Experimental study of stimulated emission of quantum-cascade lasers on an InP substrate

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Abstract. The results of the experimental study of stimulated emission of a quantum-cascade laser with a wavelength of 7.6 μm are presented in this paper. The dependence of the intensity of laser radiation on the duty cycle was obtained. The linearity of this dependence was maintained up to a duty cycle of 40%, thus achieving the quasi-continuous mode of operation of the quantum cascade laser at 110 K.

1. Introduction

Despite the significant progress made in the research and development of quantum-cascade lasers (QCL) in the West over the past 30 years [1, 2], studies of the growth and post-processing of QCL heterostructures have begun only in the last decade in the Russian Federation [3-15]. Interest in these types of lasers is primarily due to the possibility of changing the wavelength of radiation over a wide range, previously not achievable for bipolar lasers. Since QCLs are unipolar devices, only electrons take part in emitting transitions, which solves the problem of nonradiative recombination of electron-hole pairs. A number of practical tasks require a laser that operates in continuous mode, such as gas analysis, wireless transmission of information, sensorics, etc.

This work is aimed at studying the possibility of lasing in continuous mode. The objectives include measurement of the optical intensity and current-voltage characteristics, as well as measurement of the lasing spectra under pulsed pumping with a fixed pulse duration and different duty cycles.

2. Experimental setup and samples

The QCL samples at a wavelength of 7.6 μm were studied in this work. The QCL heterostructure was grown in “Connector Optics” on an InP substrate and contains 50 cascades, which are formed with an In₀.₅₃Ga₀.₄₇As/In₀.₅₂Al₀.₄₈As heteropair according to the two-phonon resonance scheme described in [12]. The thickness of the upper InP cladding layer was reduced to 750 nm. Samples of lasers in the ridge waveguide geometry were processed and mounted substrate-side down on a heatsink.

The measurements were carried out on an experimental setup based on a Bruker Vertex 80v Fourier spectrometer. QCL samples on a heatsink were mounted in a liquid-nitrogen-cooled optical cryostat. The QCL radiation passing through the interferometer of the spectrometer was detected by a HgCdTe-based photodetector cooled by liquid nitrogen. The laser was pumped electrically using a custom pulsed circuit based on a high-power FET. The circuit had a wide range of settings for...
amplitude, duration, and repetition frequency of the current pulse. The QCL inside the cryostat was connected to the supply circuit by means of a low-impedance stripline. The stripline was constructed of two parallel 5-mm-width copper foil strips isolated with a 50 μm Kapton tape. The duty cycle was changed by increasing the pulse repetition rate from 1 kHz to several MHz with a constant current pulse duration of about $\tau = 100$ ns. This made it possible to change the duty cycle from 0.01% to 50%, and, therefore, change the average applied electric power.

A temperature sensor was installed directly on the QCL heatsink. A temperature controller of the cryostat with a proportional–integral–derivative (PID) control loop allowed us to stabilize the temperature in the range of 80-300 K with the help of a built-in heater. The measurements were carried out in two modes. In the first mode, we applied current pulses of different frequencies and measured the laser parameters, as well as its temperature with the control loop turned off. The application of electrical power to the laser led to its heating. In the second mode, the temperature control loop was used to set the QCL heatsink temperature to a value slightly higher than the maximum heating obtained in the first case. The working control loop adjusted the built-in cryostat heater, so that the temperature of the QCL heatsink remained constant at different average electrical powers applied to QCL. All the measurements were carried out in these two measurement modes.

3. Experimental results

In the mode without temperature stabilization, the current-voltage characteristics and the dependence of optical peak power on current were measured. The results of these measurements are presented in figure 1. Current-voltage characteristics subside with increasing frequency. We associate this with the thermal heating of the active region of the laser. This fact is confirmed by the measured data from the temperature sensor plotted in figure 2. The temperature rises from 84 K at low frequencies to almost 100 K at high frequencies, as a result of which the sample heats up by about 15 K. The increase in temperature leads to a decrease in the voltage drop on the sample at a fixed current (figure 2(a)), and to a decrease in optical peak power at a fixed current (figure 2(b)).

![Figure 1](image)

**Figure 1.** Current-voltage characteristics and the dependence of optical peak power on current for different frequencies.
The emission spectra were also measured at different current pulse repetition frequencies. As the frequency increases, the emission spectrum shifts to the long-wavelength region, as shown in figure 3(a). For comparison, figure 3(b) shows the spectra measured at liquid nitrogen and room temperatures. The spectrum measured at room temperature shifts significantly to the long-wavelength region, which is normal behavior for the QCL [5, 16]. This fact also confirms the thermal heating of the laser structure at the high duty cycle.

Let us turn to the results obtained at a fixed sample temperature of about 110 K. The current-voltage characteristics and the dependence of optical peak power on current, measured with a working PID temperature control loop, are shown in figure 4(a). These characteristics remain constant at different frequencies. This suggests that stabilizing the laser heatsink temperature also fixes the temperature of the active region, and the heterostructure design allows to effectively remove the heat from the active region to the substrate.
Figure 4(b) shows the dependence of the average optical power on the duty cycle that remains linear up to a 40% duty cycle. Thus, we have achieved the so-called quasi-continuous mode: at this frequency, the time between pulses is comparable to the duration of pulses.

Figure 4. (a) Current-voltage characteristics and the dependence of optical peak power on current for different frequencies with the stabilized QCL heatsink temperature. (b) Dependence of the average optical power on frequency for $I = 0.9$ A (black line) and $I = 1.25$ A (red line).

4. Conclusion
This work experimentally demonstrated the possibility of stimulated emission of quantum-cascade lasers on an InP substrate with a wavelength of 7.5–7.6 $\mu$m at the quasi-CW mode with a duty cycle of up to 40% and a pulse duration of 130 ns. The heterostructure design provides effective removal of heat from the active region to the substrate, which allows one to expect the continuous mode operation of the structure if an effective external heatsink is available.

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