High-power 0.98 μm range diode lasers based on InGaAs/GaAs quantum well-dot active region

G O Kornyshov¹, A S Payusov², N Yu Gordeev², A A Serin², Yu M Shernyakov², S A Mintairov², N A Kalyuzhnyy², A M Nadtochiy¹,² and A E Zhukov¹

¹ St. Petersburg Academic University, 8/3 Khlopina, St Petersburg 194021, Russia
² Ioffe Institute, 26 Polytechnicheskaya, St Petersburg 194021, Russia
e-mail: supergrigoir@gmail.com

Abstract. We present a study of characteristics of the edge-emitting lasers operating in the 0.98 μm wavelength range and based on a new type of InGaAs/GaAs active region – quantum well-dots (QWD). Utilizing the QWD active region in broadened 1.3 μm waveguide (BWG) allowed us to decrease the internal loss down to 0.5 cm⁻¹ and to demonstrate the maximum output power of 13 W and 50 W in continuous wave (CW) and pulse operation regimes respectively. The investigation of the lasing spectra under high pulse injection currents revealed the overheating of the active region in the devices with moderate waveguide thickness (0.68 μm) in contrast with BWG devices.

1. Introduction
Quantum sized heterostructures such as self-organized quantum dots (QD) and quantum wells (QW) are widely used as an active region of the high-power edge-emitting lasers grown on GaAs substrates. Both active media have their advantages and disadvantages. A high value of the optical gain per layer and high differential gain can be obtained using InGaAs/GaAs QWs. But, the thickness of the active region and, as a consequence, the emission wavelength range are limited due to the elastic stress. In the QD-based active region the strain is relaxed and tens of the QD layers can be stacked without forming dislocations. However, the QD-based active region provides low optical gain per layer. Recently we have proposed a new type of the active medium – InGaAs quantum-well-dots [1]. QWDs may be considered as a transitionally dimensional heterostructure, and could be described as a QW comprising an ultra-dense array of indium-rich narrow-gap regions localizing electrons and holes as QDs. These nanostructures combine the advantages of both QWs and QDs [2] providing the gain per layer higher than QDs and, at the same time, the decreased elastic stress. This set of properties is very promising for using the new active region in edge-emitting lasers. QWD-based edge-emitting and microdisk lasers operated in the 1.1 μm range have been successfully demonstrated [3, 4]. In this work we present a study of characteristics of high-power QWD-based diode lasers emitting at practically demanded wavelength of 0.98 μm and show that the new active region could be considered as a promising candidate for replacement of the conventional InGaAs QWs.

2. Laser wafer design and sample processing
The laser wafers were grown by metalorganic vapor phase epitaxy (MOVPE) on the GaAs substrates misoriented on 6° toward [111] direction. The active region consisting of two layers of In0.4Ga0.6As QWDs with a nominal thickness of 1 nm and separated with 40 nm GaAs layer [5] was placed at the
center of the GaAs waveguide. In the first wafer the 0.68 μm waveguide (thin waveguide or TWG) is sandwiched between two p- and n-type doped Al0.4Ga0.6As cladding layers. In order to minimize the internal loss in the claddings their doping level of 2·10^{18} cm^{-3} was reduced down to 7·10^{17} cm^{-3} in the vicinity of the waveguide. The thicknesses of the p and n-claddings were 0.75 μm and 1.5 μm respectively. The second wafer was fabricated following the CLOC technology [6]. The composite waveguide comprising of the broadened 1.3 μm active GaAs waveguide (BWG) separated from the 220 nm GaAs passive waveguide by the 250 nm Al0.25Ga0.75As layer was designed to provide an elimination of the second order mode. The thickness of the p-Al0.25Ga0.75As cladding layer was reduced down to 450 nm in order to improve a heat extraction from the active region.

The wafers were processed into 100 μm broad-area lasers using standard photolithography. The devices where mounted p-side down onto the copper heat-sinks using indium solder in order to reduce overheating and improve current spread for long (>3mm) devices. The total thickness of the semiconductor layers located between the active region and the heatsink was 1.3 μm in the case of the TWG laser and 1.3 μm in the BWG laser. No facet coatings were used.

3. Experiment details
First the devices with different cavity length were characterized at room temperature in a pulsed regime with 300 ns pulse width and the duty cycle of 0.1%. Then the values of the internal efficiency (η) and the internal loss (αi) were extract from the dependence of the reciprocal differential efficiency on the cavity length. The pulsed voltage supply (Avtech A4-B) capable to deliver 100V was used to drive the devices. The driving current was measured as a voltage drop over 1Ω resistor connected in series with the device under test. For the light-current and spectral measurements we used 100 ns pulses and the duty cycle of 10-3%. An integrating sphere with a fast Ge photodiode connected to a 100 MHz preamp were used to measure the pulse light-current characteristics. Amplitudes of the driving current and the photocurrent were registered by a 300 MHz sampling oscilloscope. CW output power was measured using a bolometer.

The output emission from the rear facet was used to measure the lasing spectra. It was collected with 200 μm fiber and then focused onto the input slit of a 0.6 m monochromator. A fast InGaAs receiver providing 2.5 ns rise time connected to the gated integrator SR250 from Stanford Research was used to detect the signal from the output of a monochromator. The gate width (GW) and the gate position (GP) against the photocurrent pulse were controlled using the oscilloscope. The spectral measurements were performed with averaging over 100 pulses. The laser diode temperature was stabilized during measurements using a Peltier-based temperature controller. A thermistor was placed on the laser heatsink in the near proximity of the laser chip.

4. Results and discussion
TWG lasers demonstrated \( \alpha_i \sim 1.1 \text{ cm}^{-1} \) and \( \eta_i \sim 74\% \), whereas BWG devices demonstrated \( \alpha_i \sim 0.5 \text{ cm}^{-1} \) and \( \eta_i \sim 85\% \) which corresponds, as far as we know, to best up to date values for high-power edge-emitting diode lasers. We assume that significant improvement of \( \alpha_i \) resulted from the waveguide broadening rather than from variation in the optical quality of the active region.

We measured the far-field patterns in order to ensure that our devices operate on a fundamental vertical mode. The results are presented in the insets in figure 1 (a, b). One can see that both laser structures provide fundamental mode lasing. The divergence angles determined as full width on half maximum were 52° and 35° for TWG and BWG correspondingly.
Figure 1. Light-current characteristics of the QWD-based TWG (a) and BWG (b) lasers. The dash-dot lines denote slope efficiency and the insets show the far-field patterns.

Figure 1 shows the light-current characteristics of the 3 mm long TWG (figure 1 a) and BWG (figure 1 b) diodes obtained under pulse and CW operation. It is evident that the slope efficiency of the TWG laser is lower than that of the BWG device due to the higher $\alpha_i$ and lower $\eta_i$. The maximum CW output power of the TWG diodes (~7 W) was limited by catastrophic optical damage in contrast with the BWG lasers where it was limited by a thermal roll-over at 13 W. Also the BWG laser demonstrate more linear light-current characteristic in pulsed regime, and 50 W maximum output power limited by our current supply.

Figure 2. Pulse lasing spectra of the QWD-based TWG (a) and BWG (b) lasers measured with 120 ns GW.

In order to analyze the cause of the decreasing slope efficiency at high pulse currents we measured lasing spectra. Figure 2 (a, b) shows the spectra obtained with 120 ns GW which is 20 ns longer than the photocurrent pulse. We assume that this is an equivalent to the standard measurements using the lock-in technique. There are several features to observe in the results: saturation of the peak intensity, broadening to the shorter wavelength and a long wavelength tail in the spectra of the TWG laser under high currents. The former two features are completely consistent with the results previously reported by other groups [7] and the latter usually indicates an overheat of the active region. Figure 3 shows the lasing spectra of the TWG laser obtained under 75 A pulse driving current with 10 ns GW and different GPs. There is a clear 1.5 nm red shift during 100 ns current pulse. The narrower spectrum at 10 ns GP associated with the lower injection level originates from the existence of 30 ns rise time in the current
pulse. However, this fact is unimportant for using this spectrum as a reference one for the overheat detecting. In order to quantify the overheat we measured the lasing spectra of the same TWG laser under 40A pulse current at different temperatures with 10 ns GW and 50 ns GP and found the temperature wavelength shift of 0.28 nm/°C. Using this shift we estimated the overheat at 75A driving current as 5°C during 100 ns. The lasing spectra of the BWG laser showed no red shift at any current (figure 2 a) and GP used (figure 3 b). We assume that the heat dissipation in the BWG laser is improved due to the thicker p-side GaAs layer possessing higher thermal conductivity than Al-rich layers.

Figure 3. Pulse lasing spectra of the QWD-based TWG (a) and BWG (b) laser measured with 10 ns GW and different GP with respect to the photocurrent pulse.

5. Conclusion
For the first time we have investigated the characteristics of the high-power edge-emitting QWD-based lasers operating in the 0.98 μm wavelength range. Utilizing the QWD active region in 1.3 μm waveguide allowed us to decrease the internal loss down to 0.5 cm⁻¹ and to demonstrate the maximal output power of 13W and 50W in CW and pulse operation respectively. The investigation of the lasing spectra under high pulse injection currents revealed the overheating of the active region in the devices with moderate waveguide thickness (0.68 μm) in contrast with BWG (1.3 μm) devices.

Acknowledgment
Authors acknowledge the support from the Russian Science Foundation (project no. 16-12-10269).

References
[1] Mintairov S A et al. 2015 Nanotechnology 26 385202
[2] Nadtochiy A M, Mintairov S A, Kalyuzhnyy N A, Rouvimov S S, Nevedomskii, V N, Maximov M V and Zhukov A E 2018 Semiconductors 52 53–58
[3] Payusov A S et al. 2018 Journal of Physics: Conference Series 1135 17426596
[4] Moiseev E I et al. 2018 Opt. Lett. 43 4554-4557
[5] Nadtochiy A M et al. 2019 Technical Physics Letters 45 101
[6] Gordeev N Yu, Maximov M V and Zhukov A E 2017 Laser Phys 27 086201
[7] Slipchenko S O, Sokolova Z N, Pikhtin N A et al. 2006 Semiconductors 40 990.