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High-power mesa-stripe semiconductor lasers (910 nm) with an ultra-wide emitting aperture based on tunnel-coupled InGaAs/AlGaAs/GaAs heterostructures

S.O. Slipchenko, D.N. Romanovich, P.S. Gavrina, D.A. Veselov, T.A. Bagaev, M.A. Ladugin, A.A. Marmalyuk, N.A. Pikhtin

***Abstract*. The characteristics of high-power semiconductor lasers with an 800 μm emitting aperture based on tunnel-coupled InGaAs/AlGaAs/GaAs heterostructures with three optically uncoupled laser sections are studied. The maximum power achieved under pumping by current pulses with an amplitude of 47 A and a duration of 1 μs is 110 W with the maximum active region heating not exceeding 4.7 °C. At a pulse duration of 860 μs, the maximum optical power is 22.6 W, and the decrease in the optical power to the pulse end reaches 6.7 %. A decrease in the laser pulse duration to 85 μs leads to an increase in the peak laser power to 41.4 W at a pump current amplitude of 20 A.**

Keywords: *semiconductor laser, tunnel-coupled heterostructures.*

1. Introduction

Noticeable progress observed recently in the field of high-power semiconductor lasers is caused by their use in a wide range of practical applications (pumping of active media, direct laser treatment, range finding and monitoring systems, etc.). Developed technologies and designs made it possible to increase the cw output power to 10 W in the spectral region of 0.9 μm at a stripe contact width of 100 μm. High-power pulsed laser sources have also been extensively developed simultaneously with cw lasers. A decrease in the thermal load in the case of pulsed regimes allows developing bars and stacks of high-power semiconductor lasers with output optical powers exceeding the kilowatt level [1].

In addition to traditional laser heterostructures, much attention is paid to the development of new designs, which, in particular, may combine several laser sections in one heterostructure via p–n tunnel junctions [2]. This makes it possible to multiply increase the internal quantum yield and, as a result, the output power, as well as the power extracted from unit area of the emitting surface. To date, it has already been demonstrated that it is possible to fabricate heterostructures with three laser sections and use them to fabricate vertical stacks with a peak output power of ~1.5 kW emitted from a surface area of about 1 mm^2 at a wavelength of 875 nm under pumping by current pulses with durations of 100–200 ns [3]. Studies of single lasers with a stripe contact width of 100 μm and a wavelength of 1060 nm based on a heterostructure with two laser sections showed that an increase in the pulse duration and the use of a cw lasing regime leads to considerable overheating of the active region and to saturation of the light–current characteristic [4].

At present, active investigations are also devoted to alternative designs of laser crystals with the use of ultra-wide emitting apertures for operating in high-power pulsed regimes [5, 6]. Slipchenko et al. [5] demonstrated that this design has some advantages in the case of pumping by ultra-high currents due to a decrease in the injected current density. However, in the case of operation with a high excitation level, widening of the emitting aperture may cause additional thermal load in the case of long (exceeding 100 ns) pump current pulses. Thermal heating effects may be considerably stronger in lasers fabricated based on tunnel-coupled heterostructures due to multiple enhancement of the heat flow, which must be removed from the crystal to maintain its temperature and allow efficient operation of the device. Therefore, the study of the radiative characteristics of semiconductor lasers with an ultra-wide emitting aperture based on tunnel-coupled AlGaAs/GaAs heterostructures is undoubtedly important.

The present work is devoted to the development of high-power laser sources with an ultra-wide (800 μm) aperture based on a heterostructure with tunnel-coupled laser sections and to the study of their radiative characteristics in a long-pulse regime (1–1000 μs).

2. Experimental samples

To fabricate semiconductor lasers, we used a heterostructure grown by MOCVD. The heterostructure contained three laser sections electrically coupled to each other via tunnel junctions. The designs of the laser sections were chosen so that each of them operated at its own laser mode. The laser sections included wide band gap $Al_xGa_{1-x}As$ (x = 35 %) emitters 0.4 μm thick with n- and p-type conductivities, an $Al_xGa_{1-x}As$ (x = 30 %) waveguide layer with a thickness of 0.4 μm, and an active region based on the InGaAs quantum well. Mesa grooves etched in the laser heterostructure formed a lateral mesa-stripe waveguide 800 μm wide. The ohmic contacts to the p- and n-layers of the heterostructure were formed using Ti/Pt and AuGe metal compositions, respectively. The cleaved laser crystals had a length of 2.5 mm, and the obtained Fabry–Perot cavity faces were coated with antireflection (T = 5 %) and high-reflection (R = 95 %) coatings. The crystals pre-

S.O. Slipchenko, D.N. Romanovich, P.S. Gavrina, D.A. Veselov, N.A. Pikhtin Ioffe Institute, Politekhnicheskaya ul. 26, 194021 St. Petersburg, Russia; e-mail: Serghpl@mail.ioffe.ru;
T.A. Bagaev, M.A. Ladugin, A.A. Marmalyuk JSC M.F. Stel'makh Polyus Research Institute, ul. Vvedenskogo 3, stroenie 1, 117342 Moscow, Russia; e-mail: tim_himik@mail.ru

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pared for measurements were soldered p-side down to copper heat sinks.

3. Experimental results

Most practical applications require two ranges of pump current pulse durations: (1) relatively short (to 1 μs) pulses for precision treatment of materials and range finding and (2) long (longer than 100 μs) pulses for pumping solid-state active media. Therefore, the results of experimental studies described below will also consist of two parts demonstrating the radiative characteristics of lasers with aforementioned pulse durations.

In the first part of our experiments, we measured the radiative characteristics of lasers pumped by pulses with durations of 0.15 – 1 μs. For this purpose, we used a specially developed generator, which can pump the semiconductor lasers by current pulses with amplitudes of up to 47 A and a repetition rate of 1 kHz. The typical oscillograms of pump current pulses and laser pulses are shown in Fig. 1. The laser pulse shapes almost coincide with the shape of the current pulses in the entire studied range of pump currents. A specific feature of the developed generator is some instability of the plateau of the pump current pulses in the range of high amplitudes, because of which the peak power and the pump current amplitude were determined at different instants of time (at 0.12, 0.54, and 0.96 μs after the pulse initiation).

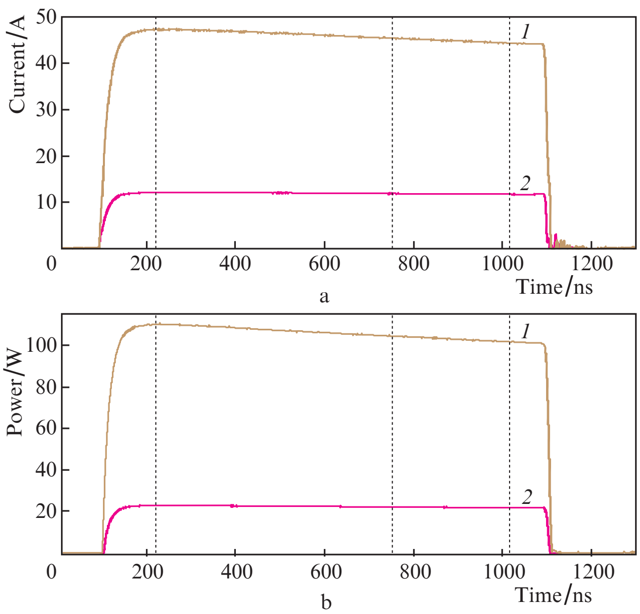

Figure 1. (Colour online) Oscillograms of (a) pump current pulses and (b) corresponding laser pulses recorded at peak current amplitudes of (*1*) 47.2 and (*2*) 12.1 A. The vertical dashed lines indicate the times corresponding to the current amplitudes and optical powers chosen for plotting the LCCs in Fig. 2.

The light – current characteristics (LCCs) plotted for the instants of time indicated in Fig. 1 are shown in Fig. 2. One can see that all LCCs are linear and identical for the instants corresponding to the beginning, middle, and end of the laser pulse. The maximum achieved output power was 110 W at a current amplitude of 47 A. To estimate the heating of the active laser region at current amplitudes

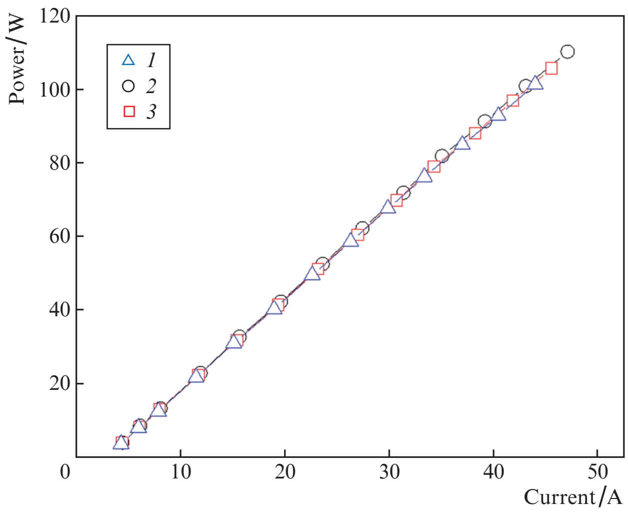

Figure 2. (Colour online) Dependences of the output power on the pump current pulse amplitude for instants of time of (*1*) 120, (*2*) 540, and (*3*) 960 ns from the pulse initiation. The oscillograms of the pulses and the corresponding instants of time are shown in Fig. 1. The current pulse duration is 1 μs.

of up to 47 A during the pump current pulse, we determined the shift of the long-wavelength edge of the laser spectrum at pump current pulse durations of 0.15 and 1.0 μs. Figure 3a shows time-averaged spectra of lasers pumped by current pulses with a duration of 1.0 μm and different amplitudes, while Fig. 3b shows the positions of the long-wavelength edge of the spectra in the case of pumping by current pulses with durations of 0.15 and 1.0 μs. The shift of the long-wavelength edge of the laser spectrum within the pump current range 12 – 47 A is 1.7 nm for pulses with a duration of 0.15 μs and 2.4 nm for 1-μs

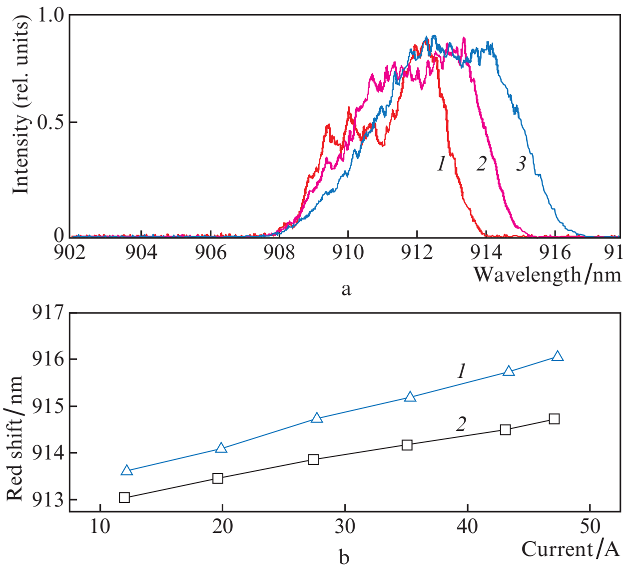

Figure 3. (Colour online) Laser spectra measured at pump current pulse amplitudes of (*1*) 12.1, (*2*) 27.7, and (*3*) 47.3 A and a pump current pulse duration of 1 μs, as well as (b) dependences of the shift of the long-wavelength edge of the laser spectra at half maximum of the pump current amplitude for pulse durations of (*1*) 1.0 and (*2*) 0.15 μs.

pulses. The obtained results clearly demonstrate an enhancement of the heating of the active laser region with increasing pump current amplitude and pulse duration. Whereas an increase in the pump current duration from 0.15 to 1 μs at a current amplitude of 12 A leads to a relative shift of the spectrum by 0.6 nm, which corresponds to an increase in temperature by 2 °C (taking into account a shift coefficient of 0.3 nm $°C^{-1}$), the same increase in the pulse duration at a current amplitude of 47 A leads to a shift by 1.4 nm, which corresponds to an increase in temperature by 4.7 °C. All this allow us to estimate that the heating of the active region corresponding to the 2.4-nm red shift of the spectrum with increasing current amplitude from 12 to 47 A at a pump current pulse duration of 1.0 μs occurs with a rate of 0.23 °C A^{-1}. Thus, the thermal overheating of the active region upon pumping by current pulses with a duration of 1 μs and an amplitude of 47 A does not noticeably affects the radiative efficiency of semiconductor lasers based on tunnel-coupled heterostructures with the emitting aperture widened to 800 μm, which is confirmed by the LCC linearity (Fig. 2).

The second part of experiments was devoted to the measurements of the radiative characteristics of the lasers pumped by long pulses (0.1 – 1 ms, repetition rate 10 Hz) at a heat sink temperature of 15 °C. The oscillograms of a pump current pulse and a lasing pulse with a duration of 860 μs are presented in Fig. 4. It is evident that, at a constant pump current pulse amplitude, the laser power and radiative efficiency decrease, which was not observed in the case of pumping by 1-μs pulses (see Figs 1 – 3).

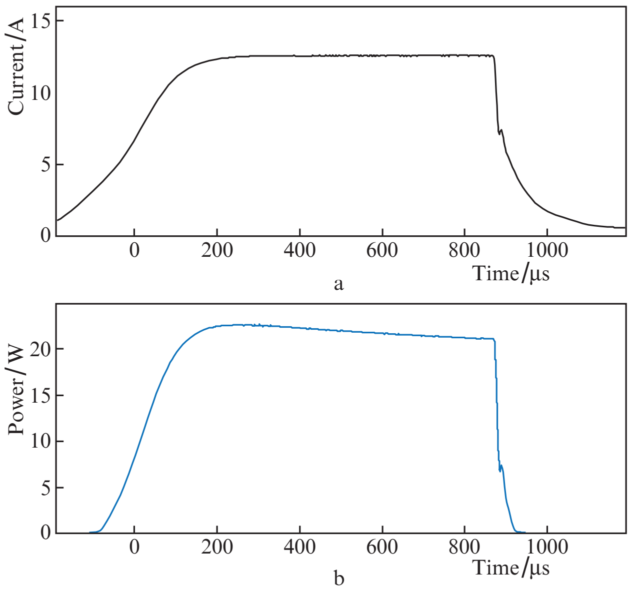

Figure 4. (Colour online) Oscillograms of (a) a pump current pulse with an amplitude of 12.5 A and (b) the corresponding laser pulse with a peak power of 22.7 W.

Figure 5 shows how the laser power changes during a pump current pulse with a constant amplitude. The oscillogram corresponding to the maximum used pump current amplitude of 12.5 A and a laser pulse duration of 860 μs can be divided into two time ranges (Fig. 5a). The decrease in the output power in the first (near) range can be approximated by a straight line with a slope of 3.07 mW μs^{-1} (dashed line in Fig. 5a), while the power in the second (far) range decreases more slowly, i. e., we can expect stabilisation of the output power level for longer pulses. In the region with a constant injection current amplitude, the emitted power decreased during the laser pulse with a duration of 860 μs by 6.7% with respect to the maximum value of 22.7 W (Fig. 5a). A decrease in the pump current pulse amplitude to 10 A led to the expected decrease in the emitted power decreasing rate to 1.46 mW μs^{-1} (dashed line in Fig. 5b). In this case, at a laser pulse duration of 740 μs, the decrease of power in the entire time range can be approximated by one straight line (Fig. 5b). It should be noted that the noticeable decrease in the emitted power during the pulse duration is absent at current pulse amplitudes below 8 A.

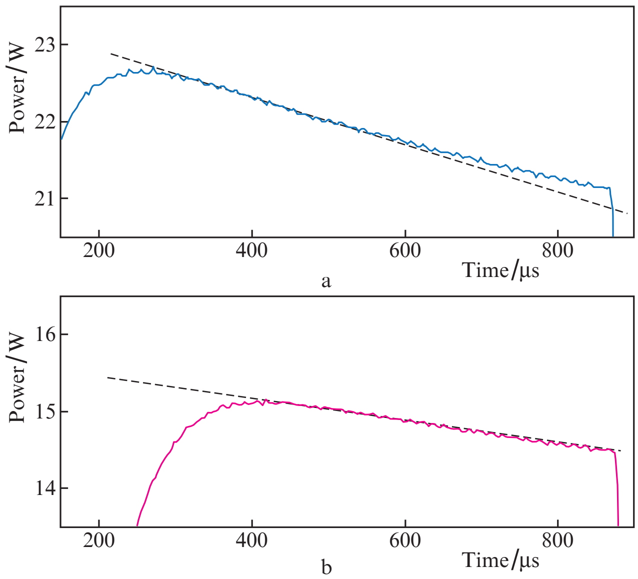

Figure 5. (Colour online) Oscillograms of the upper parts of laser pulses on an enlarged scale at pump current pulse amplitudes and durations of (a) 12.4 A, 860 μs and (b) 10.4 A, 740 μs. The dashed lines show the approximations of the linear regions of laser pulses corresponding to a constant pump current amplitude.

To estimate the thermal heating of the active laser region as one of the main factors decreasing the output power, we measured the lasing spectra under different excitation conditions (Fig. 6). The influence of the pump current amplitude on the laser spectra at the minimum pulse duration (85 μs) is demonstrated in Fig. 6a [the inset shows the laser pulse shape at the maximum current pulse amplitude (20 A) used in this experiment]. One can see that an increase in the current amplitude from 13 to 20 A leads to a shift of the long-wavelength edge of the spectrum by 3.3 nm, which corresponds to an increase in the active region temperature by 11 °C. The corresponding rate of the active region heating is 1.6 °C A^{-1}, which is considerably higher than that in experiments with 1-μs current pulses. Figure 6b presents the laser spectra recorded at a fixed amplitude (16 A) and different pump current pulse durations (the inset shows the shapes of the laser pulses). An increase in the laser pulse duration from 55 to 356 μs leads to a shift of the long-wavelength edge of the spectrum by 3.6 nm, which corresponds to the growth of the active region temperature by 12 °C. Thus, the rate of increase in the active region temperature with increasing pulse duration is 0.04 °C μs^{-1}. It

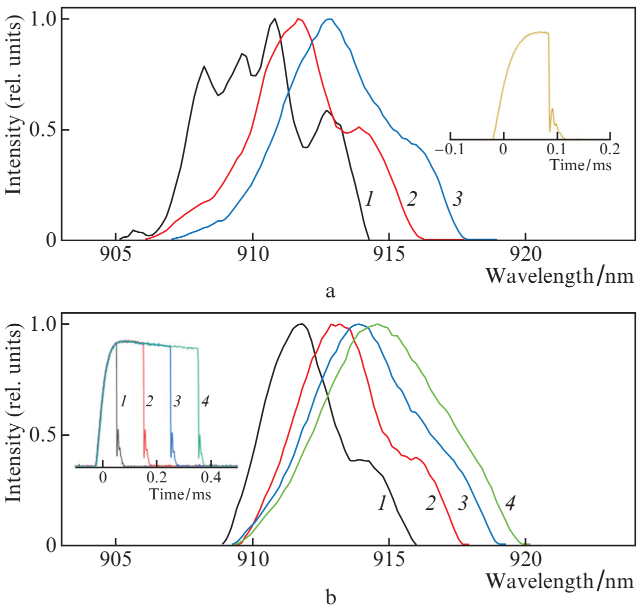

Figure 6. (Colour online) Laser spectra upon pumping by current pulses (a) with a duration of 85 μs and amplitudes of (*1*) 13, (*2*) 16, and (*3*) 20 A (the inset shows the laser pulse at a current amplitude of 20 A) and (b) with an amplitude of 16 A and durations of (*1*) 55, (*2*) 153, (*3*) 252, and (*4*) 356 μs (the inset shows the shapes of laser pulses corresponding to current pulses *1*–*4*).

is necessary to note that this rate will change with variations in the pump current pulse amplitude and shape.

Figure 7 shows the dependences of the peak power on the current pulse amplitude at pulse durations of 85, 500, and 860 μs. Since, as was demonstrated above (see Fig. 5), the emitted power decreases during the pulse, we plotted this dependence using the maximum powers of laser pulses. The dashed line is the approximation of the LCC corresponding to the pulse duration of 1 μs. It is seen that the peak powers

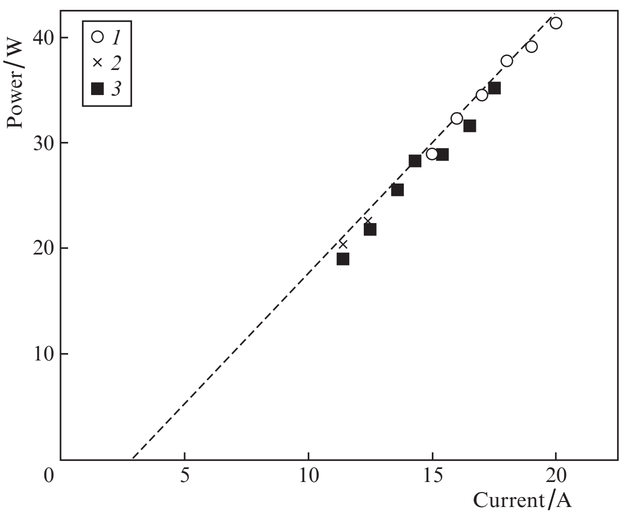

Figure 7. Dependences of the peak power on the current pulse amplitude for pump current pulse durations of (*1*) 85, (*2*) 500, and (*3*) 860 μs. The dashed line is the approximation of the LCC obtained in the case of pumping by current pulses with a duration of 1 μs.

reached in the studied range of current amplitudes are close to the amplitudes obtained for pulses with a duration of 1 μs. Hence, at the initial part of the pulse, i. e., in the range of up to ∼100 μs, the active region of the laser is not considerably heated. This will allow one in the future to use pump current pulses of the same duration but with a higher amplitude. In our case, the maximum power of laser pulses with a duration of 85 μs was 41.4 W at a pump current amplitude of 20 A.

The experimental studies of the near- and far-field radiation distribution for single emitters with an 800-μm aperture and for bars based on these emitters were previously performed for pump current pulses with durations from 1 to 100 ns [5, 7]. We believe that an increase in the current pulse duration should not cause considerable changes in the radiation distribution. In particular, it was shown in [5] that a rather uniform near-field intensity distribution forms for a time not exceeding 2 ns after the laser pulse initiation, and the maximum nonuniformity related to non-simultaneous initiation is observed only in the initial subnanosecond time range equal to 180–450 ps, which is negligible in the case of the studied pulse durations. The far-field intensity distribution in the planes parallel and perpendicular to the p–n junction has a Gaussian shape with a width at half maximum of ∼22° and 14°, respectively [7].

4. Conclusions

The reported experiments showed that the pumping regime (current pulse duration and amplitude) considerably affects the radiative efficiency of semiconductor lasers with an ultrawide aperture based on tunnel-coupled heterostructures with three laser sections. The use of pump current pulses with a duration of 1 μs does not cause noticeable heating of the active laser region at current amplitudes of up to 47 A. This allows us to suggest that the use of pump sources with a higher current pulse amplitude will allow a further increase in the output laser power with retention of high radiative efficiency, while the development of laser bars with an aperture of 1 cm will provide the possibility to reach the peak power of a kilowatt level. However, estimation of the permissible limit of the pump current requires additional investigations. The use of current pulses with durations of 0.1–1 ms leads to a noticeable enhancement of thermal heating of the active laser region. In particular, heating does not noticeably affect the radiative efficiency at a pulse duration of 85 μs in the case of current amplitudes of up to 20 A, but the laser power at a pulse duration of 860 μs noticeably decreases during the pulse even at pump current amplitudes of ∼10 A. The obtained results demonstrate the possibility of a further increase in the optical power by increasing the pump current amplitude at pulse durations of ∼100 μs and by widening the emitting aperture of laser diode bars.

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