Experimental study of power-limiting factors of 1.1 μm range edge-emitting lasers based on InGaAs/GaAs quantum well-dot nanostructures

A A Serin¹, A S Payusov¹, G O Kornyshov², Yu M Sherbakov¹, S A Mintairov¹, N A Kalyuzhnyy¹, M M Kulagina¹, A E Zhukov², N Yu Gordeev¹, M V Maximov²

¹Ioffe Institute, 26 Polytechnicheskaya, St Petersburg 194021, Russia
²St. Petersburg Academic University, 8/3 Khlopina, St Petersburg 194021, Russia
e-mail: spbgate21@gmail.com

Abstract. We present a study of high-power characteristics of edge-emitting lasers based on quantum well-dots (QWD) in a pulsed regime. QWD-based lasers with 2 and 5 active layers emitting at ~1.1 μm provided maximal optical power of 39 W limited by the pulse current source available. We have investigated the lasing spectra and shown that under the injection current above 20 kA/cm² the active region overheats approximately by 0.5°C per 1 kA/cm² during 100 ns current pulse. The active region overheating correlates well with the reducing of the differential efficiency of our devices. We believe that maximal pulse optical power of the QWD-based lasers is limited mainly by our laser wafer design rather than by the QWD active media properties.

1. Introduction

GaAs-based high-power high-brightness diode lasers emitting in the wavelength range of 1.1-1.2 μm have a great potential for a number of applications such as direct material processing, pumping of the rare earth element doped fiber lasers [1], nonlinear frequency conversion to green-yellow and yellow-orange spectral range. Currently InGaAs quantum wells (QW) are the typical choice for the active region for such devices. However, in order to shift the lasing wavelength beyond 1.1 μm one needs to increase the indium (In) content in the QWs, which results in extra strain in the active region. This strain limits the lifetime of the QW-based lasers to several thousand hours [2].

Recently a new type of InGaAs/GaAs nanostructures – quantum well-dots (QWD) have been proposed [3]. These InGaAs nanostructures allow obtaining the In content of 30-50% without strain-induced dislocations. QWD-based edge-emitting lasers have been successfully demonstrated [4]. We believe that QWD could be considered as an alternative to InGaAs QWs for high-power 1.1 μm range lasers. In this paper, we demonstrate that maximal pulse optical power of the QWD-based lasers is limited mainly by the overheating under high currents rather than by QWD active media properties.

2. Laser wafer design and sample processing

The laser wafers were grown by metal-organic vapor phase epitaxy (MOVPE) on n-(100) GaAs substrates misoriented by 6° toward [111] direction. Laser structures consist of an undoped 0.78 μm GaAs waveguide sandwiched between p- and n-type doped 1.5 μm Al₀.₄Ga₀.₆As cladding layers. In order to minimize the internal loss in the claddings their doping level of 2·10¹⁸ cm⁻³ was reduced down...
to $7 \cdot 10^{17}$ cm$^{-3}$ in the regions adjoining the waveguide. Zinc and silicon were used as p- and n-dopants respectively. The active regions consisted of 2 or 5 layers of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ QWDs (2xQWD and 5xQWD respectively) separated with 40 nm-thick GaAs spacers. The effective thickness of each QWD layer was 2 nm.

The wafers were processed into 100 μm broad-area shallow mesa lasers using standard photo-lithography. Devices with various cavity length were cleaved and mounted p-side down onto copper heatsinks with an indium solder in order to reduce overheating and improve current spread in long (>2mm) devices. 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 ($\eta$) and the internal loss ($\alpha$) were extracted 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 was used to measure the pulse light-current characteristics. Amplitudes of the driving current and the photocurrent were registered with a 300 MHz sampling oscilloscope.

![Figure 1. Schematic representation of the photocurrent pulse.](image)

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 (figure 1) were controlled using the oscilloscope. The spectral measurements were performed with averaging over 100 pulses. The diode laser 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

Both laser structures demonstrated the internal efficiency over 80%, the internal losses were estimated as 1.0 cm$^{-1}$ for 2xQWD and 1.5 cm$^{-1}$ and 5xQWD lasers. Obtained parameters are similar to ones reported in [5] for QW-based devices with the same lasing wavelength. Figure 2 a,b shows the pulse light-current (LI) characteristics for 2 and 5xQWD devices respectively. Dashed lines show slopes for the initial parts of the curves up to 15 A. Due to the higher internal loss the slope for the 5xQDW lasers is less than that for 2xQWD devices. All tested lasers demonstrated a decrease of the differential efficiency under currents over 20 A. However, the LI characteristics of the 5xQWD lasers saturate slower than 2xQWD lasers. The 2xQWD and 5xQWD laser demonstrated practically the same
maximal output power of 38 W and 39 W respectively (figure 2 a,b, red dots) which was limited by our current supply. The effect of improvement in linearity of light-current characteristic with an increasing number of active layers has been previously analyzed and reported in [5].

Figure 2. Light-current characteristics of 2xQWD (a) and 5xQWD (b) lasers with various cavity length measured in pulsed regime at 20°C.

In order to investigate the cause of the output power saturation, we measured lasing spectra at different currents in the pulsed regime from 2 mm long devices. At first, measurements were carried out with GW set to 120 ns in order to integrate a signal over the whole photocurrent pulse. The results are shown in figure 3 a,b. There is no evident saturation of the ground state emission under the high currents. Instead, one can see the long wavelength tale emerging with the increasing current. A redshift is usually associated with the active region overheat. To confirm this we measured spectra under 70 A pump current with 10 ns GW and different GPs over the photocurrent pulse. Figure 4 shows the results for 5xQWD laser with 2 mm long cavity. There is an evident red shift during the pulse without significant change in the line shape. The linewidth of the spectrum taken with 10ns GP is smaller due to the 30 ns rise time of the pump current pulse. However, this fact is unimportant for using this spectrum as a reference one for the redshift detection.

Figure 3. Lasing spectra of 2xQWD (a) and 5xQWD (b) lasers with 2 mm cavity obtained in pulse regime integrating over the whole photocurrent pulse (GW 120 ns).
In order to quantify the discovered overheat, we measured the lasing spectra under 40 A pump current with 10 ns GW and 50 ns GP at different temperatures. Temperature-induced wavelength shift was found to be 0.34 nm/°C and 0.33 nm/°C for 2xQWD and 5xQWD lasers respectively. Using these data along with the redshift we calculated the overheat under different currents (Table 1). One can conclude that overheat builds up at an approximate rate of 0.5°C per kA/cm². The overheat build-up correlates well with output power saturation.

![Lasing spectra of the 5xQWD device](image)

**Figure 4.** Lasing spectra of the 5xQWD device obtained at 70A driving current with GW of 10 ns at different GP with respect to photocurrent pulse. On the right side full width oh half maximum of the lasing line is shown.

| Current, A | Current density, kA/cm² | ΔT₂xQWD, °C | ΔT₅xQWD, °C |
|-----------|-------------------------|--------------|--------------|
| 40        | 20                      | 9            | 13           |
| 55        | 27.5                    | 11           | 17           |
| 70        | 35                      | 17           | 21           |

The power saturation mechanisms at high current densities in the pulsed regime have been previously studied both theoretically and experimentally. The carrier accumulation in waveguide layers is considered to be the main reason for increasing the optical loss and subsequent power saturation [6-8]. Meanwhile, most authors presume the absence of overheat in the pulsed regime and omit it as a factor affecting carrier escape to waveguide layers. However, the obtained results show that this assumption is not accurate at least for the devices with the designs similar to ours. We would like to point out that lasing intensity from the QWD ground state does not saturate with the increasing current, meaning that the QWD active media properties are irrelevant to the observed output power saturation. Thus, we assume that the wafer design determines the active region overheating. The main factors affecting the heat spread are the thickness and thermal conductivity of the layers in between the active region and the surface on which the device is mounted. The design of our laser waveguide is rather conventional. Therefore, we assume that the results obtained can be used to improve pulse high power properties of a great number of laser designs.
5. Conclusions
We have investigated high-power characteristics of the edge-emitting lasers based on quantum well-dots (QWD) in pulsed regime. QWD-based lasers with 2 and 5 active layers emitting at ~1.1 μm provided maximal optical power of 39 W limited by the pulse current source available. We have investigated the lasing spectra and shown that under the injection current above 20 kA/cm² the active region overheats approximately by 0.5°C per 1 kA/cm² during 100 ns current pulse. The active region overheating correlates well with the reducing of the differential efficiency of our devices. We believe that maximal pulse optical power of the QWD-based lasers is limited mainly by our laser wafer design rather than by the QWD gain properties.

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