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Spectral features and thermal resistance of 976-nm cw laser diodes with a power up to 15 W

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Abstract. **The spectral characteristics of cw laser diodes with a maximum reliable power of 15 W mounted on F-mount heat sinks are studied. It is found that the spectrum envelopes have features at emission powers exceeding 5 – 7 W. A method for determining the maximum of a spectrum envelope under the conditions of its broadening and appearance of features is discussed. The thermal resistance of diodes is determined experimentally at pump currents from threshold to maximum (14 A) and is found to be 2.25 K W^{-1} at a current of 10 A and 1.5 K W^{-1} at a current of 4 A. The results obtained are compared with the literature data. The adequacy of using the thermal resistance parameter for comparing and estimating thermal characteristics of laser diodes is considered.**

Keywords: *high-power laser diodes, efficiency, maximum reliable power, thermal resistance.*

1. Introduction

At present, one of the most important problems of laser engineering is the direct use of the emission of high-power laser diodes for materials processing. To solve this problem, it is necessary to considerably increase the output power and brightness of these diodes. Such works are performed, in particular, within the BRIDLE project [1].

The main factor limiting the power of laser diodes is still the thermal problem. In addition, to increase brightness, one must solve problems of optical resistance and service life of cavity mirrors under extremal optical loads and in multimode lasing regimes. In general, the technologies of production of high-quality mirror cleavages are already developed. All the main operations, including scribing and cleaving of heterostructures, as well as passivation of the obtained juvenile surface of the cleaved crystal planes and their protection by dielectric coatings, are performed under conditions of high vacuum in one vacuum system. The parameters of produced mirrors are close to the limit of technological capabilities, because of which one needs new approaches to solving the mentioned problems. One of the variants can be the development of heterostructures with an extremely broad waveguide, which allows one to decrease the optical power density on the output mirror of the laser cavity, but a significant increase in the thickness of the waveguide layer leads to an increase in the electrical series resistance of the structure and to an increase in the thermal resistance, which altogether can decrease the total efficiency and aggravate the thermal problem at high pump powers.

In our recent work [2], we reported that the maximum reliable power of a laser with a stripe contact width of 95 μm emitting at $\lambda = 976$ nm was increased from 10 to 15 W when mounting the laser crystal on a copper heat sink of the F-mount type instead of the C-mount type. The importance of this result also consists in the fact that we did not use expensive diamond or composite (based on diamond) submounts, because of which the laser price remained moderate. To compare our results on the increase in heat removal efficiency with the results of other authors, it is necessary to use generally accepted criteria and estimation parameters. Such a parameter is the thermal resistance of diodes, and this work is devoted to the measurement of this resistance.

2. Output power, efficiency and emission spectra of laser diodes

The light – current characteristic and the total efficiency of our sample in a cw regime are shown in Fig. 1. The measurements were performed when the temperature of the mounting surface of the basic copper heat sink plate was 20 °C. This temperature was kept constant using a thermoelectric cooler. The main parameters were measured to be as follows: the

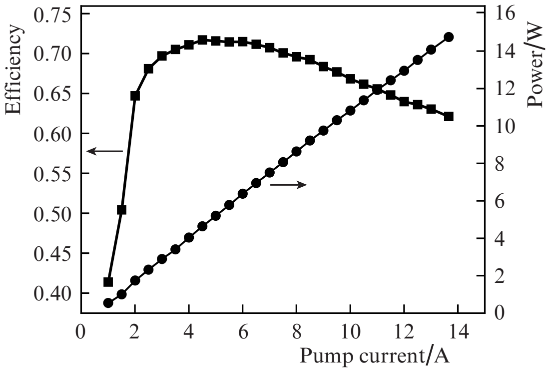

Figure 1. Light – current characteristic and total efficiency of the laser diode ($\lambda = 976$ nm) in a cw regime at a temperature of 20 °C.

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threshold current was ~0.9 A, the light–current characteristic was close to linear, its average slope was 1.11 W A^{-1} in the current range 1–14 A, the maximum efficiency (at a pump current of ~5 A) was 72%, and the output power was 15 W at a current of ~14 A.

The spectra of these lasers, as follows from our analysis of available publications, are studied insufficiently; at the same time, these spectra are of great interest for some practical applications, including pumping of active laser media. The envelopes of the emission spectra in a steady-state cw regime are presented in Fig. 2. One can clearly see that, at pump currents exceeding 5 A, the short-wavelength wing has features, which take the form of local maxima with increasing current. Since the thermal resistance is determined using spectral measurements and the position of the spectral maximum is rather important for obtaining correct values, we have to consider this phenomenon.

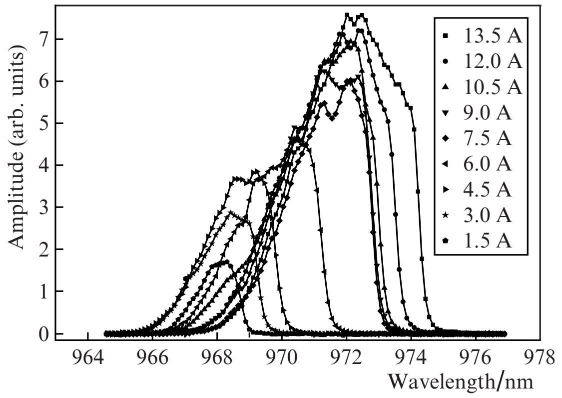

Figure 2. Emission spectra of the laser diode at different pump currents.

3. Thermal resistance: definitions and measurement technique

The thermal resistance parameter is commonly used to estimate thermal characteristics of electronic devices. This parameter with a relevant correction in its definition is also widely used to analyse thermal characteristics of high-power laser diodes.

The thermal resistance for a laser diode is defined as $R_{\rm therm} = \Delta T/P_{\rm therm}$, where ΔT is the increase in the diode temperature caused by injection of the total electric power $P = P_{\rm therm} + P_{\rm opt}$; $P_{\rm therm}$ is the thermal load; and $P_{\rm opt}$ is the power of coherent optical radiation.

The laser converts the injected power $P = IU$ (I is the current and U is the voltage) into the coherent optical radiation proportionally to the total efficiency $\eta_{\rm tot}$, i.e., $P_{\rm opt} = P\eta_{\rm tot}$, and, therefore, the thermal load is $P_{\rm therm} = P(1 - \eta_{\rm tot})$. In particular, this definition was explicitly used in [3].

The temperature of the active layer in a laser heterostructure is determined from spectral measurements and from the temperature dependence of the wavelength of the emission spectrum maximum, which is known for a given composition and thickness of the active layer. For laser diodes emitting in the spectral range 970–980 nm, $\Delta\lambda/\Delta T = 0.3$–$0.33$ nm K^{-1}; we used in our calculations the minimum value 0.3 nm K^{-1}.

It is obvious that the appearance of features in the emission spectra, which are shown in Fig. 2 in the form of local maxima, as well as the significant broadening of the spectrum envelope, complicates the determination of the maximum position and, hence, the calculation of the thermal resistance. Moreover, when calculating the thermal resistance for each of the pump current values, we observed that the intensities of the local maxima in some current ranges change so that the short-wavelength maximum becomes dominant. Processing of the spectrum by a standard computer program would yield a paradoxical result, including negative thermal resistances for some pump current regions. We believe that, in the case of a considerable broadening of the spectrum envelope and the appearance of the mentioned features, it is more reasonable to use the following method. One should determine the spectral width at half maximum by a standard program and take the centre of the obtained wavelength range as the position of the maximum.

The dependence of the envelope maximum on the pump current plotted using this approach is shown in Fig. 3. A characteristic feature of this dependence is that it can be rather precisely approximated by three linear segments with different slopes in the pump current ranges of 1–4, 4–7 and 7–10 A.

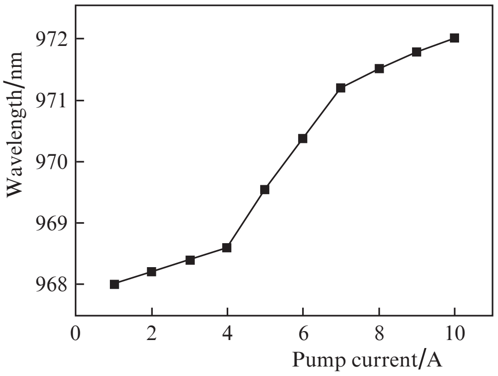

Figure 3. Dependence of the wavelength of the spectrum envelope maximum of the laser diode on the pump current.

4. Measurement results and comparison with published data

The values of thermal resistance at different pump currents are presented in Fig. 4. Correct interpretation of the data requires some explanations. The values ΔT and $\Delta P_{\rm therm}$ used to determine the thermal resistance for each pump current were calculated as the difference between the corresponding parameters at a given current and at the initial pump current of 1 A. Curve (*1*) (call it ideal) is plotted based on the assumption that the wavelength of the spectral maximum changes linearly with increasing pump current. This dependence is inversely proportional according to the thermal resistance definition, because the numerator linearly depends on the current while the first term in the denominator increases quadratically with increasing pump current.

Curve (*2*) is plotted using the real experimental dependence of the spectral maximum wavelength shown in Fig. 3. The three linear ranges of this dependence determine the existence of three regions of curve (*2*) in Fig. 4 and qualitatively correlate with the dependence of the total efficiency in Fig. 1. Indeed, the efficiency in the first region increases, and, corre-

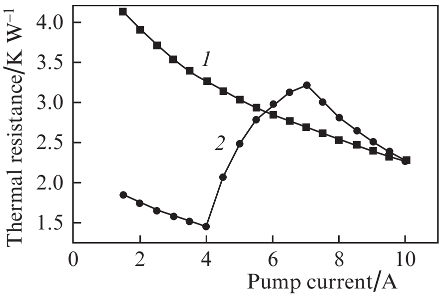

Figure 4. Dependences of the thermal resistance of the laser diode on the pump current: (*1*) calculated based on the assumption of a linear dependence of the wavelength of the spectrum envelope maximum on the pump current and (*2*) plotted by the experimental wavelengths of the spectrum envelope maximum.

spondingly, the thermal resistance slightly decreases due to increasing portion of emitted energy in the total thermal balance. Between the first and the second regions, one observes a thermal resistance minimum. In the second region, the efficiency slowly decreases from its maximum, the thermal load increases, and the thermal resistance correspondingly increases. In the third region, experimental curve (*2*) approaches the ideal curve, which testifies that the proposed method of determination of the position of the spectrum envelope maximum is sufficiently adequate. Paper [4] presents the results of measurements of the thermal resistance for a laser diode emitting at $\lambda = 980$ nm, which has a cavity length of 4 mm and a stripe contact width of 95 μm. The thermal resistance in the case of using a copper–diamond submount was 2 K W^{-1}, and, when this unit was assembled on microchannel coolers, the thermal resistance decreased to a record-low value of 1.5 K W^{-1}, which is obviously a limit for existing cooling technologies and the used materials of the submounts and heat sinks. In [3], the heat resistance for C- and F- mounts was found to be 4.25 and 2.97 K W^{-1}, respectively.

Our result obtained when mounting the laser crystals directly on the copper heat sinks is $R_{\text{therm}} \approx 2.25$ K W^{-1} at a pump current of 10 A, which is only slightly worse than the record values achieved in [4] using a copper–diamond composite and considerably better than the value found in [3]. Note that the resistance R_{therm} measured near the efficiency maximum at a pump current of about 4 A is approximately 1.5 K W^{-1} , which is equal to the record values given in [4]. We believe that adequate comparison of thermal resistances should be performed at identical pump currents. We also think that our results point to high-quality assembling and to a high heat-transfer efficiency achieved due to the technology proposed by us.

5. Conclusions

The most import conclusion of this work is obvious: the thermal resistance is an appropriate parameter for analysing thermal characteristics of laser diodes. However, this approach cannot be considered as rigorous because, even in the considered ideal case, thermal resistance by definition depends on the pump current chosen for measurements. The thermal resistance is inversely proportional to the pump current, i.e., the higher the current (and, hence, the higher the output power), the lower thermal resistance values will be obtained even in the ideal case of a linear dependence of the wavelength of the spectrum envelope maximum on the pump current. Due to this obvious fact, one must be careful when comparing the results obtained by different research groups at different pump powers, as well as using different materials of heat sinks and different cooling schemes of laser diodes. Our experiments show that an important role in the thermal resistance measurements is played by the used cooling system, including heat sinks with conductive heat removal, heat sinks with forced air cooling and liquid cooling systems (chillers), as well as thermoelectric coolers, thermal tubes, thermal chambers, etc. An important role in measurements is played by the position of the temperature sensor with respect to the laser diode housing and the laser diode itself, as well as by the working parameters of the electronic thermostabilisation system.

The broadening of the spectra and the appearance of features on the spectrum envelope at high pump powers (beginning from 5–6-fold and to 15-fold excess over the threshold power) even more complicate the adequate determination of the position of the spectrum envelope maximum and the calculation of thermal resistance. We proposed a simple and reasonable method for determining the spectral maximum wavelength and thermal resistance. In this approach, the experimental dependence of thermal resistance on pump current at high pump powers (at a 15-fold excess over the threshold power) almost completely coincides with the ideal dependence calculated for the case of a linear dependence of the wavelength of spectrum envelope maximum on pump current.

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