High temperature, magnetic field assisted (sub)THz quantum cascade laser

High Temperature, Magnetic Field Assisted (sub)THz Quantum Cascade Laser

Aaron Wade, Georgy Fedorov, Dmitry Smirnov
National High Magnetic Field Laboratory, Tallahassee, FL 32310
smirnov@magnet.fsu.edu

Benjamin S. Williams
Electrical Engineering Department and CNSI, University of California at Los Angeles, California 90095

Sushil Kumar, Qing Hu
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

John L. Reno
Sandia National Laboratories, Department 1123, MS 0601, Albuquerque, New Mexico 87185-0601

Abstract: We demonstrate magnetic field assisted, (sub)THz quantum cascade laser operating above 200K. This is achieved through the application of strong magnetic fields which provide an additional lateral confinement in order to suppress non-radiative intersubband scattering.

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A quantum cascade structure is a general concept of an optoelectronic device (laser, LED, frequency mixer, or detector) based on a cascade of radiative transitions between size-quantized energy levels in a multi-quantum-well structure. Today, Quantum Cascade Lasers (QCLs) are the only semiconductor devices operating from the mid-infrared (MIR) to the THz range of frequencies. The motivation to push QCLs to longer wavelengths and to higher operational temperatures is driven by their potential for remote sensing and imaging, spectroscopy, and communications. THz QCLs now cover the frequency range from 1.2 THz to 5 THz, though cryogenic cooling is still required [1]. Progress towards the realization of sub-THz and/or high temperature QCL's operation becomes exceedingly difficult because it requires the necessary population inversion between closely spaced electronic subbands (1 THz ~ 4 meV) to be achieved.

The similar energy and size scales of spatial and magnetic confinements allows the application of an external magnetic field to be an experimental tool to control processes that determine the performance of QCLs – quantum confinement and intersubband relaxation [2]. A magnetic field changes the 2D parabolic energy dispersion of each size-quantized subband $\varepsilon_n(k)$ into a set of discrete, equidistant, 0D-like, Landau levels (LLs), $\varepsilon_{n,N} = E_n + (N + 1/2)\hbar\omega_c$, separated by the cyclotron energy $\hbar\omega_c = \hbar eB/m^*$, where n is the subband index, N is the LL index, B is the magnetic field, and m^* is the electron effective mass. As a result, both radiative and non-radiative transitions are either reduced or resonantly enhanced by the inelastic (LO-phonon assisted) or (quasi)-elastic (interface roughness, acoustical phonons, or impurities) scattering between different LL states $|n,N>$. Here we exploit this approach of "Landau level engineering" to explore the ultimate limits of THz QCL operation.

We studied $GaAs/Al_{0.15}Ga_{0.85}As$ THz QCLs based on "resonant-phonon" design scheme [3]. The optical and electrical characteristics (current density J, voltage/period V, optical power P as well as emission spectra) were recorded as a function of the magnetic field applied perpendicular to the plane of the quantum wells.

At $B=0$ T and designed bias of ~53mV/period (Fig. 1a), the laser transition takes place between levels |6> and |5> ($E_{6,5} \approx 13$ meV or 3.1 THz) followed by a fast, LO-phonon assisted relaxation towards the triplet ground states:|3>, |2>, and |1>. At strong enough magnetic fields, it becomes possible to increase voltage bias above 60 mV/period. Here the separation of levels |5> and |4>,and levels |8>, |7>, and |6> is possible while maintaining a large dipole-matrix element, resulting in the possibility for different laser transitions. Applying appropriate electrical bias and magnetic field, we achieved laser emission in an unprecedented range of frequencies from 0.68 THz to 3.33 THz (Fig. 1b). In a narrow range of magnetic fields about 20 T, we observed strong dual-frequency lasing (0.97 THz and 3 THz) that originates from the simultaneous emission from two cascaded optical transitions in each QCL period. The detailed description of different magnetic field assisted lasing regimes can be found in ref. 4.

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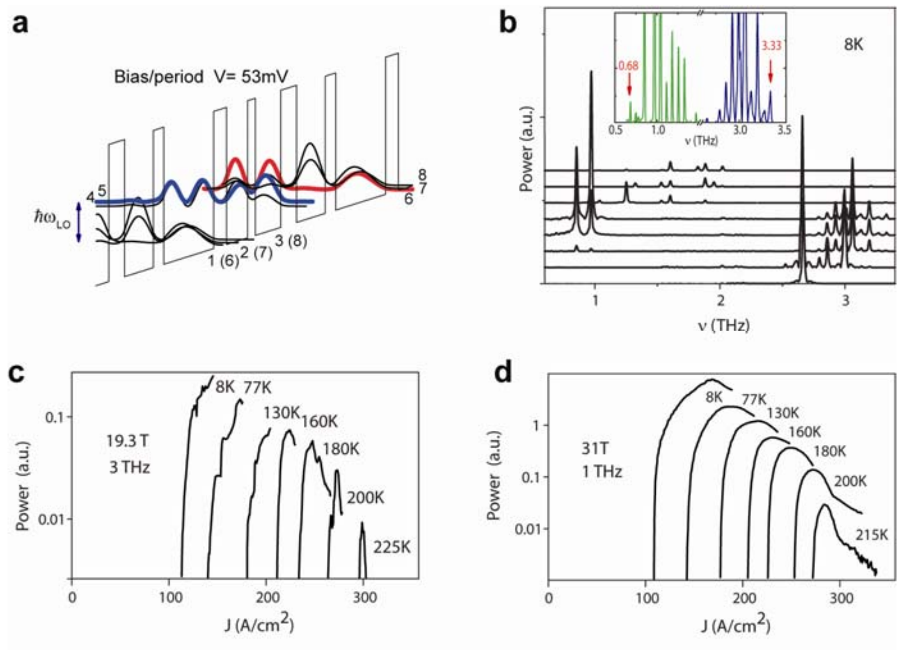

Fig. 1. **(a)** Conduction band diagram and squared wavefunctions at 53mV/period, zero B-field operational bias. Levels 3,2,1 are 8,7, 6 for the next period. **(b)** Spectral coverage of the QCL device with increasing voltage bias and magnetic field (bottom curve 54.9mV/period, 13T; top curve 88.4mV/period, 25T). The inset shows the QCLs spectral extremes: 0.68THz (69.9mV /period, 31.2T) and 3.33THz (63.9mV/period, 19T). **(c,d)** Temperature dependence of P(J) at two enhanced lasing positions at 19.3T and 31T. 1THz lasing has been omitted from the 19.3T curves for visual clarity.

Finally, we measured the temperature dependence of QCL emission (Fig.1c,d). Magnetic field assisted lasing continues up to 215K for 1 THz emission (31T), and 225K for 3 THz (19.3T). This is the longest wavelength, the widest spectral coverage, and the highest operational temperatures of any single THz solid state laser to date [1, 4]. Furthermore, these results demonstrate that additional lateral quantum confinement (i.e. a quantum box), is a route to higher temperature operation for THz QCLs.

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