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High-power tunable quantum-cascade laser

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The studies of the quantum-cascade laser (QCL) in an external resonator in the Littrow configuration with an output power of up to 1.5 W were carried out. It was shown that the used scheme of the external resonator allows obtaining single-frequency generation with continuous tuning of more than $100\,\mathrm{cm}^{-1}$ without antireflection coatings at the QCL facets.

Keywords: integrated optics, quantum cascade laser.

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The development of gas analysis methods in the mid-infrared range is a key factor in further study and improvement of quantum cascade lasers (QCLs), which have been proposed as a concept back in 1971 by Suris and Kazarinov [1] and first implemented in practice in 1994 by Capasso et al. [2]. Considerable progress in their design has already been achieved. Specifically, the output pulse powers in excess of 200 W [3] were obtained within the $4-5\,\mu$m spectral range, and an efficiency over 20% was demonstrated in the continuous mode with an output power exceeding 5 W [4]. The progress in design of long-wave QCLs with a lasing wavelength above $7\,\mu$m is also obvious: pulse powers exceeding 15 W [5,6] and an efficiency higher than 10% at an output power in excess of 1 W in the continuous mode [7] have already been achieved.

However, a number of QCL applications involving substance detection in the mid-infrared range require a narrow emission spectrum for identifying the target spectral line [8] with closely adjacent absorption lines of various substances. In addition, remote chemical monitoring and hyperspectral imaging require spectral tuning within a significant range [9]. Although certain applications do not impose strict requirements on the lasing spectrum of tunable QCLs [10], single-frequency lasing of tunable QCLs is needed in most scenarios (specifically, hyperspectral imaging [11]) to provide the necessary spectral resolution of measurements. At the same time, single-frequency tunable QCLs with a relatively high output power (to compensate for losses associated with diffraction divergence and scattering of radiation propagating over a significant distance in the atmosphere) are needed in order to ensure sufficient sensitivity of systems for remote chemical detection and industrial safety systems.

At present, the leading approach to construction of high-power QCLs tunable within a wide spectral range is the use of an external cavity containing a spectrally selective element. Both cavities with a grating in Littrow or Littman configurations and cavities based on acousto-optic modulators are viable options here [12]. The widest reported range of spectral tuning of QCLs with an external Littrow cavity is $900-1300\,\mathrm{cm}^{-1}$ with an output peak power up to 0.75 W [13]. The maximum continuous lasing powers were also obtained in this configuration [14]. The classical Littrow configuration used in these studies has a disadvantage in that a diffraction grating is positioned at the front coated output facet. Radiation is output in this case in the zero diffraction order, and the direction of its propagation changes when the cavity is tuned by rotating the grating.

In the present study, we report the results of study of a QCL with an external Littrow cavity positioned at the back output facet of the QCL. QCL chips used in the external cavity were fabricated from a structure with a strain-balanced active region based on three types of solid solutions: $\mathrm{Al_{0.63}In_{0.37}As/Ga_{0.35}In_{0.65}As/In_{0.53}Ga_{0.47}As}$ [6,15]. This heterostructure was chosen for its wide gain spectrum, which is illustrated well by the lasing spectra of four-cleaved samples [15] that extend from 6.9 to $8.1\,\mu$m. The heterostructure was subjected to standard post-growth processing [16]. Ridge waveguides of the QCL were formed

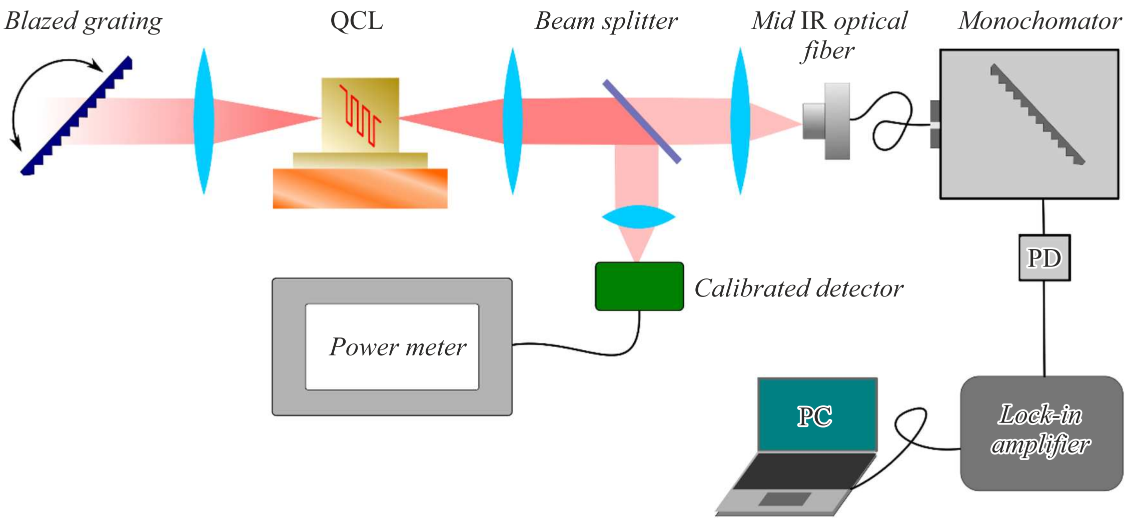

Figure 1. Schematic diagram of the setup for study of the characteristics of a tunable QCL with an external cavity in the Littrow configuration.

by etching two trenches through the active region. The post-growth processing procedure was discussed in more detail in [17]. The width of stripes of the used QCL chips was 16 μm, and their length was 5 mm, which corresponded to the heat sink length and provided free access to the output facets. The output facets were formed by cleavage along the crystallographic axes and were not processed in any way. Chips were mounted on a copper heat sink with the epi-side down (this provided better dissipation of heat from the active region). The QCL temperature was stabilized at 298 K by a thermoelectric cooler. The QCL characteristics were examined in the pulse mode. The pump pulse duration was 100 ns at a repetition rate of 48 kHz.

Radiation output from the back QCL facet was collected by an aspherical lens with a numerical aperture of 0.75, which was made of a germanium alloy, and collimated onto a feedback diffraction grating with a blaze angle in the first order and a spacing of 150 mm^{-1}. The working surfaces of the collimating lens were AR-coated. The coefficient of reflection from the lens surfaces within the operating spectral region of the tunable QCL was less than 1%. The coefficient of reflection in the first order was $\sim 90\%$. The used setup had an advantage in that the rotating feedback grating was positioned at the back end of the cavity, ensuring high efficiency while simultaneously providing easy access to the front QCL facet. The diagram of the experimental setup is shown in Fig. 1.

Radiation from the front end of the QCL was collimated by an identical aspherical lens and directed to a 20/80 beam splitter. The major part of radiation was directed to a calibrated detector to measure the output optical power, while the minor part was coupled into a mid-IR optical fiber with a silver bromide core 200 μm in diameter and used to measure the lasing spectrum of the tunable QCL. The other end of the optical fiber was coupled to the entrance slit of a monochromator. An MCT (mercury–cadmium–telluride) photodetector with four-stage cooling was installed at the output of the monochromator and connected to a lock-in amplifier, which ensured high sensitivity of the measuring system.

The current–power and current–voltage curves of the QCL with and without an external cavity were studied first. The obtained results are presented in Fig. 2. It is evident that the QCL lasing threshold decreases by more than 0.5 A when operating in the external cavity. This is attributable to a significant reduction in output losses, since the grating provides fine backward reflection in the first order, and the entire optical feedback circuit supports a high coefficient of radiation coupling to the QCL waveguide. The maximum power in both modes was close to 1.5 W. Measurements of the current–power curve in the external cavity were carried out at the peak of the gain curve. The insets in Fig. 2 present lasing spectra of the QCL with the external cavity at pump currents of 3, 4, and 5 A. The narrowing of the lasing spectrum to a level of several nanometers, which corresponds to the resolution of the monochromator, is clearly visible. This narrow spectrum implies single-mode lasing. The best side-mode suppression ratio was observed at a pump current of 4 A and was close to 10 dB. A further enhancement of side-mode suppression requires improving the procedures of post-growth processing of QCL wafers with a focus on perfecting the suppression of higher-order lateral waveguide modes. Two technological approaches to this problem are feasible. The first involves selective overgrowth of the trenches forming the ridge of the QCL with indium phosphide, while the second approach consists in reducing the width of the waveguide core by etching narrow trenches with vertical walls. Both approaches will be the subject of our further research.

A pump current amplitude of 4 A was chosen for studies of the spectral tuning of QCL radiation via rotation of the diffraction grating. Figure 3 presents the lasing spectra

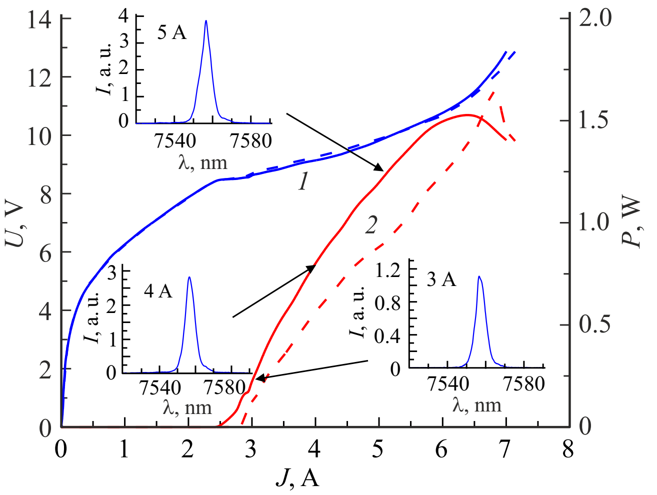

Figure 2. Current–voltage (*1*) and current–power (*2*) curves of the QCL with (solid curves) and without (dashed curves) the external cavity. Lasing spectra measured in the external cavity at pump currents of 3, 4, and 5 A are shown in the insets.

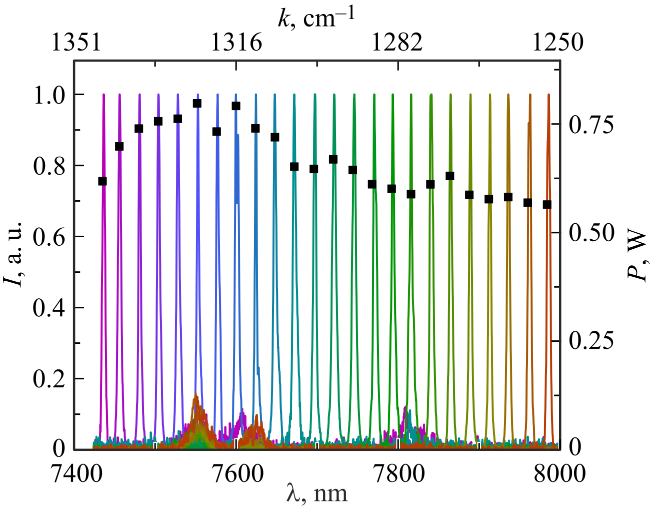

Figure 3. Tuning spectrum of the QCL in the external cavity in the Littrow configuration. Black squares indicate the power at each spectral point.

recorded at equal spectral intervals. The output power was recorded at each point. The overall spectral tuning range exceeded 600 nm (or 100 cm^{-1}). The output power was approximately equal to 0.75 W at the peak gain and decreased to 0.5 W at the long-wavelength lasing edge. In addition, the side-mode suppression ratio decreased sharply near the boundaries of the gain spectrum, and lines associated with a Fabry–Pérot cavity formed by cleaved facets were observed in the lasing spectrum. This parasitic lasing may be suppressed by applying an antireflection coating to the output facet of the chip through which feedback is established in the external cavity. The interval of spectral tuning on the short-wavelength side is narrow compared to the one reported in [15]. This is likely to be associated with an increase of internal losses due to absorption in the dielectric and scattering at the side faces in the ridge waveguide in the short-wavelength part of the spectrum.

In summary a tunable QCL with an external cavity in the Littrow configuration with an output power of single-frequency lasing up to 1.5 W was studied. The continuous tuning range exceeded 600 nm (or 100 cm^{-1}). An antireflection coating needs to be applied in order to expand the QCL tuning range further. A further enhancement of side-mode suppression requires improving the post-growth processing of QCL wafers with a focus on suppression of higher-order lateral waveguide modes.

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Conflict of interest

The authors declare that they have no conflict of interest.

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