

Single-frequency generation of a terahertz quantum-cascade laser with distributed feedback near 4.11 THz

© M.V. Vinokurov¹, D.A. Belov^{1,2}, A.V. Ikonnikov², M.V. Maytama¹, I.A. Glinskiy¹, I.E. Rykov¹,
R.R. Galiev³, A.Yu. Pavlov³, D.S. Ponomarev^{1,3}, A.A. Afonenko⁴, D.V. Ushakov⁴,
F.I. Zubov^{1,5}, R.A. Khabibullin^{1,3}

¹ Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Moscow Region, Russia

² Moscow State University, Moscow, Russia

³ National Research Center „Kurchatov Institute“, Moscow, Russia

⁴ Belarusian State University, Minsk, Republic of Belarus

⁵ Alferov University, St.Petersburg, Russia

E-mail: vinokurov.mv@phystech.edu

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Single-frequency generation of a terahertz quantum-cascade laser (THz QCL) with an active region based on GaAs/AlGaAs has been achieved through the formation of a 1st-order distributed feedback (DFB) grating. The measured emission spectra of the THz QCL with DFB demonstrate single-frequency operation near 4.11 THz, which is in good agreement with the calculated target frequency. The DFB THz QCL operates in continuous-wave mode with an average power in the tens of μW at temperatures up to 70 K.

Keywords: distributed feedback, terahertz lasers, spectrum, quantum-cascade laser, single-frequency generation, double-metal waveguide.

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Terahertz (THz) quantum cascade lasers (QCL) have demonstrated the possibility of generating radiation in the sub-THz range [1], at frequencies from 1.2 [2] to 6 THz [3] and even higher [4,5]. This makes these sources extremely promising for terahertz spectroscopy applications. Generation in such a wide frequency range opens up the possibility of detecting dangerous substances [6] and studying the structure of atoms and ions in plasma with high spectral resolution [7]. The ability of terahertz QCL to operate in continuous generation mode with a laser beam close to the Gaussian [8] distribution allows these sources to be used as the basis of a heterodyne spectrometer [9].

One of the features of traditional strip QCL with a Fabry–Perot resonator is that the radiation they generate is usually multimode, with a large number of longitudinal and transverse modes. This significantly complicates the use of such devices for a number of tasks, in particular for the detection of atoms and molecules with intense absorption lines in the THz range [10].

Single-frequency QCL generation can be achieved in various ways, including the use of Fabry–Perot resonators of small length, two-section lasers with coupled Fabry–Perot resonators [11], as well as photonic crystals [12]. However, these methods have a number of disadvantages: a significant reduction in the power of the generated THz-radiation, the difficulty of achieving the required generation frequency, and the technological complexity of implementing such designs. The most reliable and sought-after method for achieving single-frequency generation in QCL is the creation

of distributed feedback (DFB) for the selection of spectral components of the generated radiation [13].

A terahertz QCL with DFB with single-frequency generation in a continuous mode is demonstrated in this paper. The active region of the laser is based on a resonant-phonon design with four GaAs/Al_{0.15}Ga_{0.85}As quantum wells (QW) in the period, which allows maintaining the laser generation condition to temperatures exceeding 70 K (Fig. 1) [14]. The thickness of the layers in the period starting from the injection barrier was 3.39/**9.03**/4.80/**8.18**/1.69/**6.77**/3.95/**16.37** nm, where the thickness of the GaAs core is shown in bold. Wide GaAs QWs (16.37 nm) were doped with a silicon donor impurity with a concentration of $N_d = 3.0 \cdot 10^{10} \text{ cm}^{-2}$. The number of periods in the structure was 185, which corresponds to a total thickness of the laser core of about 10 μm .

To achieve single-frequency QCL generation, a first-order DFB was formed based on a periodic change in the width of a double metal waveguide, which corresponds to a modulation of the refractive index of the medium in which the radiation propagates. The advantage of using this approach is the relative simplicity of calculating the laser generation frequency and minimal changes in the QCL manufacturing route with a double metal waveguide [15,16]. The intense absorption line of the water isotopologue HD¹⁶O — of 4.08 THz was selected as the target frequency [17]. Using the finite element method and solving a system of rate equations by analogy with the work of [18] the optimal

geometric parameters of the QCL with DFB were selected: the DFB period of $\Lambda = 10.8 \mu\text{m}$, waveguide width from $W_{\min} = 30 \mu\text{m}$ to $W_{\max} = 48 \mu\text{m}$ (see box in Fig. 1), which determines the depth of the modulation. The DFB includes a quarter-wave shift located in the center of the laser strip. The presence of a quarter-wave shift is a necessary condition for achieving single-frequency generation for such waveguide geometry [19,20]. It should be noted that the filling factor used (the ratio of the width of the „tooth“ to the DFB period) was 50 %. With numerical optimization of the DFB geometry, it was possible to obtain the calculated Bragg frequency $f_{Br} = 4.07 \text{ THz}$, close to the target frequency.

The production of QCL with DFB was carried out within the framework of the standard route for the production of QCL with a double metal waveguide (described in detail in the Ref. [15,16]). The formation of DFB with the above parameters occurs by the method of plasma chemical etching, where the upper metal of the laser waveguide is used as an etching mask. The central part of the waveguide with a width of $W_{\min} = 30 \mu\text{m}$ allows for welding with gold wire using the „ball-wedge“ method for efficient current injection.

Measurements of current-voltage characteristics (I-V) and light-current characteristics (L-I) in continuous mode were carried out using a Keithley 2400 measuring source and a calibrated GC-1P optoacoustic receiver manufactured by „Tidex“ LLC in the temperature range of 40–70 K. The QCL was cooled and the set temperature was maintained by a Stirling TC4189 cryogenic refrigerator manufactured by Lihan Cryogenics, Ltd. Spectral studies of QCL with and without DFB were carried out using a Bruker Vertex 70v vacuum Fourier spectrometer. A standard pyroelectric receiver was used as a detector, and a Mylar Multilayer — was used as a beam splitter. The spectral resolution was 0.2 cm^{-1} (6 GHz). Happ–Genzel's function was used for apodization.

The generation of QCL with a continuous increase with an output power of tens of microwatts was observed in the specified temperature range (Fig. 1). For comparison, characteristics are also shown for a QCL made of the same structure with a Fabry–Perot strip resonator (hereinafter QCL without DFB) operating in continuous mode at a temperature of 50 K. The densities of threshold currents J_{th} at $T = 50 \text{ K}$ are 535 and 562 A/cm^2 for QCL without DFB and with DFB, respectively. The given values of J_{th} show that the formation of the DFB structure introduces minimal optical losses and does not lead to a significant increase in J_{th} . At the same time, the L-I linear growth areas in the frequency range for QCL with and without DFB are practically the same, i.e., the inclusion of DFB in the QCL does not lead to a decrease in radiated power. The gain in radiation power from QCL without DFB at high pump currents is most likely due to a significant shift in the gain spectrum to the high-frequency region, where DFB suppresses generation at high frequency modes. It should be noted that the manufactured continuous QCL with DFB

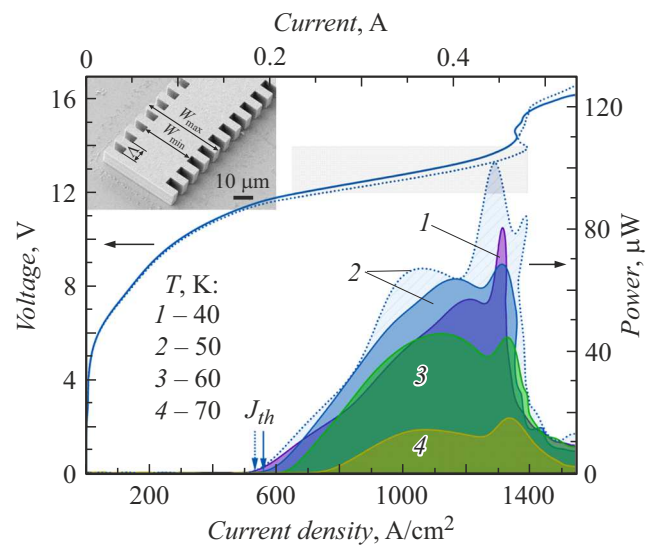


Figure 1. I-V and L-I for QCLs with and without DFB (solid lines) (dotted lines) at different temperatures. For clarity, the I-V are given only for $T = 50 \text{ K}$. The arrows indicate the values of the threshold current densities at $T = 50 \text{ K}$. The upper axis (current) refers only to QCL with DFB. The gray area corresponds to the operating voltage range for which the spectra were measured. An image of a part of the QCL with DFB obtained using a Carl Zeiss Supra 35 scanning electron microscope is shown in the inset. The color version of the drawing is presented in the electronic version of the article.

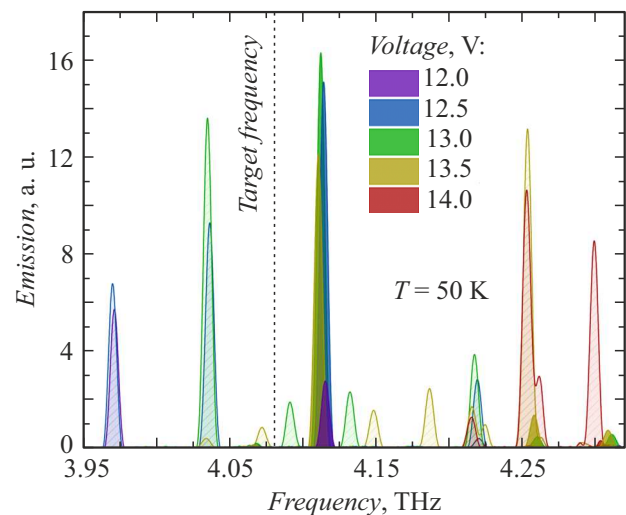


Figure 2. The emission spectra with $T = 50 \text{ K}$ QCL with DFB (highlighted by fill) and without DFB (highlighted by shading) at different laser voltages. The vertical dotted line indicates the target frequency corresponding to the HD^{16}O absorption line. The color version of the drawing is presented in the electronic version of the article.

demonstrate similar parameters in terms of output power and maximum operating temperature when compared with foreign papers [21–24].

Fig. 2 shows the spectra of QCL generation with and without DFB, measured at different voltages at $T = 50$ K. The QCL with the increase due to the presence of a quarter-wave shift in almost the entire operating voltage range (12–14 V) demonstrates single-frequency generation at a frequency of 4.11 THz, which is consistent with the calculated Bragg frequency $f_{Br} = 4.07$ THz. A slight difference (by 40 GHz) in the frequency of QCL radiation from the calculated f_{Br} is most likely due to the inaccuracy in determining the effective refractive index of the multilayer QCL active medium. It is important to note that the spectral line of the QCL with a frequency of 4.11 THz does not coincide with the set of Fabry–Perot modes. This confirms the work of DFB on the suppression of Fabry–Perot modes and the generation of a laser at the Bragg frequency based on the theory of coupled waves [25]. The QCL spectrum without DFB is multimode, covering the frequency range of 3.97–4.33 THz. As the voltage increases, energy is pumped into high-frequency modes, which is associated with the Stark shift of the gain loop QCL.

Thus, we have developed, manufactured and experimentally characterized a QCL with DFB, including a quarter-wave shift, with single-frequency generation over a wide voltage range. The spectral line of the QCL DFB near 4.11 THz is in good agreement with the calculated Bragg frequency aimed at the absorption line of semi-heavy water HD¹⁶O. The operation of QCL with DFB in a continuous generation mode with a power of tens of microwatts at temperatures up to 70 K is demonstrated, which makes it possible to use compact cryogenic refrigerators for cooling lasers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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