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Tuning the emission frequency of U-shaped mid-infrared quantum cascade lasers

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The frequency tuning of a pulsed single-frequency quantum cascade laser with U-shaped cavity was studied when the temperature varied from 300 to 10 K in the wavelength range 7.7–7.5 μm, amounting to about 35 cm^{-1}. The tuning of the laser frequency $\Delta\nu \sim 1\,\mathrm{cm}^{-1}$ was demonstrated in a time of about 50 ns during a laser power pulse. When the laser radiation frequency was swept during a pulse at room temperature, an absorption line of water vapor in the atmosphere was observed at a frequency of 1296.7 cm^{-1}.

Keywords: quantum cascade laser, U-shaped cavity, frequency tuning, water vapor absorption.

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Compact semiconductor middle infrared (IR) radiation sources have various applications in medicine, environmental engineering, and security systems. Quantum cascade lasers (QCLs) utilizing interband transitions of carriers were found to remain operational at room temperature within a wide spectral range that covered, among other things, water transparency windows at 3–5 and 8–12 μm. The use of a single-frequency and tunable radiation source is advantageous in various spectroscopic applications. Single-frequency lasing in mid-IR QCLs is often achieved via spectrally selective feedback through the use of an external cavity with a diffraction grating (see, e.g., [1]) or by forming a diffraction grating on a laser waveguide (see, e.g., [2]). In the former case, the device can no longer be made compact, and the design requires accurate mechanical alignment of the optical system. The formation of a diffraction grating with a small period on the waveguide surface requires the use of significantly more complex post-growth technologies.

Other ways toward single-frequency lasing in QCLs have been discussed in literature. QCLs with a short Fabry–Pérot cavity, two coupled cavities, and an asymmetrical Mach–Zehnder interferometer have been presented in [3], [4], and [5], respectively. Lasers with a U-shaped (hairpin) cavity with one semicircular section and two straight ones have been proposed in [6,7]. The procedure of fabrication of such a cavity is similar to the one used in production of stripe QCLs and does not involve any additional post-growth operations. Although the mentioned three sections of a U-shaped cavity have no physical separating boundaries, they may be regarded as individual cavities that form a monolithic coupled cavity together. Radius R of the semicircular cavity section is set to be much smaller than length L of linear sections. Thus, the separation between whispering-gallery modes in the semicircular waveguide section

$$\Delta k_{\mathrm{WG}} \approx 1/(2\pi R n_{eff})$$

turns out to be much greater than the separation between longitudinal modes of Fabry–Pérot cavities formed by linear waveguide sections,

$$\Delta k_{\mathrm{FP}} \approx 1/(2L n_{eff}),$$

where n_{eff} is the effective refractive index of the waveguide. Owing to this, single-frequency lasing at the frequency of a specific whispering-gallery mode, which matches the „Fabry–Pérot cavity“ mode, may be implemented in certain QCLs with U-shaped cavities instead of multifrequency lasing with Fabry–Pérot cavities (see, e.g., [8]). The suppression of side modes (spaced by Δk_{FP}) may be as strong as 20–25 dB in this case [6,7]. The authors of [6] were apparently the first to report on single-frequency lasing at wavelengths around $\sim 4.4\,\mu$m achieved in a QCL with a U-shaped cavity that operated within the greater part of the 80–240 K temperature range with a frequency tuning magnitude of 13 cm^{-1}. The fabrication of a single-frequency QCL with a U-shaped cavity operating at room temperature at a wavelength of 7.7 μm has been reported in [7]. The

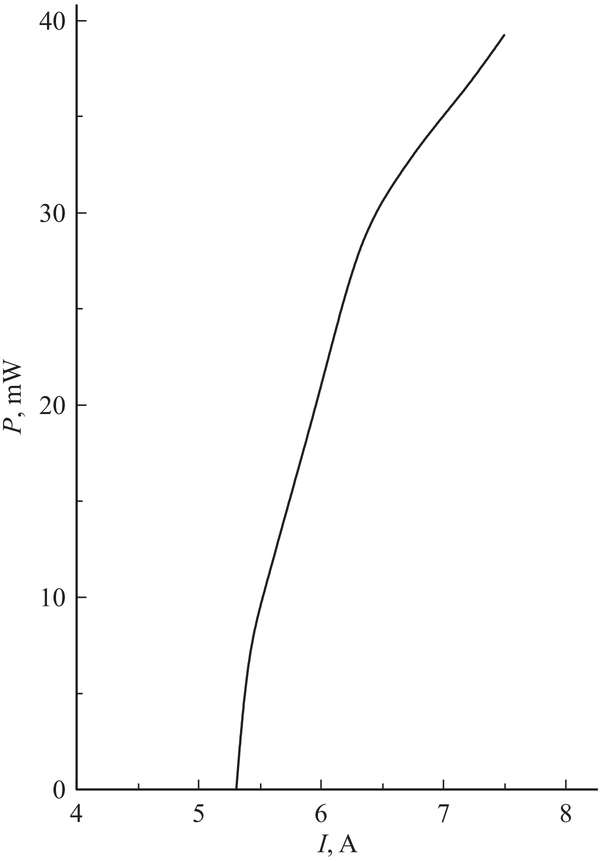

Figure 1. Light-Current characteristic of the studied QCL at $T = 288\,\mathrm{K}$.

present study is focused on frequency tuning of a U-shaped QCL fabricated from the same heterostructure that was used in [7].

The studied QCL was fabricated from a heterostructure grown at Connector Optics LLC by molecular beam epitaxy on an InP (001) substrate doped with sulfur to a level of $n = 1 \cdot 10^{17}\,\mathrm{cm}^{-3}$ [9]. The active region of the device featured 50 cascades with ten $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells operating on the principle of two-phonon resonance carrier scattering [9,10]. The laser stripe width was $20\,\mu$m, the length of linear sections of the laser cavity was 1 mm, and the radius of the semicircular cavity section was $37.5\,\mu$m. Laser mirrors were formed by cleaving the waveguide ends. The device was then secured (with its epitaxial surface facing downward) to a copper heatsink with indium solder.

Figure 1 shows the Light-Current characteristic of the QCL measured in the pulsed mode (the pulse duration was 70 ns, and the repetition rate was 48 kHz). The radiation power was measured with a Thorlabs S401 thermoelectric transducer. QCL radiation spectra were recorded by a Bruker Vertex 80V Fourier spectrometer in the step-by-step scanning mode. The sample was mounted on the cold finger of an optical closed-cycle cryostat with a zinc selenide window. Measurements were carried out with a spectral resolution of $0.2\,\mathrm{cm}^{-1}$ at temperatures ranging from 10 to 300 K. The QCL was powered by current pulses with a duration of 100 ns and a repetition rate of 1 kHz. QCL radiation was focused by two parabolic mirrors at the input aperture of the Fourier spectrometer and detected by a fast (< 1 ns) Vigo PVI-4TE-10.6 photodetector. The pulsed signal from the photodetector output was digitized by a fast analog-to-digital converter in 2.5 ns intervals, allowing one to obtain time-resolved QCL radiation spectra by applying Fourier transform.

The QCL radiation spectra dynamics during a pulse at various device temperatures is presented in Fig. 2 in the form of 3D plots. As in [6], a reduction in temperature led to an increase in the QCL lasing frequency, which shifted by $35\,\mathrm{cm}^{-1}$ as the temperature dropped from 300 to 10 K (Fig. 3). A similar effect was observed in multimode $8\,\mu$m QCLs based on the same material system and was attributed to changes in the amplification spectrum [11]. Apparently, the transition energy increases (this is confirmed by the results of measurement of electroluminescence spectra; see Fig. 1, a in [12]) due to an increase in barrier height at lower temperatures. Single-mode lasing was observed at the initial instant at all temperatures. The lasing mode then shifted downward in frequency by up to 1 cm^{-1} within 50–60 ns; following that, lasing shifted over to a higher-frequency mode distanced approximately by $1.4\,\mathrm{cm}^{-1}$. This value apparently corresponds to the separation between modes of a Fabry–Pérot cavity formed by the linear section of the QCL waveguide 1 mm in length (cf. [8]). A downward shift of the mode frequency during a pulse has been observed earlier in QCLs with a Fabry–Pérot cavity operating both in middle IR (see, e.g., [8]) and terahertz ranges [13] and was attributed to variation of the effective refractive index of the laser waveguide (and, consequently, optical length of the Fabry–Pérot cavity) due to heating within a pulse (see, e.g., [14]). Although the thermal capacity and thermal conductivity of QCL materials at room and cryogenic temperatures differ significantly, the magnitude of mode frequency tuning in single-frequency lasing ($\sim 1\,\mathrm{cm}^{-1}$) reveals almost no variation with temperature. It appears that single-frequency lasing remains stable in all cases only up to the point when the magnitude of mode frequency tuning during a pulse becomes comparable to the separation between modes of the linear section of the U-shaped cavity. Note that under certain conditions, two-frequency lasing was observed in [6] in experiments with a U-shaped QCL powered by short (15 ns) current pulses. These two frequencies corresponded to neighboring modes of the Fabry–Pérot cavity formed by the linear waveguide section.

The tuning of frequency of single-mode lasing of a U-shaped QCL during a pulse opens up opportunities for application of such devices in express diagnostics of gas mixtures. If the frequency of a certain sufficiently strong absorption line of gas, which needs to be detected or monitored for its concentration, is known, one may set the QCL lasing frequency to be slightly above the absorption

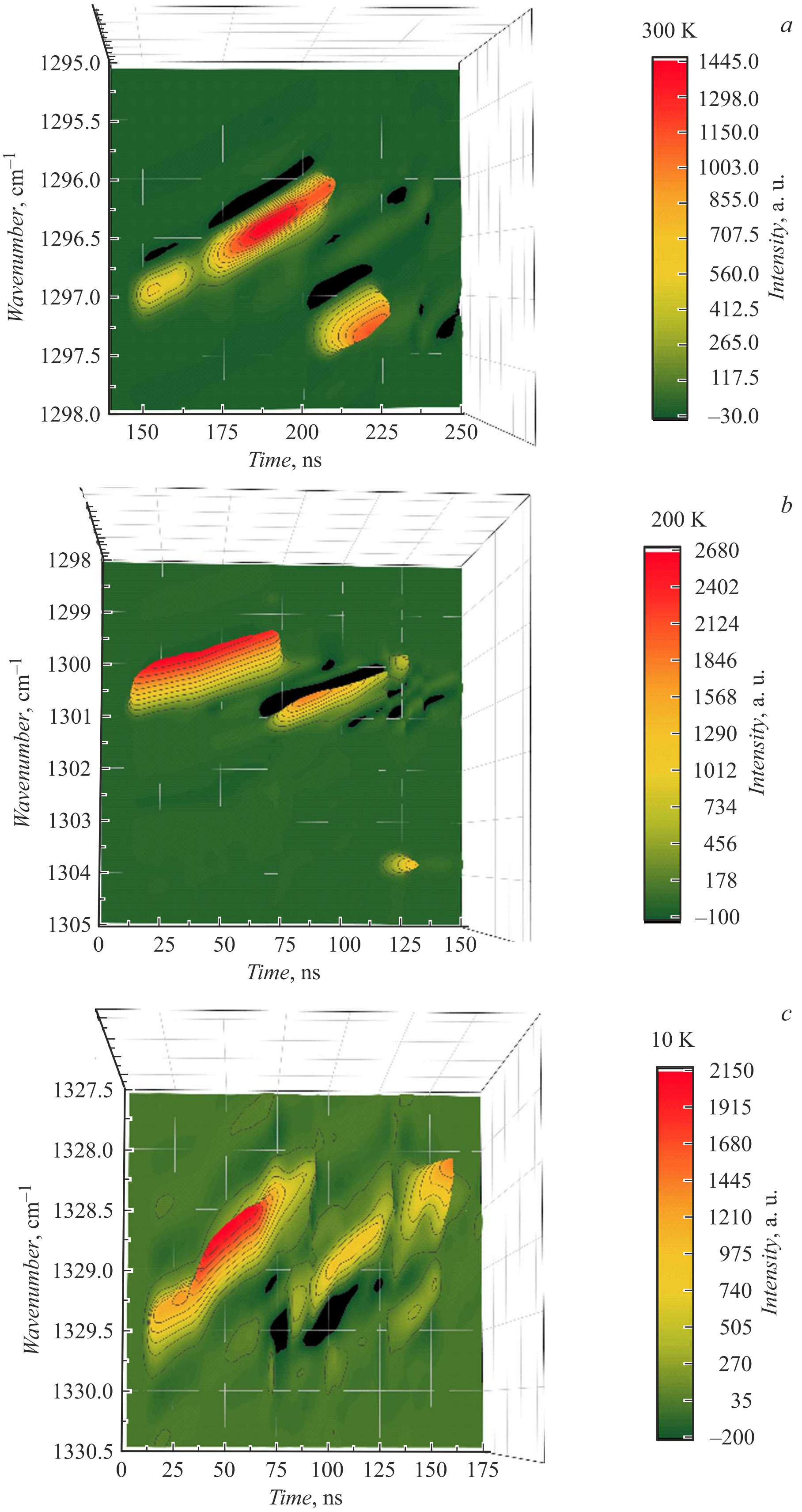

Figure 2. Evolution of QCL radiation spectra during a pulse at various temperatures (current $I = 6\,\mathrm{A}$).

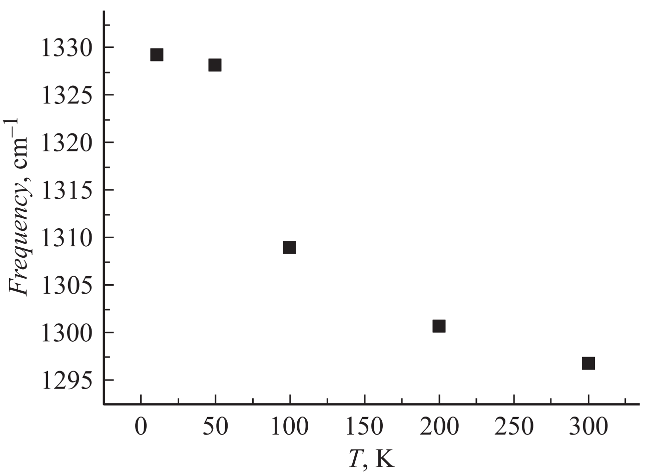

Figure 3. Temperature dependence of the QCL radiation frequency at the start of a pulse.

Measured [15] and calculated [16] intensities of water vapor absorption lines within the frequency interval from 1295 to 1298 cm^{-1} normalized to the intensity of the line with a frequency of 1296.709705 cm^{-1}

k, cm^{-1} [15]	I [15]	I [16]
1295.612131	0.160	–
1296.408780	0.233	–
1296.490427	0.899	0.631[*]
1296.709705	**1**	**1**
1296.777923	0.178	–
1297.183450	0.245	0.081[**]
1297.206022	0.222	–

[*] Integrated intensity for the lines with frequencies of 1296.49003 and 1296.49043 cm^{-1}.

[**] Integrated intensity for the lines with frequencies of 1297.18295 and 1297.18323 cm^{-1}.

line frequency by adjusting the operating temperature. Resonance radiation absorption, which may be detected as a dip in the QCL radiation signal at a photodetector, should then occur when the lasing frequency matches the gas absorption line frequency in the course of lasing frequency sweeping during a pulse. An example implementation of this absorption line detection method is presented in Fig. 2, a, where a dip in the signal is observed at 168 ns (the moment when the QCL lasing frequency goes through 1296.7 cm^{-1}, which is the frequency of a strong water vapor absorption line [15,16]). Experimental [15] and calculated (using the „Spectroscopy of Atmospheric Gases" information computer system [16]) data on water vapor absorption lines within the frequency interval from 1295 to 1298 cm^{-1} are listed in the table. Calculated and experimental data on the relative intensities of lines presented in this table differ significantly. However, the absorption line with a frequency of $\sim$ 1296.71 cm^{-1} (given in bold) is dominant in both data sets; the adjacent line at $\sim$ 1296.49 cm^{-1} with a somewhat lower intensity did not reveal itself in our measurements, which probably were performed with an insufficiently high spectral resolution (0.2 cm^{-1}).

Thus, frequency tuning of a QCL with a U-shaped cavity within the 1296–1330 cm^{-1} range at a temperature varying from 300 to 10 K was demonstrated. The single-frequency lasing mode was preserved within the first 50 ns of a laser power pulse. The lasing frequency shifted downward by $\sim$ 1 cm^{-1} in the process, allowing us to observe, for instance, the atmospheric water vapor absorption line at 1296.7 cm^{-1} at room temperature.

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Conflict of interest

The authors declare that they have no conflict of interest.

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