High k-space lasing in a dual optical transition quantum cascade laser

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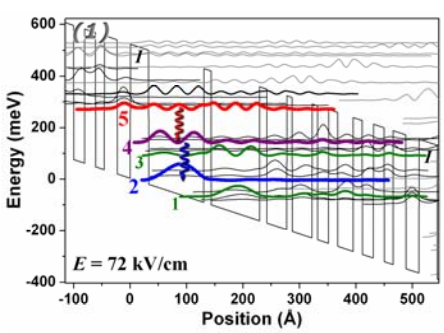
Population inversion between the upper and lower energy states of an optical transition is fundamental to most laser systems. In semiconductor lasers, ultra fast non-radiative transitions from high- to low-*k*-space states within the same energy band mean population inversion is generally only achieved between states at the Γ point, $k = 0$. We report an excited state quantum cascade (QC) laser, shown in Fig. 1, that exhibits lasing from two distinct optical transitions in each QC active region [1]: one at the customary $k = 0$ position (labeled transition 5–>4), and one higher in *k*-space (labeled transition 4–>2) [2], with the two transitions sharing a common, middle energy subband.

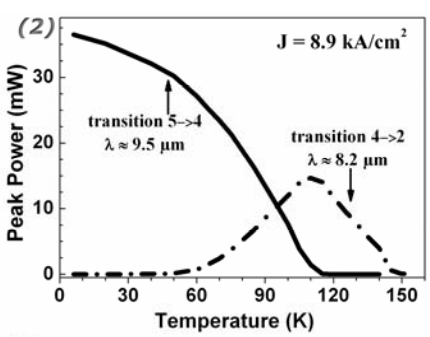
We observe optical transitions at ~9.5 µm (transition 5–>4) and ~8.2 µm (transition 4–>2) [1], each having distinctive temperature-dependent characteristics. Light from the 5–>4 transition shows a behavior typical of a QC laser intersubband optical transition. The highest output power and lowest threshold currents are achieved at low temperatures, as indicated by the solid lines in Figs. 2 & 3. As temperature increases, shorter non-radiative transition times and other processes make population inversion more difficult. Consequently stronger pumping is required to achieve laser action, until a temperature is reached where the laser is unable to reach threshold, in this case near 115 K.

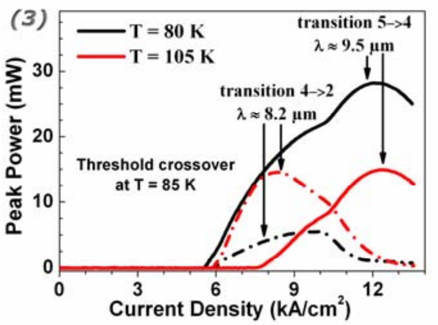
The lower, 4–>2, transition, however, deviates from the standard behavior significantly. Most strikingly, the transition does not lase at low temperature; rather, as shown in Fig. 2, lasing onset is thermally induced near 60 K. Peak output power with constant current density *increases* with temperature to near 115 K, while threshold current simultaneously *decreases*. For temperatures above 115 K, a thermal roll-off in power is observed. The light-current curves in Fig. 3 reveal more: A threshold "crossover" is observed at 85 K, at which point the 4–>2 transition develops a lower threshold than the 5–>4 transition. At temperatures below this crossover, if the 4–>2 transition is lasing, the 5–>4 transition is also lasing. After the crossover and for low pumping rates, a regime exists where only the 4–>2 transition lases. However, as soon as the 5–>4 transition reaches threshold, an abrupt drop in 4–>2 output power is observed.

The mechanism by which the 4–>2 transition behavior is supported is depicted in Fig. 4. Several different electron transport paths between the three subbands can be envisaged; two are labeled *A* and *B*. Path *A* is typical for a QC laser optical transition, where electrons undergo a radiative transition followed by LO phonon scattering. When the 5–>4 transition is lasing, cavity photon densities at 9.5 µm ensure this is the dominant electron path. However, at elevated temperatures, path *B* becomes available with increased LO phonon scattering out of state 5, populating state 4 high in *k*-space. If threshold has not yet been reached for the 5–>4 transition, lasing can then occur at high *k*-space for the 4–>2 transition. If at any time path *A* turns on, path *B* and therefore 4–>2 population inversion is quenched because (1) fewer electrons are available to populate the upper state of the 4–>2 optical transition and (2) electrons are injected into the lower state of the 4–>2 optical transition. The two transitions are thus anti-correlated, in that for any given set of operating conditions, one transport path will always be preferred. Results of standard rate equation modeling are consistent with the observed behavior.

In conclusion, we have presented a QC laser that exhibits emission from two separate optical transitions, one being high in *k*-space. The two optical transitions result from two different electron transport paths, one of which will be preferred over the other for a given set of operating conditions.







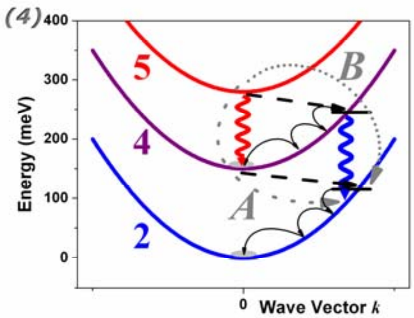


Fig. 1. The conduction band diagram of QC laser herein reported. Details of the structure are available in Ref. (1). Optical transitions are indicated by squiggly arrows.

Fig. 2. Peak output power of each optical transition with varying temperature and a constant pumping current density of 8.9 kA/cm^2.

Fig. 3. Light-current curves for each optical transition at 80 K and 105 K. A "crossover" in transition thresholds occurs at 85 K, where the 4->2 transition achieves a lower threshold than the 5->4 transition.

Fig. 4. A schematic representation of the high k-space lasing herein described. The three subbands 5, 4, and 2, shown in Fig. 1, are mapped into k-space. Electrons can flow through path A or path B.

[1] K.J. Franz, et al., Appl. Phys. Lett. **90** 091104.
[2] S. Menzel, K.J. Franz, et al., *in preparation*.