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Temperature performance of ring quantum-cascade laser with staircase-like distributed feedback grating

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Abstract. Direct ion-beam lithography was used to realize the staircase-like second order distributed feedback grating formed in the top cladding layers of ring quantum-cascade laser. As a result, the depth of grating slits was varied from 0.6 to 2.6 μm along the ring cavity. The whispering gallery modes lasing with near 1 kA/cm^2 threshold current density at 77 K temperature was obtained with lasing wavelength close to 7.64 μm. Rise of the temperature up to 292 K yields the multi-mode lasing near to 7.94 μm with moderate threshold current density ~4 kA/cm^2. Time-resolved spectral characterization results are also discussed.

Keywords: molecular-beam epitaxy, quantum-cascade laser, indium phosphide, ion-beam etching, direct lithography, ring cavity

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Материалы конференции
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Температурное поведение квантово-каскадного лазера с селективным кольцевым резонатором, сформированным за счет травления дифракционной решетки с переменной глубиной

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Аннотация. С помощью метода прямой ионно-лучевой литографии была реализована дифракционная решетка второго порядка, обеспечивающая распределенную обратную связь, вытравленная в верхних слоях обкладки волновода квантово-каскадного лазера с селективным колцевым резонатором. Глубина травления штрихов дифракционной решетки изменялась в диапазоне 0,6–2,6 мкм при движении вдоль поверхности кольцевого резонатора. Была получена многомодовая генерация на модах шепчущей галереи вблизи 7,64 мкм. Величина пороговой плотности тока составила около 1 кА/см^2 при температуре 77 К. Повышение температуры до 292 К приводит к появлению многомодовой генерации вблизи 7,94 мкм с величиной пороговой плотности тока ~ 4 кА/см^2. Также представлены результаты исследования время-разрешенных спектров лазерной генерации.

Ключевые слова: молекулярно-лучевая эпитаксия, квантово-каскадный лазер, фосфид индия, ионно-лучевое травление, прямая ионная литография, селективный кольцевой резонатор

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Introduction

Single-mode quantum-cascade lasers (QCLs) are attractive for optical spectroscopy since many gaseous species are absorbing in mid-infrared spectral range. QCL lasing wavelength could be tuned by drive current and temperature aimed to realize the 1–5 cm^{-1} tuning range for detection of the narrow gas absorption lines. As a result, quartz-enhanced photoacoustic spectroscopy (QEPAS) allows one to determine the methane (CH_4) trace in a gaseous species. In fact, usage of QEPAS sensor with 8 μm range QCLs as laser source allows one to evaluate the methane with concentrations from less than 0.5 ppm and up to 10000 ppm with accuracy about 10% [1]. Ring QCLs are very perspective to realize stable (mode-hop free) single mode surface emission lasing [2, 3], but emission from opposite sides of the ring results destructive interference along the axis of symmetry [4, 5]. Aimed to realize the center node of the beam profile one can apply two π-phase shifts at 90 and 270 degrees along the ring cavity or staircase-like second order distributed feedback (DFB) grating [4].

Herein, the first results on fabrication and optical study of surface-emitting ring QCL with staircase-like second order DFB grating are presented.

Materials and Methods

The QCLs heterostructure was grown by molecular-beam epitaxy on InP substrate with $(1-3)\cdot10^{17}$ cm^{-3} sulfur doping level. 500 nm thick bottom buffer layer was $In_{0.53}Ga_{0.47}As$ with $0.5\cdot10^{17}$ cm^{-3} silicon doping level. The active region included 50 stages and was based on two-phonon escape design. The top cladding was formed by 3.9 thick InP layer with $1\cdot10^{17}$ cm^{-3} silicon doping level. The doping level of $In_{0.53}Ga_{0.47}As$ top contact layers with total 120 nm thickness was in the range of $(0.5-1.0)\cdot10^{19}$ cm^{-3}. Ring double-channel mesa was fabricated by wet etching. The ring radius was fixed at 291 μm and the average mesa width was 25 μm. A 300 nm thick silicon dioxide (SiO_2) layer was used to isolate the ridge sidewalls. The top metallization was formed by Ti/Au. The bottom metallization was applied after substrate lapping down to 120 μm. The ring QCL was mounted on copper submount using indium solder. The DFB grating was formed by direct high-vacuum ion-beam lithography. The etched slits size was $0.71\cdot16$ μm^2 (see Fig. 1). The grating duty-cycle was fixed at 70%. As a result, the second order grating period was 2.37 μm. The depth of slits etching, d was variable along the ring cavity and described as $d = (0.605+1.95\cdot(k-1)/(772-1))$ μm, where k was the integer number in the range of 1–772. As a result, the maximal etching depth of slits was 2.55 μm.

The laser spectra were collected at 77–293 K temperature range by Bruker Vertex 80v Fourier-transform spectrometer operating in a step-scan mode. The spectral resolution was 0.5 cm^{-1}. The lasers were tested under pulsed pumping with a pulse width of 150 ns and a repetition rate of 15 kHz.

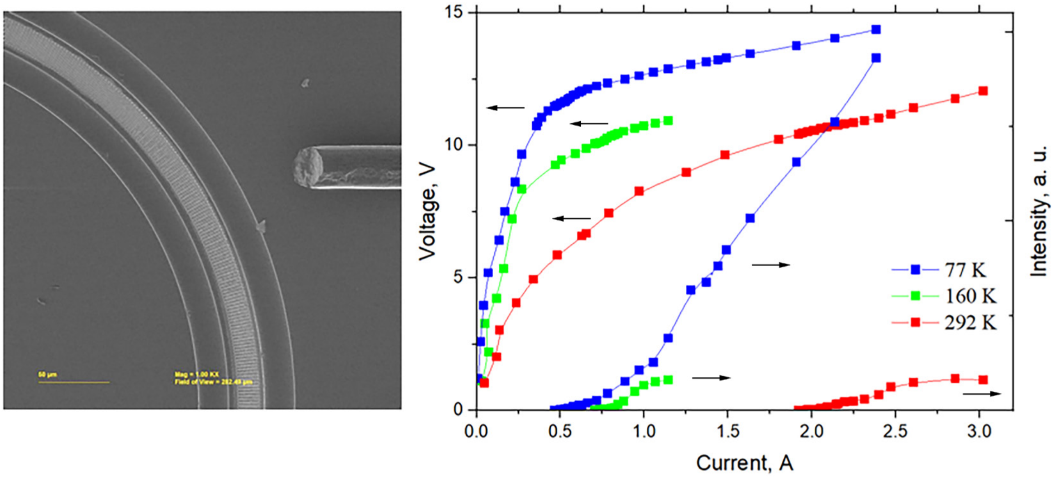

Fig. 1. SEM image of ring QCL (left panel). Light output characteristics of ring QCL measured at different temperatures

Results and Discussion

The threshold current determined at 77 K temperature was about 0.47 A (see Fig. 1) that coincided to about 1 kA/cm^2 threshold current density (j_{th}). The threshold voltage was around 12 V. Rise of the drive current to about five times above the threshold current reveals no reach to roll-over of light intensity versus current dependence due to high laser dynamic range. Near the threshold current the multi-mode lasing around 7.64 μm was measured with fringes distance coincided to whispering gallery modes (WGMs). The group of ten modes was evaluated in 7.59–7.68 μm spectral range (see Fig. 2). Above twofold threshold current (>1 A) the long wavelength modes group was demonstrated along with mode intensity redistribution. As a result, at 2.4 A drive current the modes sequence was observed in the 7.66–7.88 μm spectral range.

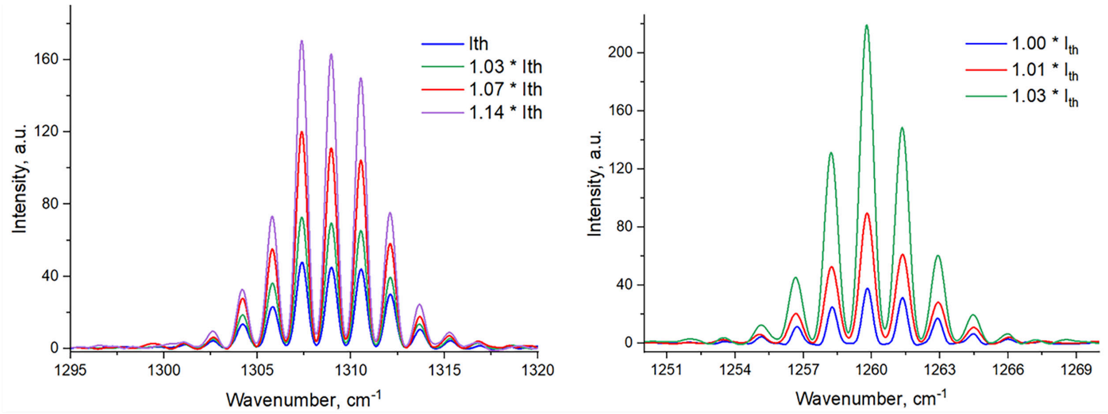

Fig. 2. Lasing spectra measured at 77 K (left panel) and at 292 K (right panel)

Increasing the temperature up to 160 K reveals the lasing with 0.7 A threshold current (j_{th}~1.5 kA/cm^2). The threshold voltage is around 18 V at 160 K. Near the threshold the multi-mode lasing spectrum has maximum close to 7.8 μm. Increase of the drive current up to 1.5 threshold value results no considerable chirp of the lasing wavelength.

At room temperature (292 K) the lasing was around 7.94 μm. The threshold current was about 1.9 A (j_{th}~4.2 kA/cm^2). Rise of the temperature results in falling of threshold voltage down to 10 V. Increase of the drive current up to 1.6 I_{th} yields to multi-mode lasing with four WGM modes with maximum intensity near 7.94 μm.

For a gas sensor based on a ring QCL, the spectroscopic characterization is important, especially its time-resolved tuning behavior [6]. Previously, for a ring QCL, the time-resolved spectra demonstrated a long-wavelength shift in the lasing wavelength during the pump pulse. The estimated time shift in the position of the lasing mode (the mean chirp rate) was $1.8 \cdot 10^{-2}$ cm^{-1}/ns [6]. As a result, the spectroscopic characterization of ring QCL under study was conducted.

Time-resolved spectra measured at a temperature of 77 K are presented in Fig. 3. Close to threshold, the spectrum is represented by several WGMs. Two characteristic peaks are observed, with a redistribution of their intensity during the pump pulse. The first peak corresponds to a time

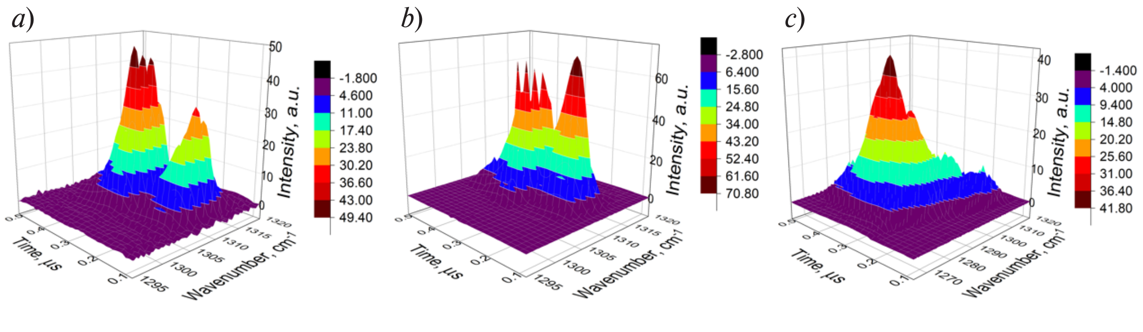

Fig. 3. Time-resolved lasing spectra measured at 77 K
Panels *a*, *b* and *c* are at I_{th}, 1.2I_{th} and 5.1I_{th}

of 0.15 μs, the second peak – 0.3 μs. The intensity of the peak at a time of 0.15 μs is less the intense of the peak corresponding to a time of 0.3 μs. At a fixed time of 0.15 μs, the maximum intensity line corresponds to the wavenumber of 1310.5 cm^{-1}. On the contrary, at a fixed time of 0.3 μs, the maximum intensity line corresponds to the wavenumber of 1307 cm^{-1}.

At $1.2I_{th}$ (see Fig. 3,*b*), at the time of 0.3 μs the line at 1310 cm^{-1} is slightly less intense than the line at 1307 cm^{-1}, which differs from the case of evolution of the spectrum at the I_{th} and $1.1I_{th}$ pump level. It should also be noted that the intensity of the "minority" modes decreases in comparison with the spectra measured at lower current pump levels. Exceeding the I_{th} value to about 24% yields that the lasing line at 1310 cm^{-1} is maximum both at the time of 0.15 μs and at the time of 0.30 μs. The intensity of the "minor" modes noticeably decreased. An additional increase in the pumping level to $1.4I_{th}$ leads to the line at 1310 cm^{-1} is maximum at all times moment. The peaks at 0.15 and 0.30 μs begin to merge (there is no longer a gap between them). Exceeding the I_{th} value to about 90% yields that the in the intensity (time) graph, it is no longer possible to clearly distinguish two peaks. The line at 1310 cm^{-1} is also maximum at all times, but at the same time a noticeable suppression of the remaining WGMs lines also began.

At $2.2I_{th}$, the ring QCL begins to heat up and modes in the long-wavelength region are ignited, which were not there before (at all lower pumps there were no modes with a wavenumber less than 1302 cm^{-1}). A further increase in the pump level to $3.1I_{th}$ yields an expansion of the lasing spectrum due to an increase in the number of WGMs in the long-wavelength region. Increasing the current pump level to approximately five laser thresholds (see Fig. 3,*c*) results to an additional expansion of the lasing spectrum.

Based on the measured time-resolved spectra, a study was carried out of the shift in the position of the lasing mode during the action of a 150 ns pulse. At 160 K, the value of the initial position of the lasing mode was 1281.75 cm^{-1}, determined by the magnitude of the exponential decay of the wavenumber position (ν) from the pumping time [6]: $\nu = A \cdot \exp(-t/B(I)) - c$. The tuning time t was about 365 ns. At a temperature of 292 K and a pump current of $1.57 \times I_{th}$, the value of the initial position of the lasing mode was 1259.21 cm^{-1}. The tuning time was lower and amounted to 254 ns. The value of the initial position of the other WGM was 1263.62 cm^{-1}. The tuning time was about 177 ns. Similar t value (~189 ns) was obtained for the longer wavelength WGM (1258.9 cm^{-1}). Thus, due to the increase in the j_{th} value with temperature, a decrease in the tuning time is observed, which is due to an increase in thermal losses with temperature. As a result, thermal losses exceed the gain at the end of the pump pulse, resulting in shorter tuning times obtained at room temperature.

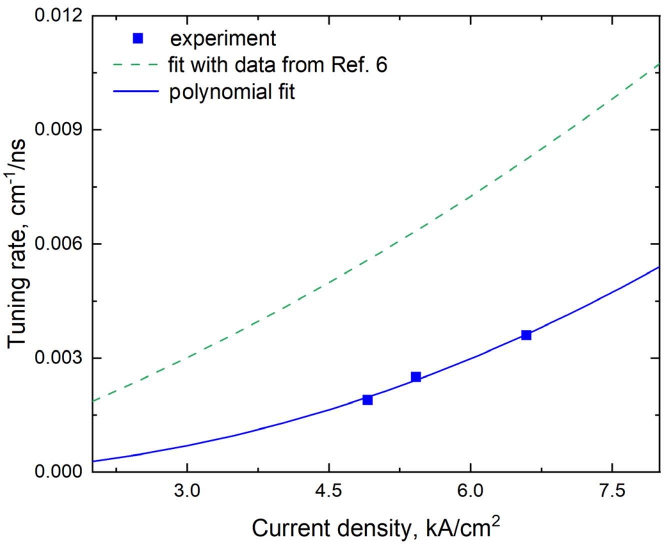

Fig. 4. Experimentally determined tuning rates of ring QCL under study depending on current densities (blue squares).
The polynomial fit to the tuning rates is represented by the blue solid line. Polynomial approximation of tuning rates for ring QCL [6] is shown with a dashed line

During the duration of the pulse at $1.6I_{th}$, the tuning range was 0.67 cm^{-1}. Considering the estimated a temperature tuning rate under study is 0.092 cm^{-1}/K [7], which corresponds to previously presented data (0.085 cm^{-1}/K [6] – 0.1 cm^{-1}/K [8]) the observed shift corresponds to heating is on the order of 7.3 K during the pump pulse. This value correlates with the previously discussed heating value during the 200 ns pump pulse (7.2 K [6]). The average shift in the lasing mode during the pump pulse was estimated (~$3.6\cdot10^{-3}$ cm^{-1}/ns) and corresponds to a current density of 6.3 kA/cm^2.

During the duration of the pulse at $1.29I_{th}$, the tuning range was 0.33 cm^{-1}. Decreasing the pump current density to 5.2 kA/cm^2 leads to a smaller average shift in the lasing mode during the pump pulse, which amounted to $2.5\cdot10^{-3}$ cm^{-1}/ns. During the pulse action at $1.17I_{th}$, the tuning range was 0.23 cm^{-1}. A decrease in the pump current density to 4.7 kA/cm^2 leads to an average shift in the lasing mode during the pump pulse, which amounted to $1.9\cdot10^{-3}$ cm^{-1}/ns. During the duration of the pulse at a pump current level of $1.09I_{th}$, the tuning range was 0.01 cm^{-1}. Reducing the pump current density to 4.4 kA/cm^2 leads to the absence of a shift in the lasing mode during the pump pulse. The dependence of the average shift in the lasing mode during the pump pulse on the pump density is shown in Fig. 4. It was shown that the average shift in the lasing mode during the pump pulse was $3.2\cdot10^{-3}$ cm^{-1}/ns at a threshold current density of 3 kA/cm^2 and $1.8\cdot10^{-2}$ cm^{-1}/ns at a threshold current density of 12.37 kA/cm^2. Thus, a smaller shift in the lasing wavelength during the pump pulse was demonstrated compared to the previously presented results [5].

Conclusion

New type of surface emitting ring cavity quantum-cascade lasers was created and studied. The lasing of several whispering-gallery modes close to 8 µm was observed in 77–300 K temperature range with about 1–4 kA/cm^2 threshold current density. Time-resolved spectra were measured at different temperatures. The average shift of the lasing wavelength in a ring QCL with a radius increased to 291 µm has been assessed. It is shown that due to an increase in the threshold current density with temperature, a decrease in the tuning time during the pulse action is observed, which is due to an increase in thermal losses with temperature. As a result, thermal losses exceed the gain at the end of the pump pulse, resulting in lower tuning times at room temperature. It is shown that the average shift of the lasing wavelength during the pump pulse action is smaller (by a factor of two) in comparison with previously results for a ring QCL with 150 µm radius when comparing data for a similar current density. As a result, the thermal load decreases with increasing radius of the ring cavity.

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