

Terahertz quantum cascade laser in a quantizing magnetic field

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Received July 17, 2025

Revised September 23, 2025

Accepted September 23, 2025

Transport and emission characteristics of a quantum cascade laser with a „resonant-phonon“ design with an emission frequency of 2.3 THz in high magnetic fields up to 11.5 T at liquid helium temperature were studied experimentally and theoretically. In the 5–6 T magnetic field range, suppression of generation was observed due to „resonant“ scattering from the zero Landau level (associated with the upper laser level) to the first Landau level (associated with the lower laser level) leading to a reduction in the population inversion of the working transition of the laser. A threefold decrease in the laser's threshold current was demonstrated under a strong magnetic field up to 11.5 T (compared to the zero field), attributed to the zero-dimensional nature of electron states, which suppresses parasitic scattering.

Keywords: quantum cascade laser, terahertz range, current-voltage characteristics, emission characteristics, strong magnetic field.

DOI: 10.61011/SC.2025.07.62475.8378

1. Introduction

The possibility of amplification and generation of electromagnetic radiation by a superlattice of quantum wells (QW) when passing an electric current was predicted more than 50 years ago in the study of R.F. Kazarinov and R.A. Suris [1]. This idea stimulated many years of research efforts at Bell Labs, which led in 1994 to the creation of the first quantum cascade laser (QCL) [2]. QCL lasers are currently superior in efficiency to mid-IR diode lasers and are used in many industrial and scientific applications [3].

The efficiency of QCL is fundamentally limited by a wide spectrum of two-dimensional subbands and the corresponding free movement of electrons in the QW plane. The wide spectrum leads to rapid nonradiative recombination of electrons from the upper to the lower operating subband due to the emission of phonons, the rate of which significantly exceeds the rate of radiative recombination. As a result, the population inversion required for laser operation can only be achieved at a sufficiently high threshold current, reaching several kA/cm² [2]. The two-dimensional nature of the electron spectrum in the QW also leads to strong absorption by free carriers and corresponding losses due to the current excited by the electric field component in the plane of the laser mode. It was proposed in Refs. [4,5] to use superlattices of quantum dots to create QCL, a purely discrete spectrum of which would significantly reduce the

rate of nonradiative recombination, optical losses, and the QCL threshold current (up to ~ 10 A/cm²). However, even attempts to partially implement this idea (a structure with quantum dots in QW) did not lead to the expected result (see, for example, [6]).

The „zero-dimensionality“ of the electronic spectrum can also be achieved in ordinary QCL by applying a quantizing magnetic field, the induction vector of which is directed perpendicular to the layers of the structure. In this context, „zero-dimensionality“ refers to the case when the cyclotron energy exceeds the energy of the QCL radiation quanta and radiative transitions occur between the zero Landau levels related to the upper and lower operating levels of the laser. Naturally, in order to form such a discrete spectrum, cyclotron energy must be many times greater than the width of the Landau levels. The first studies of the influence of the magnetic field on the operation of lasers were performed in relation to the mid-infrared (IR) range, where, when the pulsed magnetic field was expanded to 60 T, oscillating dependences of the intensity of laser radiation on the magnetic field were observed (outwardly sometimes resembling the Shubnikov-de Haas oscillation), which was associated with the dependence of the lifetime at the upper laser level on the magnitude of the magnetic field [7,8] (see also Ref. [9]). At the same time, the intensity of the QCL radiation was many times higher at the maxima of the oscillations than the signal at

$B = 0$. However, such magnetic fields are not sufficient to reliably fulfill the condition of „zero-dimensionality“ of the spectrum of electronic states in QCL of the mid-IR range of $\hbar\omega_c \geq \hbar\omega$. Here \hbar is the Planck's constant, and $\omega_c = eB/m^*c$ is the cyclotron frequency of electrons, e is the charge of an electron, c is the speed of light. For $\hbar\omega = 100$ meV and the typical value of the effective mass in GaAs QW $m^* = 0.069m_0$ [10] (m_0 is the mass of a free electron), this estimate gives $B \geq 60$ T. At the same time, for the terahertz range QCL, where the quantum energies are an order of magnitude lower, the condition of the spectrum „zero-dimensionality“ can be fulfilled in stationary magnetic fields accessible using superconducting solenoids. Since the creation of THz QCL, a number of studies have been carried out on their characteristics in magnetic fields (see, for example, [10–20]). Oscillations of the intensity of radiation versus the magnetic field have already been observed in permanent magnetic fields up to 6 T [10–15]. In subsequent works, the main attention was paid to switching generation to transitions between other subbands under the influence of the magnetic field [16–20]. The effect of a magnetic field up to 5 T on the emission characteristics of various QCL in the 3.3–3.7 THz range with a „resonant-phonon“ design was studied in our recent paper [21]. In the present work, a lower-frequency (2.3 THz) QCL was studied in magnetic fields up to 11.5 T, for which the effects of magnetic quantization are more pronounced.

2. Experimental methodology and calculations

A QCL with an active region based on four tunnel-coupled GaAs/Al_{0.15}Ga_{0.85}As quantum wells in the period of the structure with a resonant-phonon depopulation scheme of the lower laser level was studied. The thicknesses of the layers, starting from the injection barrier, were 3.39/9.61/5.65/8.19/3.11/7.06/4.24/16.10 in nm (GaAs QW are shown in bold). Wide (16.10 nm) GaAs QW were doped with a donor Si impurity with a concentration of $1.9 \cdot 10^{16} \text{ cm}^{-3}$. The structure with a total thickness of $\sim 10 \mu\text{m}$ was grown by the method of molecular beam epitaxy by Yu.G. Sadofiev. Next, laser strips with a metal-metal waveguide were manufactured using the technology described in Ref. [22]. The Fabry-Perot resonator was formed by chipping a metal-metal waveguide, which makes it possible to form mirrors on the chipped facets. The width of the ridge of the studied QCL was $100 \mu\text{m}$, the length of the ridge was 2.4 mm. The laser was mounted on a copper heat sink of the C-mount type, several gold wires with a diameter of $30 \mu\text{m}$ were welded to the upper metal contact, evenly distributed along the entire length of the strip for uniform current injection. For measurements in magnetic fields of up to 5 T the QCL, as in Ref. [21], was placed in a liquid helium cryosta at a temperature of 4.2 K in the center of a superconducting solenoid. The laser was oriented so that the magnetic field was perpendicular

to the layers of the structure (parallel to the current) and the radiation went out in a direction perpendicular to the magnetic field. To output the radiation from the cryostat it was directed using a mirror through a light pipe made of a polished stainless steel tube. The radiation was recorded using a cryogenic Ge:Ga photodetector positioned outside the magnetic field of the solenoid, or it was channeled into a Bruker Vertex80v Fourier spectrometer to record the radiation spectrum. In this case, Ge:Ga was also used as a photodetector, placed in a light pipe insert in a Dewar transport helium vessel STG-40. In stronger magnetic fields, up to 11.5 T, QCL was placed in the Optistat PTR cryostat insert, which was placed in the „warm“ hole of the cryostat of the Cryofree Superconducting Magnet superconducting solenoid from Oxford Instruments. In this case, the QCL positioned in a heat exchange gas — helium at a temperature of ~ 4 K. In this case, the magnetic field was perpendicular to the layers of the QCL structure. The laser radiation was recorded by a nearby impurity photodetector Ge:Ga, oriented in such a way that the photodetector current was parallel to the magnetic field. The latter excluded the complete suppression of sensitivity by a strong magnetic field, but led to its oscillations and a multiple decrease with an increase in the field [23]. The QCL characteristics were measured in pulse mode (pulse duration was several microseconds, repetition rate was 40–100 Hz).

The band spectrum, amplification and generation spectra were calculated on the basis of a system of balanced equations for localized states with periodic boundary conditions [24–26]. The basic wave functions were determined using the $\mathbf{k} \cdot \mathbf{p}$ -method [25,26] followed by a special transformation to account for dephasing [24]. The transition probabilities were calculated taking into account changes in the density of states in the magnetic field, and the processes of tunneling, scattering by optical phonons, charged impurities, and roughness of heterogeneities were taken into account for

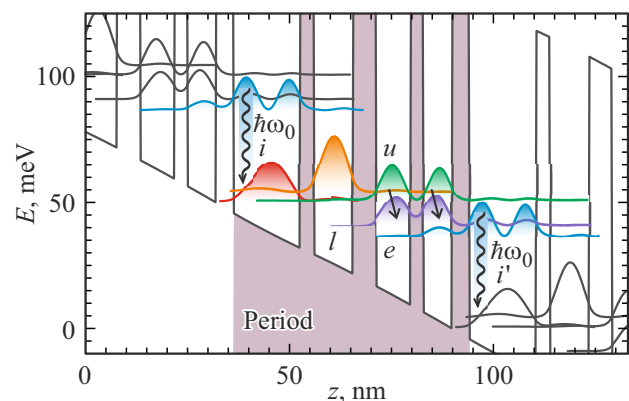


Figure 1. Diagram of the conduction band and squares of the moduli of the wave functions of the electrons of the studied QCL, calculated by the $\mathbf{k} \cdot \mathbf{p}$ method at a temperature of $T = 55$ K and voltage over the period of the structure $V = 50$ mV. The straight arrows indicate the radiative transitions, $\hbar\omega_0$ is the energy of the longitudinal optical phonon.

RMS fluctuations in the thickness of layers 0.3 nm and the correlation length between inhomogeneities in the plane of layers 9 nm. Scattering by acoustic phonons was neglected. In this case, approximate matrix elements of interactions were used, calculated at a zero magnetic field for the energies of the initial and final states corresponding to the energies of the Landau levels. Figure 1 shows a diagram of the conduction band calculated in a zero magnetic field and the squares of the moduli of the electron wave functions at a temperature of $T = 55$ K and a voltage over the period of the QCL active region of $V = 50$ mV. The straight arrows indicate the radiative transitions. The upper laser level (u) for efficient electron transfer between cascades is tunneled to the injector level (i). The lower laser level (l) is tunneled to the extractor level (e), which, for effective depletion, is separated by the energy of the longitudinal optical phonon $\hbar\omega_0$ from the level of the injector (i') of the next period. The temperature of the charge carriers was assumed in the calculations to be equal to the temperature of the crystal lattice.

3. Results and discussion

Figure 2 shows the measured dependences of the integral radiation intensity on the magnetic field up to 5 T at different currents. It can be seen that generation occurs only when a magnetic field is applied at currents 1 A and 1.1 A, i.e. they are less than the threshold current in a zero magnetic field. At all currents, the radiation is strongly suppressed when approaching the magnetic field 5 T, in addition, at various currents, a minimum is visible at $B = 2.8$ T. The insert to Figure 2 shows the emission spectra in the zero magnetic field and in the 3.75 T field. It can be seen that the application of the field does not change the generation frequency of 2.31 THz ($\hbar\omega = 9.54$ meV), i.e., transitions occur between the same operating levels.

Additional measurements of the radiation spectra in a closed-loop optical cryostat in a zero magnetic field showed that generation persists up to $T = 105$ K. The observed dependences of the radiation intensity on the magnetic field are naturally associated with the relative position of the Landau levels belonging to the upper and lower laser levels. When the n -th Landau level belonging to the lower laser level, intersects the zero Landau level belonging to the upper laser level, scattering mechanisms on impurities, defects and interface irregularities are activated, leading to depletion of the upper laser level and decrease of inversion. This effect should be most pronounced for $n = 1$ at $B = \hbar\omega m^* c / e = 5.6$ T ($m^* = 0.069m_0$ is the effective electron mass in GaAs [10]), which taking into account the finite widths of the levels corresponds well to the observed suppression of the QCL radiation intensity when approaching 5 T (Figure 2). The observed minimum of the radiation intensity at $B = 2.8$ T corresponds to the case of $n = 2$. Similar minima of radiation intensity during the magnetic field sweep

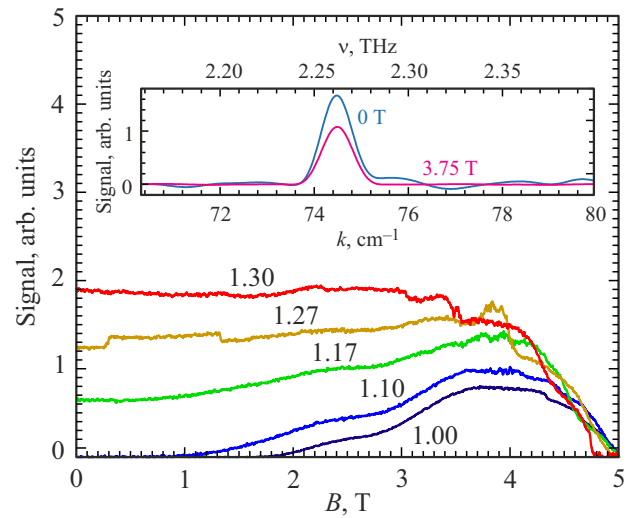


Figure 2. Dependences of the integral intensity of the QCL radiation on the QCL magnetic field at different operating laser currents (in A). $T = 4.2$ K. The insert shows the emission spectra of QCL in a zero magnetic field and at $B = 3.75$ T.

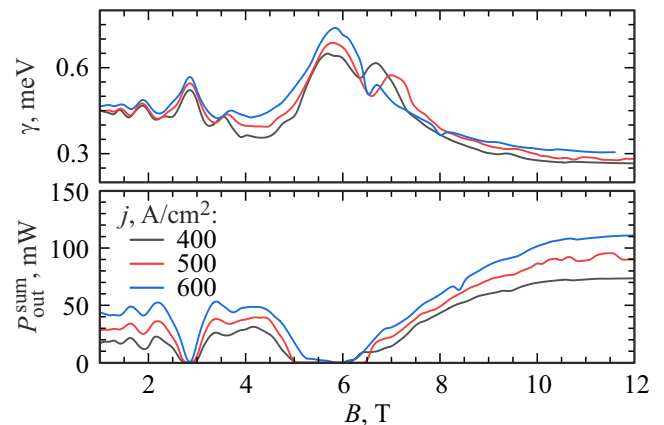


Figure 3. Calculated QCL generation power (lower panel) and reverse electron lifetime at the upper laser level (u in Figure 1) in energy units γ (upper panel) depending on the magnetic field at different densities current.

for the cases $n = 2, 3$ were observed earlier and for other THz QCL [21].

It is of interest to study the effect of a stronger magnetic field on the radiative characteristics of the QCL. Figure 3 (bottom panel) shows the calculated dependences of the radiation power of a given QCL on the magnetic field up to 12 T. As can be seen from the figure, the calculation predicts complete suppression of generation in fields from 5 to 6 T (case $n = 1$) and deeper minimum at 2.8 T in comparison with the experiment (case $n = 2$). A minimum is also visible near 2 T, which obviously corresponds to $n = 3$. The calculation predicts a multiple increase in the radiation power in 10–12 T fields compared to the power in weak magnetic fields. A decrease in the intensity of laser radiation in „resonant“ magnetic fields correlates with

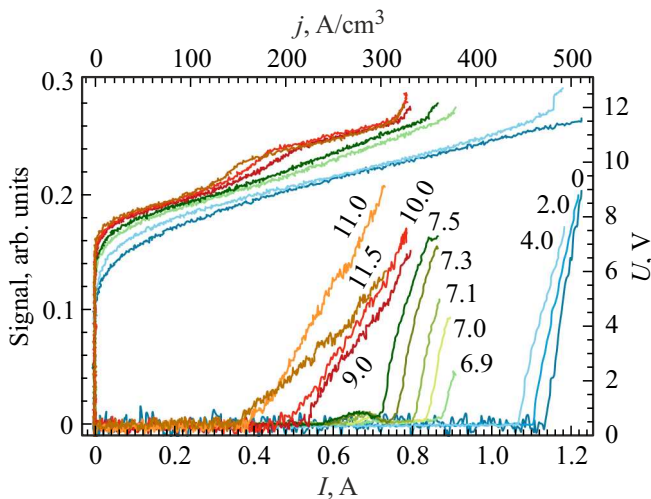


Figure 4. I - V and L - I -characteristics of QCL in various magnetic fields (in T). The signal level (L - I -characteristics) in magnetic fields of 0–4 T is reduced by 3 times.

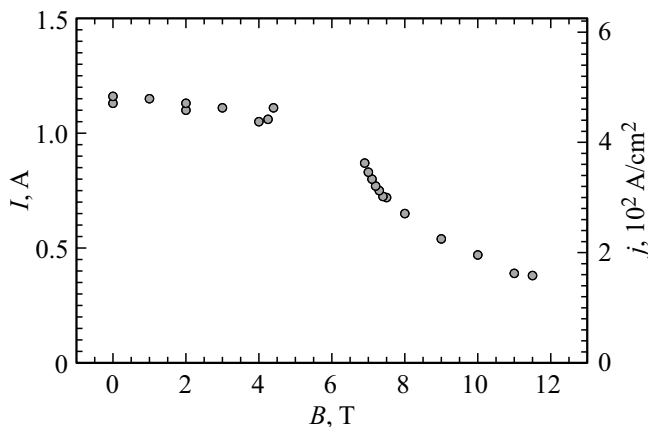


Figure 5. Dependence of the QCL threshold current on the magnetic field.

a decrease in the calculated lifetime at the upper laser level (u in Figure 1) — the upper panel in Figure 3. The corresponding scattering frequency (inverse lifetime) in energy units at maximum at $B = 5.75 \text{ T}$ is $\sim 0.7 \text{ meV}$, which is apparently less than the actual width of the Landau level, which is also determined by the frequency of „intra-level“ scattering. Ref. [9] provides an estimate of the width of the Landau level in the QCL structure of the THz range in the case of a strong magnetic field $\Delta E \approx \delta B^{1/2}$, where $\delta = 1 \text{ meV/T}^{1/2}$. For a magnetic field of 9 T, this estimate gives a Landau level width of 3 meV, which is several times less than the energy of the quantum of radiation QCL, and allows talking about the formation of a discrete spectrum in the active region of the laser.

Figure 4 shows the results of studies of the QCL in the Oxford Instruments closed-cycle cryomagnetic system in magnetic fields up to 11.5 T. The I - V characteristic clearly shows that the „switching on“ of current becomes

sharper in strong magnetic fields ($B > 7 \text{ T}$), which indicates a narrowing of the levels of size quantization through which charge carrier transport occurs. In the strongest magnetic fields (10–11.5 T), characteristic fractures are observed on the I - V characteristic (at currents of 0.4–0.45 A), corresponding to the moments of occurrence of stimulated radiation. Such fractures of the I - V characteristic, caused by the acceleration of current transfer due to the radiative transitions of electrons between the operating levels of the laser, indicate a sufficiently high quality of the laser structure [27].

As can be seen from the family of L - I -characteristics in magnetic fields of 0–11.5 T shown in Figure 4, a significant, almost threefold decrease in the QCL threshold current occurs with an increase in the magnetic field. These data are presented in more detail in Figure 5, where it can be seen that the threshold current varies slightly to the „resonance“ region $\hbar\omega_c \sim \hbar\omega$ ($\omega_c = eB/m^*c$ is the cyclotron frequency) in the fields of 5–6 T, where generation is not observed, and then decreases rapidly with the field, which is obviously due to the zero-dimensionality of states in the magnetic field and the expected suppression of parasitic scattering and an increase in the lifetime of carriers at the upper laser level. As can be seen in Figure 4, in magnetic fields of 7–7.5 T, a „bump“ of laser radiation is observed in the current range of 0.6–0.7 A „preceding“ the QCL current thresholds. Judging by the differential resistance of the QCL in this current range, a current change of 0.1 A leads to a voltage change over the period of the structure by $\sim 3 \text{ mV}$. As follows from Figure 1, this value of the voltage change is close to the characteristic distances between the levels of dimensional quantization in the „active“ region of the QCL structure period, in particular, between the lower laser level l and the extractor level e . With such a change in current, generation apparently switches from one pair of levels to another (in the general case, generation is possible not only at transitions $u \rightarrow l$, but also at junctions $i \rightarrow l$ and $u \rightarrow e$), which also leads to generation at currents below the „true“ threshold value.

4. Conclusion

Thus, for a QCL with a „resonant-phonon“ design operating at a frequency of 2.3 THz, suppression of generation near a resonant magnetic field ($\hbar\omega_c \sim \hbar\omega$) was demonstrated due to „switching on“ of scattering from the zero Landau level, pertaining to the upper laser level, to the first Landau level, pertaining to the lower laser level, and by suppressing the transition inversion. It is shown that the application of a high magnetic field up to 11.5 T leads to a threefold decrease in the threshold current due to the nullification of electronic states and a decrease in parasitic scattering.

Funding

The study was supported by the NCPM (project „Studies in high and ultra-high magnetic fields“ — studies of $I-V$ characteristics, $L-I$ - and $L-B$ -characteristics of the QCL) and grant of the Russian Science Foundation No. 23-19-00436 (calculations of the band structure and QCL radiation characteristics in high magnetic fields). Post-growth operations for the manufacture of QCL were carried out with the financial support of the state assignment of the National Research Center „Kurchatov Institute“. Measurements of the QCL radiation spectra were performed using the equipment of the Common research center „Physics and Technology of Micro- and Nanostructures“ IPM RAS.

Acknowledgments

The authors are grateful to D.A. Shmyrin for his help in automating measurements of QCL characteristics in strong magnetic fields.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by A.Akhtyamov