Dual-band generation around 8 µm by quantum cascade lasers in wide temperature range

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Abstract We present a study of the characteristics of quantum-cascade lasers with a wavelength around 8 µm in a wide temperature range up to 338 K (+65°C). Spectral studies reveal lasing in two bands around ~ 7800 nm and ~ 8100 nm. The observed competition between short and long wavelength lasing lines leads to non-monotonic behaviour of the radiation intensity in relation to the pumping current.

1. Introduction
Efficient generation of terahertz radiation in the frequency range from hundred gigahertz to several terahertz (0.1 – 10 THz) remains in the focus of research for more than 20 years. Terahertz frequency range is very important for many applications, including chemical and biological sensing, spectroscopy, astrophysics, etc [1,2]. These applications utilise the most important advantage of terahertz radiation, the ability to penetrate through fine anhydrous media (plastics, paper, textiles, wood, etc.), while the level of Rayleigh scattering is dramatically reduced. Terahertz radiation is harmless to humans, which allows its use in medical diagnostics, advanced security systems, environmental monitoring, quality control of medicines and food, high-speed communication.

For generation of terahertz radiation at room temperature, the methods using infrared lasers seem very advantageous. In particular, pumping of narrow gaps between deposited on the semiconductor surface electrodes connected to the antenna radiating in terahertz range with ultrashort laser pulses is well-known [3]. However, since recently the most attractive option have become dual-line quantum cascade lasers (QCL) emitting terahertz radiation via difference frequency generation [4-6].

2. Experimental Samples
This paper presents the study of dual band generation in QCL in a wide temperature range in a spectral region of 8 µm. The experimental QCL heterostructures were grown using molecular beam epitaxy with Riber 49 set-up at Connector Optics, LLC. The heterostructures were grown on n-doped InP substrates. The active area of QCL consisted of fifty stages based on alternated quantum wells In₀.₅₃Ga₀.₄₇As and barriers Al₀.₄₈In₀.₅₂As, the thickness of which in nanometres was the following: 2.4/2.6/2.1/2.6/1.8/2.7/1.6/2.9/1.7/3.1/2.5/4.4/1.2/5.2/1.2/5.3/1.0/1.7/4.3, where bold print refers to the thickness of quantum wells and regular print refers to the thickness of barrier layers. All layers of the active region were lattice-matched to the InP substrate. The detailed description of studied QCL
heterostructures is given in [7]. The selected cascade structure is designed for radiation in the spectral range of about 8 µm. The relaxation of an electron after photon emission in such a structure is performed according to dual-phonon level depopulation scheme [8], wherein, after emitting a photon, the electron relaxes into the next quantum well of the cascade with emission of LO phonon. Then, once again emitting LO phonon, the electron proceeds to the quantum well immediately before the injector, after which it is released into the injector. This mechanism enables rapid depopulation of the lower level of quantum wells of the optical transition and supports the population inversion. However, a prerequisite condition for its successful operation is the adherence to the energy gap value between the levels of adjacent quantum wells, which is close to the LO phonon energy ~ 34 meV [6] for the studied structure.

Experimental QCL samples with area of ~ 0.5x0.5 mm² were cleaved out from the heterostructure after applying metal contacts. The tests were conducted when pumping the samples with pulsed current with frequency of 48 kHz and duration at half of the maximum amplitude of ~ 70 ns. The temperature of the experimental samples were stabilized using a thermoelectric cooler. The tests were performed in a wide spectral range from 288 K to 338 K. The maximum amplitude of pumping current was 15 A.

![Figure 1](image-url)

**Figure 1** Light-Current curves of QCL for temperatures 288 K, 293 K, 318 K, 328 K and 338 K.

3. Results and Discussion
The samples demonstrated laser generation in the spectral region of about 8 µm throughout the temperature range 288 K to 338 K. Light-Current characteristics for temperatures 288 K, 293 K, 318 K, 328 K and 338 K are presented in Figure 1. The figure shows that with increasing temperature the threshold current is growing from 6.4 A up to 9.8 A and the maximum output power is reducing.

One can notice from the data that, with increasing operating temperature of QCL, the non-monotonous behaviour of Light-Current characteristics is decreasing. To investigate the causes of the observed inhomogeneities of Light-Current characteristics as well as changing of its slope at lower temperatures, we have carried out studies of the dynamics of QCL output radiation. Using fast-response photodetector and pre-amplifier with 1 GHz bandwidth, we recorded a series of QCL output radiation waveforms at different operation temperatures. The experimental technique is discussed in detail elsewhere [9,10]. Figure 2 shows a series of output radiation waveforms for temperatures 288 K and 338 K.
Figure 2 QCL output radiation waveforms a) at a temperature 288 K and b) at a temperature 338 K.

The presented data clearly demonstrate that at temperature 293 K there is a significant change in the output radiation pulse form when current exceeds 8 A. At the same time, the change in the output radiation pulse form at temperature 338 K occurs only when the amplitude of the pumping current is higher than 13 A. It is worth noting that the pulse shape of pumping current remains the same across the whole range of amplitudes. Typical pump pulse waveform for amplitude 15 A is shown in Figure 3.

The measured spectral characteristics of QCL demonstrated that significant difference between output radiation pulse shape and the pumping current pulse shape appears only at such current amplitudes, when the spectrum of QCL lasing demonstrates, besides the main long wavelength generation line at 8100 nm, the generation of shorter wavelength line near 7800 nm.
Figure 3 Pumping current pulse shape at amplitude 15 A.

A typical dual-band generation spectrum at temperature 288 K is shown in Figure 4. For the temperature of 288 K, the threshold current of lasing at the short wavelength line is \( \sim 8 \) A, and for the temperature of 338 K it is \( \sim 13 \) A.

Figure 4 Typical two-band QCL spectrum. The amplitude of pumping current is 13 A, operation temperature is 288 K.

The preliminary spectrally resolved dynamical measurements demonstrated that the generation of the short wavelength line occurs near falling edge, and then, with increasing pumping amplitude, it extends over the whole output radiation pulse. Figure 5 shows the spectrally resolved waveforms for long wavelength and short wavelength generation lines, as well as their sum for pumping current 13A at temperature 288 K. It is clearly noticeable that there is a significant temporal overlap between the long-wave and short-wave QCL lasing lines in the generation process. This fact indicates the potential of studied QCL to become a basis for sources of terahertz radiation.
Figure 5 The waveform of output radiation pulses for long-wave generation line (red line), short-wave line (black line) and total (blue line) at pumping current amplitude 13 A.

4. Conclusion
The paper presents the study of dual-band QCL generation in the region of 8 µm in a wide temperature range from 288 K to 338 K. The dynamics measurements with spectral resolution have revealed the presence of concurrent generation at long wavelength and short wavelength lines. This fact points to the potential of using these QCL as a basis of compact terahertz sources.

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References
[1] Tonouchi M 2007 Nature Photonics 1 97.
[2] Ferguson B, Zhang X-C 2002 Nature Materials 1 26.
[3] Daghestani N S, Sokolovskii G S, Bazieva N E, Tolmatchev A V, Rafailov E U 2009 Semiconductor Science and Technology 24 095025.
[4] Lu Q Y, Bandyopadhyay N, Slivken S, Bai Y, Razeghi M 2014 Applied Physics Letters 104 221105.
[5] Vijayaraghavan K, Jiang Y, Jiang M, Jiang A, Choutagunta K, Vizbaras A, Demmerle F, Boehm G, Amann M C, Belkin M A 2013 Nature Communications 4 2021.
[6] Fujita K, Hitaka M, Ito A, Edamura T, Yamanishi M, Jung S, Belkin M A 2015 Applied Physics Letters 106 251104.
[7] Babichev A V, Gladyshev A G, Filimonov A V, Nevedomskii V N, Kurochkin A S, Kolodeznyi E S, Sokolovskii G S, Bugrov V E, Karachinsky L Ya, Novikov I I, Bousseksou A, Egorov A Yu 2017 Technical Physics Letters 43 666.
[8] Xu G, Moreau V, Chassagneux Y, Bousseksou A, Colombelli R, Patriarche G, Beaudoin G, Sagnes I 2009 Applied Physics Letters 94 221101.
[9] Sokolovskii G S, Cataluna M A, Deryagin A G, Kuchinskii V I, Novikov I I, Maximov M V, Zhukov A E, Ustinov V M, Sibbett W, and Rafailov E U 2007 Technical Physics Letters 33(1) 4.
[10] Sokolovskii G S, Dudelev V V, Kolykhalova E D, Deryagin A G, Maximov M V, Nadtochiy A M, Kuchinskii V I, Mikhrin S S, Livshits D A, Viktorov E A, and Erneux T 2012 *Applied Physics Letters* **100** 081109.