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Modelling and experimental study of temperature profiles in cw laser diode bars

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Abstract. **Three-dimensional simulation is used to theoretically assess temperature profiles in proposed 10-mm-wide cw laser diode bars packaged in a standard heat spreader of the C–S mount type with the aim of raising their reliable cw output power. We obtain calculated temperature differences across the emitting aperture and along the cavity. Using experimental laser bar samples with up to 60 W of cw output power, the emission spectra of individual clusters are measured at different pump currents. We compare and discuss the simulation results and experimental data.**

Keywords: *laser diode bars, cw operation, temperature distribution.*

1. Introduction

High-power semiconductor laser diodes possess a record high total electrical-to-optical power conversion efficiency (total efficiency), up to 50%–70%, among solid-state lasers [1]. Along with the optical damage resistance, the most serious problems limiting the maximum reliable output power and brightness of laser diodes are the insufficiently effective cooling of the active region of the laser chip when extremely large heat fluxes should be dissipated and temperature profile nonuniformities in the gain element.

The reduction in internal loss in modern heterostructures has made it possible to increase the laser diode cavity length to 4–5 mm and above, thus reducing the thermal load density. However, when this approach is used for reducing the thermal load, temperature profile nonuniformities along the length of the cavity and across the emitting aperture begin to play a more significant role. In particular, as shown earlier [2] temperature differences along the length of a laser cavity can reach a considerable level (16–17 °C), which is rather essential for the long cavities characteristic of state-of-the-art chips in high-power laser diodes.

The problem of temperature field nonuniformities in the gain element is no less important for laser diode bars (LDBs), which have a standard width of 10 mm.

In previous work [3, 4], cw LDBs with 60 W of output power and quasi-cw LDBs with up to 300 W of output power were demonstrated. An important incentive to study the temperature fields in high-power LDBs is reports that a kilowatt output power can potentially be obtained from one such LDB [5]. If the slope of a light–current (L–I) characteristic at a high pump power is 1 W A^{-1}, the pump current at output powers in the kilowatt range reaches a kiloampere level and the thermal load rises by more than one order of magnitude. Under such conditions, a threshold current of 20 A plays no significant role for a typical 10-mm-wide bar. To reach an output power in the kilowatt range, it is necessary to considerably improve heat dissipation efficiency and emission uniformity across the LDB aperture. In an ideal case, to ensure that all LDB clusters have identical output powers, they should have identical current–voltage and light–current characteristics.

At high pump powers, the total efficiency decreases, so at a cw output power of 1 kW the pump current will exceed 1 kA. Therefore, with increasing output power and thermal load, the ability to evaluate temperature profile nonuniformities in a laser chip becomes more critical. Such information is necessary for the practical implementation of modern laser bar design optimisation techniques with the aim of raising the maximum reliable optical output power. In this context, it is of interest to numerically model the temperature field in high-power LDBs, obtain isothermal surface distributions, construct the temperature profiles across the emitting aperture and along the cavity of LDBs differing in the emitting cluster fill factor of the output aperture and assess the influence of output power and thermal load on the profiles in order to optimise parameters of the entire system.

Another important incentive to perform thermal calculations and experimental studies in this area of research is the considerable interest in improvement of the uniformity of output parameters in systems for the summation of the emission power of individual clusters of laser bars. Beam combining schemes are used to raise the emission brightness in the case of the summation of the emission power of individual emitting clusters of monolithic laser bars and the emission power of two-dimensional laser diode arrays for use in direct laser processing of materials (cutting, welding, milling, drilling, etc.) [6]. Various schemes and methods are used for emission power summation. In particular, impressive advances

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have been made using wavelength beam combining, an approach that made it possible to raise the emission brightness of a diode laser emitter by two orders of magnitude and obtain 2, 4 and 6 kW of cw output power [7]. Beam combining schemes employ complex optical systems. A laser chip bend in a bar (so-called diode bar smile) and thermoelastic stress, in particular, that arising from nonuniform temperature fields, lead to considerable optical distortions and reduce the efficiency of such systems [8, 9].

2. Simulation

In this study, thermal processes in a laser bar were simulated by the finite element method in the COMSOL Multiphysics environment. We examined 10-mm-wide cw bars mounted on a copper heat sink of the C–S mount type.

The following assumptions were made in the simulation: uniform pumping of all the clusters in the bar and zero bend of the laser chip over the entire range of pump currents studied, uniform thermal contact between all the clusters in the bar, constant thickness of the solder layer over the entire heat transfer area and, hence, identical conditions of heat flow propagation from individual emitting clusters of the bar to the lower, thermally stabilised face of the heat spreader. The boundary condition was the constant temperature (20 °C) of the lower face of the C–S mount.

In accordance with the geometry of the gain elements used, in our simulations the length of the laser cavity in cw bars was 2 mm and the LDB width was 10 mm. We varied the output power and thermal load, taking into account the experimentally determined dependence of the total efficiency on pump current. As a basic model, we considered a 19-cluster bar with an emitting cluster fill factor of the output aperture FF = 50 %.

3. Simulation results

Figure 1 presents a simulated temperature distribution in a laser bar at a thermal load of 60 W. The shape of the isothermal surfaces obtained points to characteristic thermal field nonuniformities. It is seen that the temperature in the central part of the bar considerably exceeds that in the peripheral parts. An analogous picture is observed along the length of the cavity, with the highest temperature on the output mirror of the bar. The simulation results indicate that the spectral parameters of high-power diode bars are determined to a significant degree by the thermal load distributions in the laser chip. Individual clusters of a laser chip have different temperatures because of the differences in heat flow dissipation efficiency. The central part of the laser bar has a higher temperature because there are less favourable conditions in terms of heat dissipation efficiency in comparison with the peripheral parts. This has a significant effect on the spectral parameters of emission from individual clusters, which depend on their position across the emitting aperture of the LDB.

Figure 2 shows distributions of temperature profiles across the emitting aperture for a standard, 10-mm-wide cw laser bar with a cavity length of 2 mm, consisting of 19 clusters with FF = 50 % in a steady state at a thermal load power varying from 10 to 100 W in 10-W steps. The temperature is seen to be modulated with the period in the position of the emitting clusters. As the thermal load is raised from 10 to 100 W, the calculated temperature of the central cluster in the bar increases relative to the stabilised temperature of the heat sink (20 °C) by 3 and 38 °C, respectively, and the temperature modulation amplitude increases from 0.5 to 4 °C.

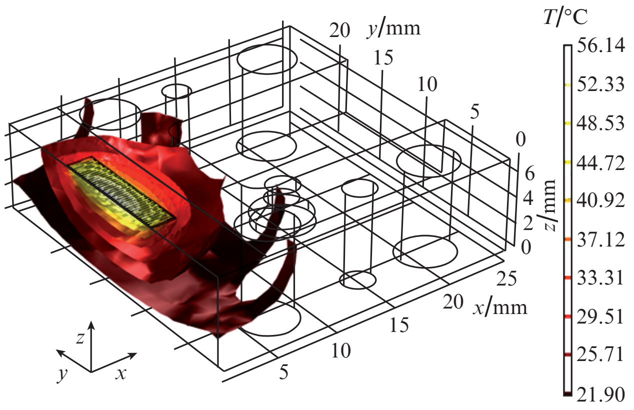

Figure 1. Thermal model of an LDB. Isothermal surfaces for an LDB chip bonded on a C–S mount; thermal load, 60 W.

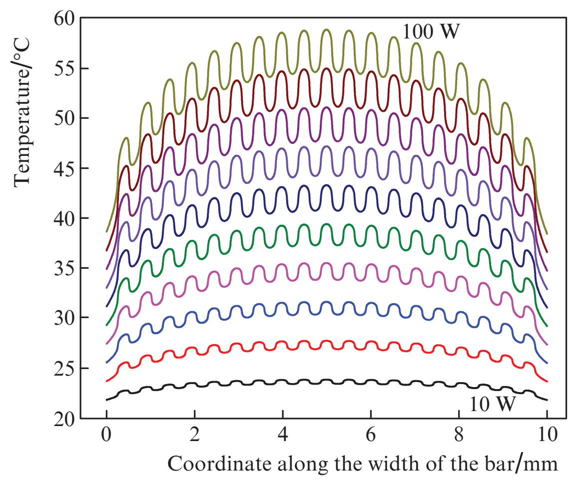

Figure 2. Temperature profiles of a laser bar across the emitting aperture on the active region line at thermal loads from 10 to 100 W (10-W step).

Figure 3 shows the temperature difference between the central and peripheral clusters as a function of thermal load. It is seen that increasing the number of the cluster leads to a superlinear increase in the slope of the graphs. At a thermal load of 100 W, the calculated temperature difference between the central and peripheral clusters is about 10 °C. The corresponding separation between the maxima in the envelopes of the emission spectra is about 2.5–3 nm. This is more clearly seen in Fig. 4, which shows the temperature difference between the central cluster and all the peripheral clusters of a laser bar at thermal loads from 10 to 100 W. Note that the temperature difference is a linear function of thermal load.

From Fig. 4, we can estimate the calculated temperature difference between the central and peripheral clusters, whose parameters can be measured in experiments in order to compare the predictions of the theoretical model with the real situation. According to the simulation at a thermal load of 25 W, the separation between the maxima in the envelopes of the emission spectra should be less than 1 nm. Simulations show that the temperature difference between the clusters decreases along the length of the cavity in going from the out-

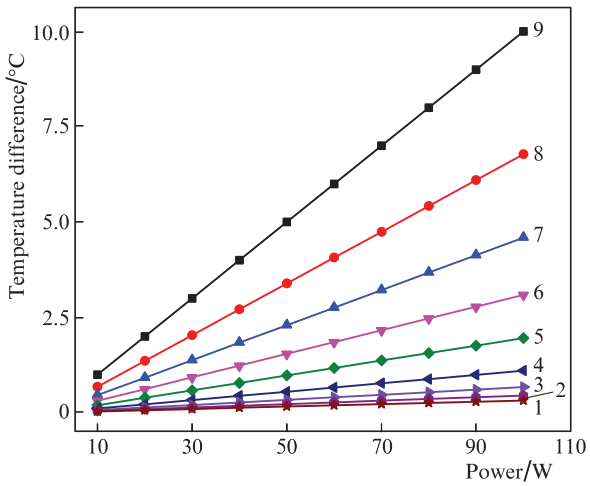

Figure 3. Temperature difference between the central (zeroth) cluster and peripheral clusters (±1 to ±9, where ±1 denotes the clusters closest to the central one and ±9 denotes the outermost clusters) as a function of thermal load power.

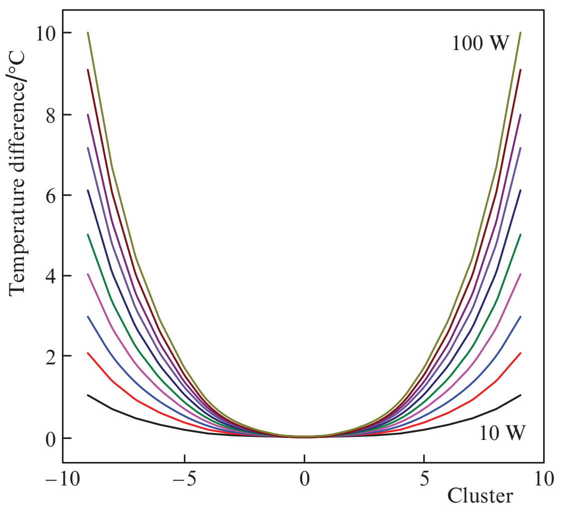

Figure 4. Temperature difference between the central and peripheral clusters of a laser bar at thermal loads from 10 to 100 W (10-W step).

put mirror to the high-reflectivity one. Moreover, the temperature differences between the central and peripheral clusters on the output mirror are similar to those of the peripheral cluster along the length of the cavity.

4. Experimental results

Figure 5 shows a schematic of the experimental setup used to measure emission parameters and temperature profiles of cw LDBs. The bars (emission wavelength, 808 nm), 10 mm in width, consisting of 19 clusters with FF = 50 %, were mounted on a C–S mount type heat sink. The packages of the C–S mounts of the LDBs were mounted on a massive copper block connected to a liquid cooling system (chiller). The bars were powered by a pump driver (Fedal, St. Petersburg) with a built-in pump control system. The integrated power of the LDB was measured using Gentec instruments. The emission spectra and power of individual clusters were measured by

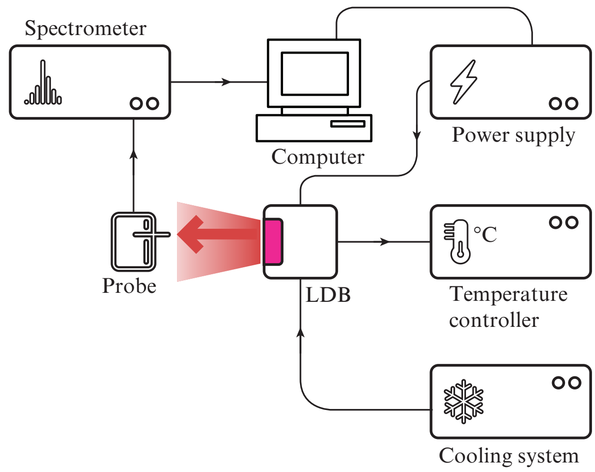

Figure 5. Experimental configuration.

probing the emission of individual clusters in the LDB across the aperture (10 mm) using a specially designed and produced probe, which had the form of an optical waveguide with a 300-μm-diameter receiving area. The probe was adjusted and translated relative to the output mirror of the LDB by a three-coordinate, two-angle micrometer head.

After a change in pump power, especially at a high thermal load, a certain time was needed for the LDB to reach a steady thermal state, so the emission power and spectrum at each point of the $L-I$ characteristic were measured after thermal equilibration. The data thus obtained were fed to a computer for further processing.

Figure 6 shows the emission spectra of the central and peripheral clusters at an output power of 60 W. It is seen that the emission spectra of individual clusters have a complex shape, so the exact peak position is difficult to determine. At the absolute maximum of the spectra, the spectral shift is 2.4 nm. If the spectra are approximated by their envelope, the spectral shift is 1.6 nm. According to our estimates, the temperature difference between the central and outermost peripheral clusters of the bar is 8–9.6 or about 5–6 °C.

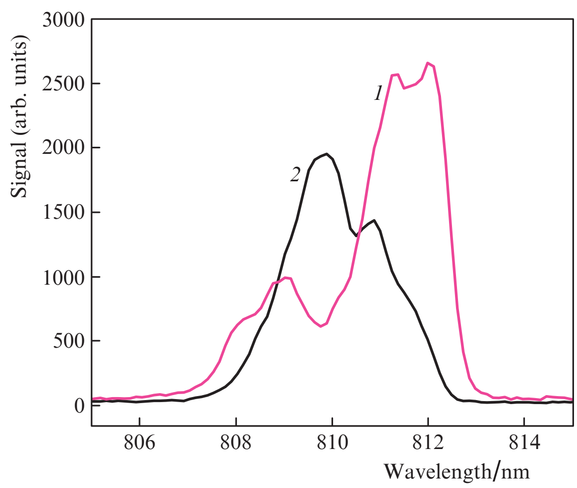

Figure 6. Emission spectra of the (*1*) central and (*2*) outermost clusters at an output cw optical power of 60 W.

5. Discussion and conclusions

At an output power of 60 W and thermal load of 90 W, the measured total efficiency of the laser bar was 40%. According to the simulation results presented in Figs 3 and 4, the temperature difference between the central and outermost peripheral clusters at this thermal load is about 9 °C. The temperature coefficient of the emission wavelength of the 808-nm laser diodes lies in the range 0.25 – 0.3 nm K^{-1}. To more accurately determine it, special measurements on model samples of single-stripe laser diodes fabricated from analogous heterostructures are needed. The spectral separation between the position of the absolute maxima in the emission spectra of the central and outermost peripheral clusters (Fig. 6) is 2.4 nm. This corresponds to a temperature difference of 8 – 9.6 °C, in agreement with the simulation results. Given the complex shape of the emission spectra of individual clusters and the insufficient accuracy in determining the position of the maximum in the envelope of the spectra, and taking into account the rather rough simplifications in the simulation model as to the uniformity of pumping and the heat flow being removed from the clusters, we conclude that there is qualitative correlation between the present simulation results and experimental data. (Note that the simulation results and experimental data were compared for a thermal load power of 90 W and output power of 60 W.)

Estimates suggest that, at kilowatt LDB powers, the temperature of the active region and the temperature difference across the emitting aperture may exceed those obtained in this study by more than one order of magnitude, reaching 100 – 150 °C. Note that, with the existing LDB cooling methods, including microchannel plates, reliable operation of LDBs at such high temperatures and large thermal field nonuniformities is quite problematic. Clearly, the simulation model used here needs further development because, in addition to the above-mentioned rather rough assumptions as to the uniformity of pumping and the heat flow being removed from the clusters, it leaves out of account the thermoelastic stress in the fairly long (10 mm) LDB chip. The stress may also have as significant effect on the spectral characteristics of emission from different clusters, because a uniform thermal contact between an LDB and planar heat spreader is only possible if the chip is elastically deformed to minimise its bend.

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