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High-power quasi-cw semiconductor lasers (1060 nm) with an ultra-wide emitting aperture

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Abstract. **High-power quasi-cw semiconductor lasers with an emitting aperture 800 μm wide and a continuous p-contact are developed. Laser operation with a pulse duration of 1 ms, a repetition rate of 10 Hz, and a maximum peak power of 87 W at a wavelength 1060 – 1070 nm is demonstrated under pumping by current pulses with am amplitude of 97 A. Experimental estimates show that overheating of the active region at the end of the laser pulse at a current of 97 A may reach 36.7 °C.**

Keywords: *semiconductor lasers, mesa-stripe design, heterostructure, quasi-cw regime.*

1. Introduction

The application of high-power semiconductor lasers in various fields imposes specific requirements on their operation regime. Owing to the high energy efficiency of these lasers, they are widely used for pumping fibre and solid-state lasers. The range of direct application of high-power semiconductor lasers for treatment of various materials also rapidly widens. In this case, the most preferable operation regime of laser diodes is a quasi-cw regime with millisecond pulse durations, which is caused either by the lifetimes of excited states in the active media or by the necessity of reaching a definite pulse energy for material treatment. The most popular approach to increasing the emitted power is the use of laser diode bars with an individual emitter aperture of ~100 μm and a total emitting region width of up to 1 cm [1], as well as of vertical stacks based on these bars. However, to achieve reliable and efficient operation of such structures, it is necessary to use technological solutions to minimise mechanical stresses appearing in the process of assembling [2].

Another problem is related to the development of optical systems that can form high-power laser beams with characteristics needed, for example, for radiation coupling into optical fibres. An alternative approach to creating high-power quasi-cw semiconductor lasers for kilowatt-level pumping systems is proposed in [3, 4]. This approach is based on individual emitters with an ultra-wide (400 – 1200 μm) emitting aperture, as well as on microbars composed of them. To solve the problem of inhomogeneous radiation distribution over the aperture, the aperture was formed using a set of stripe contacts, which also made it possible to avoid parasitic gain of radiation perpendicular to the cavity axis and excitation of high-Q closed modes [5]. As a result, an emitter with an aperture width of 400 μm and a set of micro-stripe contacts with a width of 2 – 7 μm and a period of 14 μm demonstrated a maximum power of 86 W under pumping by current pulses with an amplitude of 100 A, a duration of 500 μs, and a repetition rate of 14 Hz. In this case, the light – current (L – I) characteristic exhibited a pronounced saturation in the region of maximum currents due to heating of the laser. Another important aspect of using ultra-wide apertures is a decrease in the current density with unchanged output optical losses [6], which decreases the influence of the growth of internal optical losses at high pump currents [7].

In the present work, we report the results of investigation of the radiative characteristics of high-power quasi-cw (pulse duration 1 ms) semiconductor lasers with an aperture width of 800 μm. The main specific feature of the design under study is the use of a continuous ohmic contact from the p-side, which does not require additional technological operations related to the formation of a structured aperture.

2. Experimental investigations

We used a laser heterostructure grown by MOCVD. The structure included $Al_xGa_{1-x}As$ ($x = 30\%$) n- and p-type emitters 1.5 μm thick each, an $Al_xGa_{1-x}As$ ($x = 10\%$) waveguide layer 1.7 μm thick, and an active region based on one InGaAs quantum well 9 nm thick. For mode selection in the transverse multimode waveguide and fulfilment of threshold conditions for the zero mode, the quantum well should be shifted to the p-emitter with respect to the waveguide layer centre by 0.2 μm. To avoid current filamentation in the plane of the p – n junction in the case of the continuous ohmic contact, we formed a Ti/Pt/Au ohmic p-contact, which provided a high homogeneity of the contact resistance over the entire area. From the substrate side, we used a continuous AuGe/Au n-contact. A mesa-stripe waveguide structure was formed in the lateral direction. The laser crystals with a cavity length of 2900 μm were cut from the obtained structure and had antireflection (5%) and high-reflection (95%) coatings. The laser crystals were mounted with the p-side down on a copper heat sink using indium solder. The measurements were performed at a constant heat sink temperature of 15 °C. The lasers were pumped using a generator of current pulses with a repletion rate of 10 Hz and a duration of 1 ms. The shape of laser pulses

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was detected using an InGaAs photodetector, which ensured high sensitivity and stability of measurements in the studied spectral range.

Figure 1 presents the typical shapes of current and laser pulses. All pump current pulses had a stable amplitude (except for the turn-on and turn-off edges). The shape of the laser pulses was identical to the shape of current pulses at amplitudes up to ~50 A, but, at higher current amplitudes, the laser power smoothly decreased (Fig. 1b).

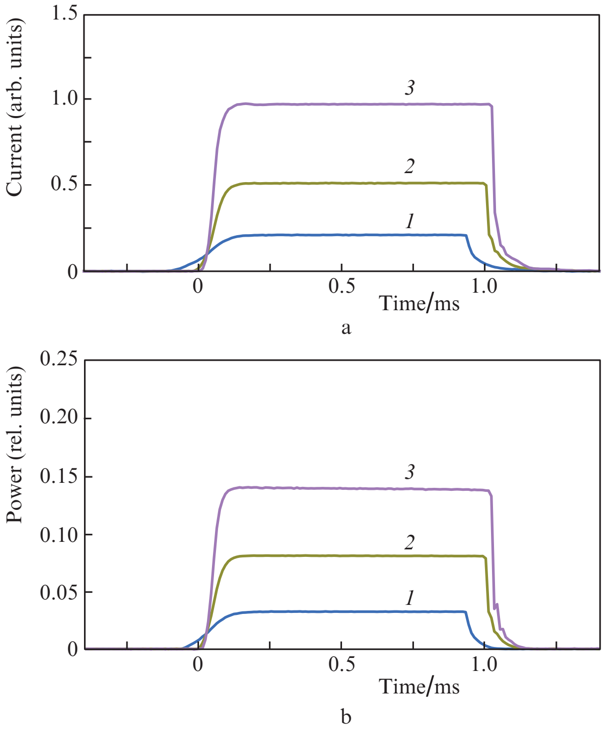


Figure 1. Shapes of (a) pump current and (b) laser pulses at pump current amplitudes of (*1*) 21, (*2*) 51, and (*3*) 91 A.

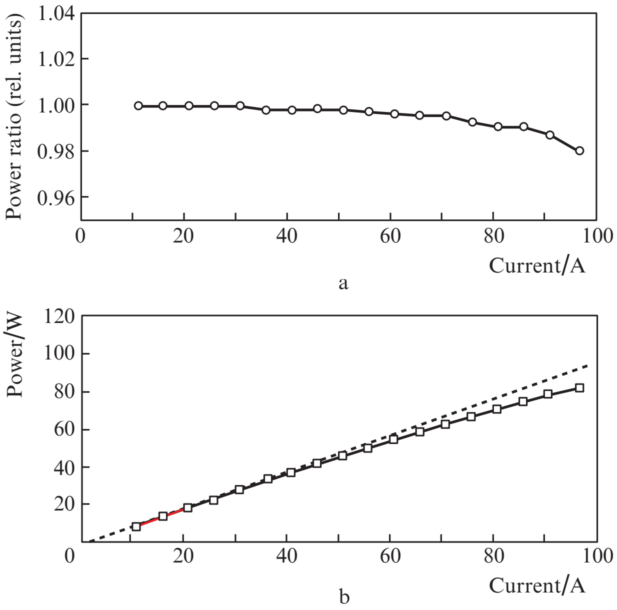


Figure 2. Dependences (a) of the ratio between the output optical powers at the pulse end and beginning and (b) of the maximum laser pulse peak power on the pump current amplitude. The cavity length of the semiconductor laser is 2900 μm, the reflection coefficients of the cavity faces are AR(5%)/HR(95%), the heat sink temperature is 15 °C, the pulse duration is 1 ms, and the pulse repetition rate is 10 Hz.

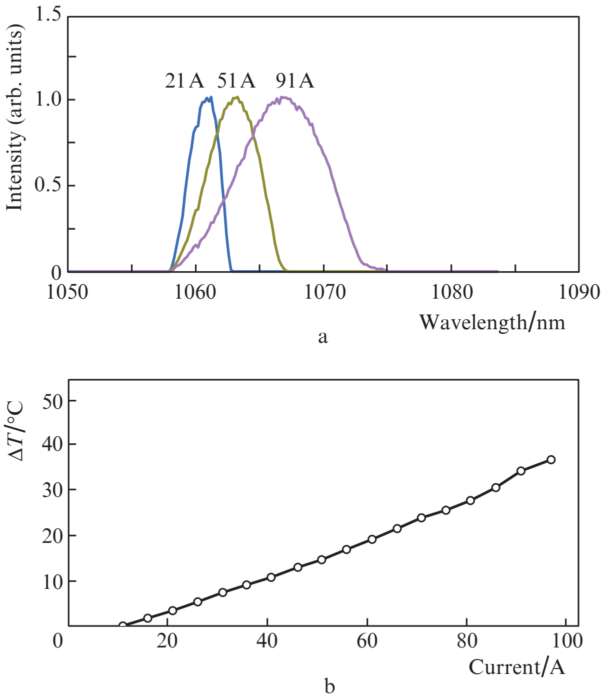
Figure 2a shows how the laser power at the pulse end changes with respect to the initial pulse power at different pump current amplitudes. One can see that the output optical power decreases to the pulse end by 2% at the maximum pump current of 97 A, while this decrease in the current range 0–50 A does not exceed 0.2%. Figure 2b presents the dependence of the maximum peak power on the pump current amplitude. The maximum output power of the developed samples was 83 W at a current of 97 A. A noticeable deviation from the linearity of the L–I characteristic is observed at currents exceeding 40 A.

We can point out two main factors affecting the output optical power saturation and the deviation from the L–I characteristic linearity with increasing injection current, namely, an increase in the internal optical losses and a decrease in the radiative efficiency due to increasing temperature of the active laser region. At a maximum current density of 4.18 kA cm^{-2}, an increase in the internal optical losses is ~0.5 cm^{-1} [8], which does not explain the observed saturation of the L–I characteristic. The laser spectra measured to estimate the contribution of heating by the injection current (Fig. 3a) demonstrate broadening to longer wavelengths with increasing current, which is a typical feature of thermal heating. To calculate the heating of the active region from the shift of the long-wavelength spectral edge, we measured the laser spectra in the range of heat sink temperatures 20–50 °C upon pumping by 10-ns pulses (when heating by the pump current can be neglected) with amplitudes of 20 and 40 A, i.e., under the conditions when the measured heat sink temperature corresponds to the temperature of the active region. The obtained results showed that the shift of the long-wavelength edge of the laser spectrum $\Delta\lambda_{\mathrm{LE}}$ (in nm) with the temperature change ΔT (in °C) can be with a sufficiently high accuracy described by the linear dependence

$$\Delta\lambda_{\mathrm{LE}} = \Delta T k,$$

where k is a constant coefficient found from approximation of experimental dependences and equal to 0.36 nm C^{-1} for the studied samples. Using this k and the experimentally measured laser spectra (Fig. 3a), the active region overheating can be determined by $\Delta\lambda_{\mathrm{LE}}$. This overheating was estimated with the use of the shift of the long-wavelength edge of the normalised laser spectra at a level of 0.02 from the maximum. The dependence of the active region overheating on the pump current is shown in Fig. 3b. The shown values were calculated with respect to the active region temperature corresponding to a pump current of 10 A. One can see that overheating at the pulse end at a maximum current of 97 A reaches 36.7 °C.

To determine the contribution of the main mechanisms, which are related to thermal heating and lead to a decrease in the optical power at the maximum pump current level, we measured characteristic temperatures T_0 and T_1 which determine the temperature dependences of the threshold current and of the external differential efficiency, respectively. It was found that, for the studied samples, $T_0 = 110$ K, which means



a

b

Figure 3. (a) Laser spectra at different pump current pulse amplitudes and (b) dependence of overheating of the active laser region on the pump current amplitude. The laser parameters and operation conditions are the same as in Fig. 2.

that the threshold current equal to 1.9 A at the working temperature will increase to 2.65 A at a temperature of 51.7 °C corresponding to the pulse end. At $T_1 = 332$ K, the slope efficiency equal to 0.976 W A^{-1} for a working temperature of 15 °C decreases to 0.874 W A^{-1} for a temperature of 51.7 °C corresponding to the pulse end. The maximum power for a current of 97 W determined by the linear approximation of the initial L–I characteristic range is 91.3 W, while, according to the experimental estimate of thermal heating and a change in the characteristic temperature, the power should decrease to 82.4 W. The experimentally measured maximum power at the pulse end was 81.3 W. The decrease in power obtained in the experiment is insignificant and can be caused by underestimation of the contribution of internal optical losses at the working current [8] because the characteristic temperatures were determined in the near-threshold pumping regime. Our estimate shows that the decisive contribution to the output optical power saturation at pump currents exceeding 90 A is made by the mechanisms related to thermal heating.

3. Conclusions

The obtained results demonstrate the possibility of creating kilowatt quasi-cw laser sources based on stacks or bars of emitters with an ultra-wide aperture and a continuous p-contact. However, generation of millisecond pulses is accompanied by enhanced heating of the active region, which leads to saturation of the L–I characteristic of the laser at high (~100 A) pump currents. Thus, an increase in the output optical power at high pump currents can be achieved by increasing the temperature stability of the output characteristics of semiconductor lasers. A step in this direction can be related to a decrease in the threshold material gain due to, for example, an increase in the optical confinement factor in the active region, which will make it possible both to increase the temperature stability of the threshold current and to reduce a decrease in the slope efficiency caused by increasing internal optical losses in the range of working pump currents.

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