Transition 2 has a higher threshold than transition 1 at low temperatures. A threshold “crossover” is observed between transition 1 and transition 2 near 85 K, whereafter transition 2 turns on before transition 1. At temperatures above the crossover, transition 2 has a characteristic temperature $T_0 \approx 220$ K; below the crossover, $T_0 \approx -64$ K. Furthermore, an abrupt roll-off in transition 2 output power is observed above the crossover and at the transition 1 threshold current, an effect that is more pronounced with higher transition 1 laser power. These anti-correlated properties in threshold and output power are indicative of an interaction between the transition 1 & 2 carrier populations.

We used standard laser rate equations with temperature-dependent parameters to model our excited state system. We find that a sequential transition scheme where both transitions lase from $k = 0$ is not feasible with realistic materials parameters, and the sequential scheme would furthermore not allow for the observed anti-correlated behavior. The data instead suggest a mechanism whereby transition 2 is in competition for charge carriers with and subordinate to transition 1. A high k-space transition 2 explains the observed behavior. When electrons enter the active region, they may either make an optical transition or a non-radiative transition between the fifth and fourth energy levels. The optical transition option is typically the source of QC laser photon generation, and is associated with transition 1 in our device. The non-radiative transition out of the fifth energy state is mediated by phonon scattering, which puts the scattered electrons into the fourth energy subband, but high in k-space. Here, we achieve population inversion high in k-space, and thus we have the source of the transition 2 emission.

[1] K.J. Franz et al., APL, 90, 091104 (2007).