Intersubband spectroscopy of electronic and optical processes in quantum cascade lasers under operating conditions: experiments and theory

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Although quantum cascade lasers (QCLs) have recently achieved tremendous improvements in their performance, there remains significant scope for detailed investigations of QCL physics, particularly the intersubband energy distribution of electrons in functioning devices. Here we present results from a new intersubband transmission technique which is potentially very informative for such studies. The first results on the detailed spectroscopic investigation of electrically induced optical transmission changes in QCLs under operating conditions over a wide temperature range will be discussed.

The broadband thermal “globar” emission from the FTIR spectrometer was used as the incident light. This emission was focused precisely onto one facet of the QCL under investigation and only the light transmitted through the waveguide was collected from the other side of the laser ridge and detected with a cooled HgCdTe detector. This technique allows spectroscopic study of light transmission through the waveguide of QCLs in the very broad spectral range (λ~1.5-12 µm) which is limited only by the detector response and by the interband absorption of the materials used in the QCL core region. The QCL was mounted in a helium cryostat and spectra were studied as a function of cw bias (up to laser threshold) and temperature. The transmittance spectra were measured for incident light with polarization both in-plane (TE) and perpendicular to the layers (TM).

The lasers investigated here were based on the lattice matched InGaAs/InAlAs/InP material system and emit at λ~7.7 µm. The transmittance spectrum for TE light reveals the waveguide properties of the lasers, while the intersubband transitions within the QCL active regions are probed by TM polarized incident radiation. Very marked changes of intensity and position of absorption peaks have been observed for TM polarization at different drive currents through the QCLs. These measurements clearly show the depopulation of the lower laser levels as bias is increased, the onset and growth of optical amplification at the energy corresponding to the laser transition as current is increased towards threshold, and the thermal filling of the second laser level and decrease of material gain at high temperatures. This technique also allows direct determination of key parameters such as the temperature of the laser core region, the modal gain coefficient and waveguide loss, thus providing a unique, comprehensive picture of electronic and optical processes occurring in these devices under operating conditions.

A nonequilibrium Keldysh Greens Functions theory has been applied to the description of the experimental data. The approach is fully microscopic and treats the main scattering and dephasing mechanisms by means of selfenergies. Excellent agreement is obtained for the evolution of absorption/transmission spectra as a function of applied voltage. No phenomenological fit parameters are necessary demonstrating the predictive power of our algorithms.