Determination of the temperature and thermal resistance of a half-disk laser diode by measuring pulsed current-voltage characteristics

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A technique is proposed for determining the temperature of a laser diode operating in a continuous mode, as well as thermal resistance of the device by comparing its current-voltage characteristic with pulsed current-voltage characteristics measured at different temperatures. The technique was applied to a $\varnothing 200\,\mu$m half-disk microlaser with an active region based on InGaAs/GaAs quantum dots. It was found that at currents corresponding to the peak laser power and lasing quenching due to overheating of the active region, the device temperature reaches 101 and 149°C, respectively. The thermal resistance of the laser is 110 K/W.

Keywords: half-disk microlaser, laser temperature, thermal resistance, quantum dots, laser diodes.

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1. Introduction

The temperature of the active region and adjacent heterolayers of a semiconductor laser is its key value, since the characteristics of the device can very strongly depend on it. The thermal resistance R_{T}, which determines what the operating temperature of a laser of a particular design will be (the sequence of layers of the heterostructure, the type of mounting of the chip on the heat sink, etc.) at a given pump current I, is expressed by the following formula:

$$R_{\mathrm{T}} = \frac{\Delta T}{\Delta Q}, \quad (1)$$

where ΔT — an increase in the temperature of the device T in response to an increase in the heat output in it ΔQ. The experimental determination of temperature and thermal resistance is an important task in the research and development of semiconductor lasers.

A number of existing methods for determining the temperature of laser diodes (LD) are based on measuring the displacement of spectral peaks with increasing pump current: the peak of laser generation [1], the peak of spontaneous emission [2], or the peaks of the whispering gallery modes (WGM) [3], if the laser resonator supports them. Knowing of the temperature coefficient of peak shift from the reference literature or additional measurements allows determining the temperature of the device at different pumpings. Thermal resistance can be determined using expression (1) according to the experimentally established dependence of the thermal power of the device $Q = UI - P$ on the current, where U — the voltage across the laser, and P — its output optical power.

The following disadvantages of these methods should be noted. Tracking the peak shift of the laser spectrum can be complicated with the increase in pumping if multi-frequency generation is observed in the laser and the spectrum has a complex shape. In addition, the simultaneous increase in the population of the active region and its temperature with the current introduces additional inaccuracy, since an increase in population leads to a shift of the peak to the short-wave region, and an increase in temperature leads to a shift of the peak to the long-wave region. In the case of WGM shift control, this uncertainty can be avoided if the inter-mode distance is sufficiently large (small size of the resonator), since in fairly wide ranges of pumping currents, the mode shift is mainly determined by a change in the refractive index of heterolayers. The control of the peak of spontaneous radiation (namely, the displacement of the long-wave peak decay at half-height) may require the creation of an additional window in the structure of the device, from which the output of laser radiation is suppressed. Finally, the use of these methods to determine the temperature of the device at high pumping (for example, near the laser generation quenching) may be unacceptable due to the relatively long duration of the spectrum recording process, during which the device can degrade.

The patent [4] proposes a method for determining the LD temperature based on pulsed measurement of the reduction of the voltage across the device associated with heating. However, this method is applicable only for pulsed (quasi-continuous) pumping: measuring pulses of low current (below the generation threshold) are applied between high pumping operating laser pulses.

Another method of measuring laser temperature, similar to that used in this work, is based on a comparison of pulsed watt-ampere characteristics (*L-I* curves) and *L-I* curve measured in continuous pumping mode [5]. This method requires the use of a high-speed optical power meter. However, in the case of measuring low-power laser radiation (for example, microlasers), simultaneously ensuring acceptable accuracy of measuring pulsed optical power and sufficiently short photocurrent pulse fronts (< 50 ns), which is necessary to avoid device heating, may turn out to be a non-trivial technical task.

In this paper, using the example of a half-disk microlaser, a method for determining the temperature of the device under continuous pumping and its thermal resistance is considered, based on measuring the pulsed volt-ampere characteristics (*U-I* curves). The proposed method is quite simple and at the same time provides good accuracy.

2. Studied microlasers

The laser heterostructure was synthesized on a substrate n^+-GaAs, misoriented by 6° towards [111] direction. A 720 nm thick GaAs waveguide enclosed between AlGaAs emitters in the central part contained 7 layers of InGaAs high-density quantum dots (the so-called quantum well-dots [6]). Mesas in the form of disks with a diameter of 200 μm were created on the surface of the structure by optical lithography and dry etching to a depth of 6 μm, through all epitaxial layers. Further, AgMn/Ni/Au annular contacts with a width of 15 μm and an indentation of 2 μm from the edge of the disks were created on their surface using optical lithography and vacuum deposition. The semiconductor wafer was thinned by chemical-mechanical polishing to thickness of $\sim 160\,\mu$m. A solid layer of AuGe/Ni/Au metal was plated on the back of the substrate. Half-disk resonators were formed by cleaving the crystal through the centers of the disks. The chips with half-disks were soldered *p*-contact up onto the copper heat sinks so that the cleaved facet of the half-disks was on the edge of the heat sink. Gold microwires with a diameter of 18 μm were bonded to half-ring contacts (see insert in Figure 1). We previously studied in detail such devices supporting WGM, the output power of which is mainly radiated from the cleaved facet [7,8].

3. Experimental details

The heat sink with mounted device was fixed on a copper plate, the temperature of which was set using a Peltier element, a resistive temperature sensor placed next to the heat sink, and a temperature controller. The temperature was maintained with an accuracy of ± 0.25°C.

Contacts were soldered to power supplies to apply constant and pulsed bias to the laser. Note that the use of probes (needles) to pump microlasers can lead to an additional error in measuring the voltage across the laser due to the instability of the contact resistance.

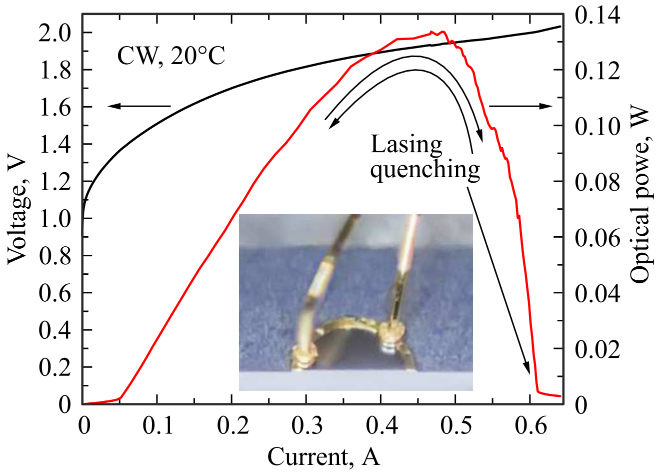

Figure 1. Volt-ampere and watt-ampere characteristics of a half-disk laser ⌀200 μm with a half-ring contact, measured at continuous pumping and heat sink temperature 20°C. On the insert — a photo of a laser with bonded gold wires. (Colored version of the figure is presented in electronic version of the article).

The *U-I* and *L-I* curves of the device were measured in continuous mode using a programmable NI PXI 4110 power supply, NI PXI 4065 multimeters and a calibrated Ge photodiode (PD) ⌀5 mm Thorlabs FDG05-CAL, placed close to the microlaser (the radiation collection angle was $\geq 130°$). The accuracy of voltage and current measurement in continuous mode was no worse than ± 1%, and optical power — ± 5%.

Figure 1 shows the *U-I* and *L-I* curves of the device measured in continuous pumping mode and at heat sink temperature of 20°C to a very high pumping, at which complete quenching of laser generation is observed due to overheating of the active region. The current at which the peak optical power is reached was 468 mA, and the laser generation quenching current was 610 mA. The small optical power observed above the current of lasing quenching is associated with residual spontaneous emission. Since the recording of the *U-I* and *L-I* curves of the microlaser in continuous mode was relatively quickly (within a few seconds), the laser did not have time to degrade and the presented characteristics were reproduced repeatedly.

Excitation of the device with square-topped pulses was carried out using a pulse driver based on a field-effect transistor, which was controlled using an external pulse generator that sets the duration and frequency of pulse repetition. The amplitude of the voltage pulses across the LD and connected in series test resistance was set using a programmable power supply NI PXI 4110. The pulses of voltage across the LD and current through it, determined by the test resistor, were recorded automatically using a Tektronix MDO3014 oscilloscope, which made it possible to plot pulsed *U-I* curves of the device.

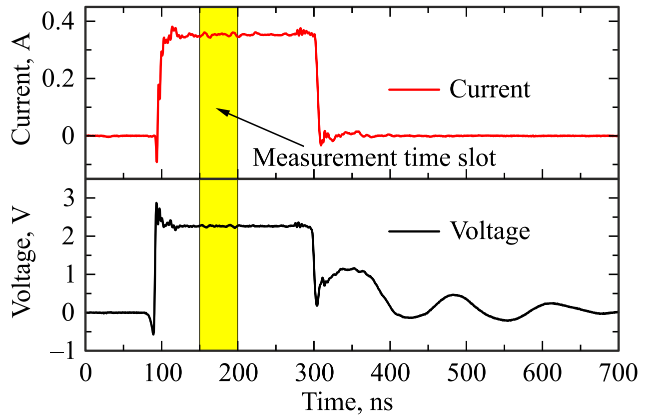

Figure 2. An example of current pulses through a laser and the corresponding voltage across it.

The pulse repetition rate was 1 kHz. An example of current and voltage pulses with a duration of ~ 200 ns at pulsed pumping of ~ 350 mA is shown in Figure 2. The pulse leading and trailing edges, together with small overshoots at the fronts, were ~ 30 ns. Voltage oscillations at the end of the pulse (starting from 300 ns on the chart) are associated with charge relaxation after the transistor is locked. The time window for measuring current and voltage was chosen so that during it the heating of the device was negligible. The heating was determined by spectra. With its onset, the laser lines begin to shift into the long-wave region. In our case, the pulse amplitude was measured in a time window of 50–100 ns from the beginning of the pulse to avoid the effect of heating. 125 points of the waveforms within this window were averaged to reduce the impact of noise. Averaging was also carried out over several oscillograms. Using the spectra, namely by varying the duration of the pumping pulse, it was found that the heating of the device, averaged over the time window used at the maximum pulsed pumping of (640 mA) was $\sim 0.5^\circ$C.

Before measuring the pulsed *U-I* curves we performed calibration of the measuring system using a resistor, the nominal value of which is known with high accuracy and which was soldered instead of the LD. After the introduction of the correction factor, the deviations of the pulsed *U-I* curve of the resistor from the one calculated according to Ohm's law were $\leq 1\%$.

4. Description of the methodology, results and discussion

The *U-I* curve of „an ideal laser" with zero thermal resistance, i.e., its heat generated is removed instantly and the active region does not heat up, in continuous pumping mode after turning into conducting state the LD should demonstrate a linear growth, determined by the resistance of the structure. In practice, for a laser with nonzero thermal resistance, a sublinear increase of *U-I* curve is observed during continuous pumping (or pumping with long-duration pulses) due to an increase in the temperature of the heterostructure (see Figure 1). In the case of pumping with sufficiently short pulses, during which the LD does not have time to heat up significantly, it is possible to observe „ideal" *U-I* curves with a linear increase up to high current densities.

The proposed method for determining the LD temperature is based on measuring the *U-I* curve of the device in continuous mode (its nominal mode) and measuring a set of pulsed *U-I* curves when heating is prevented, in the same current range at different temperatures of the heat sink. Figure 3 shows the superposition of the *U-I* curve measured in continuous pumping mode at the temperature of the heat sink of 20°C, and a set of pulsed *U-I* curves at different temperatures of the heat sink, setting the temperature of the laser. It can be seen that the *U-I* curve in continuous pumping mode and the pulsed *U-I* curve at 20°C coincide in the region of small pumpings where the heating is negligible. Branches of these *U-I* curves diverge with an increase in the current. It is possible to determine the laser temperature values at different continuous pumping currents based on the intersections of *U-I* curve measured in continuous mode and pulsed *U-I* curves at elevated temperatures ($> 20^\circ$C).

The temperature of the device determined in this way, however, like in case of other above-mentioned methods, is a kind of a temperature averaged over heterolayers in the current flow region (in our case, under a half-ring contact, where the laser WGM nodes are concentrated [9]), and the

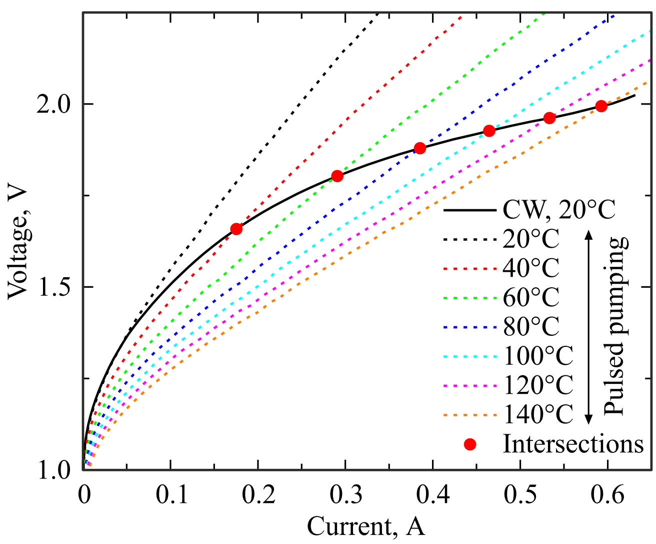

Figure 3. Volt-ampere characteristic of the device under continuous pumping and at heat sink temperature of 20°C, as well as a set of pulsed *U-I* curves at temperatures from 20 to 140°C with a step of 20°C. Circles — *U-I* curves intersection points, which can be used to determine the temperature of the device at various continuous pumping currents. (A color version of the figure is provided in the online version of the paper).

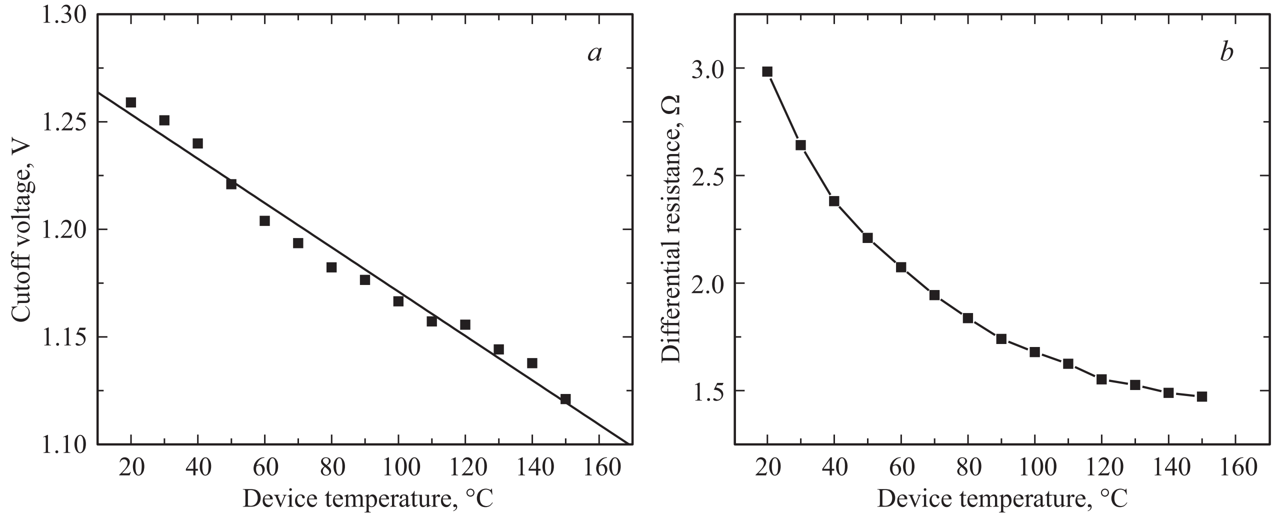

Figure 4. Dependences of the cutoff voltage (*a*) (straight line — linear approximation) and the differential resistance of the microlaser (*b*) on the temperature of the heat sink (laser temperature) in the absence of internal heating, determined by pulsed *U-I* curves.

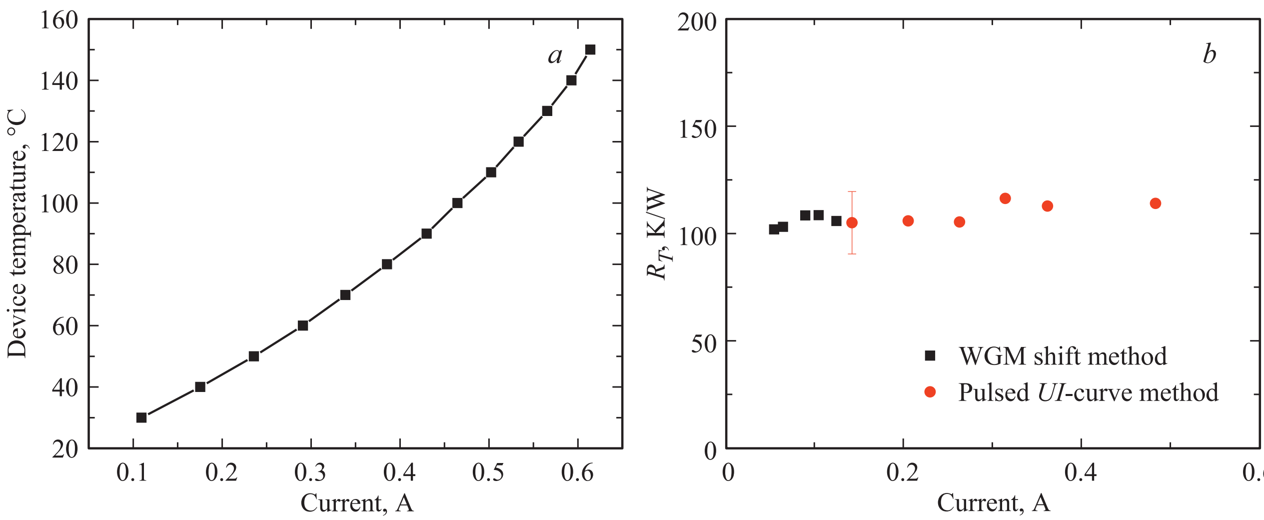

Figure 5. Dependences of the laser temperature (*a*) and its thermal resistance (*b*) on the continuous pumping current at the temperature of the heat sink of 20°C. On the panel (*b*): squares — values determined by the spectral shift of the whispering gallery modes, circles — values determined by pulsed *U-I* curves.

determined thermal resistance corresponds to heat removal from this region.

Figure 4 shows the dependences of the cutoff voltage U_0 (*a*) and the differential resistance of the microlaser R_d (*b*) in the conducting state on the temperature of the device in the absence of heating, determined by pulsed *U-I* curves. The values of U_0 and R_d were determined by the intersection of the extrapolation of the linear section of *U-I* curve with the ordinate axis and as the tangent of its angle of inclination, respectively. It can be seen that U_0 decreases approximately linearly with increasing temperature with an average rate of decline 1.03 mV/K, which is associated with a decrease in the band gap of the heterolayers. The resistance is also decreasing, but with some slowdown. The decrease in resistance with temperature can be explained by an increase in the concentration of charge carriers in the waveguide.

Figure 5, *a* shows the dependence of the temperature of the microlaser on the continuous pumping current, the temperature of the heat sink of which is stabilized at a level of 20°C. It can be seen that the growth of dependence is superlinear, which is expected, given the Joule heating. These data make it possible to determine the temperature of the active region of the laser when peak power is reached and the lasing is quenched: 101 and 149°C, respectively.

Figure 5, *b* shows the dependence of the thermal resistance of the device R_T on pumping, determined using the proposed method (circles). In our case, the error in determining the thermal resistance for the selected temperature increment (10 K) was ±7%. The value of R_T averaged over the entire current range was 110 K/W. In the region of low pumping, we also determined the thermal resistance from the WGM spectral shift (squares in Figure 5, *b*). A good consistency of the data obtained by different methods can be stated.

5. Conclusion

Thus, we considered a method for determining the temperature and the thermal resistance of a LD based on a comparison of *U-I* curves measured in continuous and pulse modes. The method does not require prolonged current impact onto the device, so the risk of its degradation when determining the laser temperature is minimized even at high pumping. This made it possible to determine the temperature of the device at the lasing quenching which was 149°C. There is a good agreement between the thermal resistance values obtained using the proposed method and the method based on measuring the spectral shift of the whispering gallery modes. Although the method is illustrated by the example of a half-disk microlaser, we believe that it can also be considered as an alternative to existing methods for determining thermal resistance and temperature for other types of lasers as well.

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Conflict of interest

The authors declare that they have no conflict of interest.

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