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# How to enhance a room-temperature operation of diode lasers and their arrays

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A key problem to be solved during designing productive diode lasers and their lasing arrays is their proper thermal management enabling efficient high-power operation. Strictly speaking, the above demand leads to optimization of their structures to enhance lasing performance for high operation currents. It is well-known that deterioration of laser performance is mostly induced by excessive temperature increases within their volumes. In diode-laser arrays, additionally thermal crosstalk between array emitters should be taken into account. In the present paper, physics of heat-flux generation within the laser-diode volume and its extraction from it is analysed and described with the aid of our self-consistent simulation procedure. Then their thermal optimization is discussed including a proper design of a heat-flux generation within the laser volume, enhancement of its transport towards a laser heat-sink and, additionally in laser arrays, reduction of a thermal crosstalk between individual array emitters. The analysis is carried out using modern nitride edge-emitting ridge-waveguide lasers and their one-dimensional arrays as well as arsenide semiconductor disk lasers as typical examples of modern diode-laser designs. Physical processes responsible for heat-flux generation within these devices and heat-flux extraction from their volumes are analysed and an impact of some construction details on these processes is explained.

Keywords: diode-laser thermal management, thermal crosstalk in semiconductor arrays.

## 1. Introduction

Generally, a laser is composed of two principal parts: the active region, where optical radiation is gained, and the cavity (resonator), where lasing modes are created. For the lasing action, the operation current (or pumping optical beam) should be at least equal to its threshold value, for which all radiation losses within and outside the cavity are compensated by radiation gain within the active region. First semiconductor active regions were of bulk homojunction or heterostructure types, nowadays optical gain in semiconductor lasers is usually delivered in quantum wells (QWs) or quantum dots (QDs).

Electric power supplied to an electrically driven semiconductor laser is within it exchanged into heat, noise and radiation output as a result of a series of physical phenomena: current spreading, Joule heating, radiative and nonradiative recombination, spontaneous and stimulated emission and absorption. All of the above phenomena are strongly dependent on temperature. Distribution of the supply power into the above three final parts, *i.e.*, heat, noise and output, depends on a laser structure.

At the early stage of semiconductor laser history, the excessive heat generation within laser structures was one of the most important problems preventing a common application of these devices. Later thermal issues have been slightly reduced in significance due to technological development and fabrication of more optimal laser structures. However, a continual pursuit of obtaining higher output powers and designing novel semiconductor structures have caused that a problem of heat generation and an influence of temperature increase on other physical processes taking place within laser structures have recently become again very important for designers and technologists [1]. In the present paper, an impact of various construction details of edge-emitting diode lasers (EELs) and their one-dimensional lasing arrays on temperature increases within their volumes is investigated and an influence of these increases on device operation properties is analysed and discussed. Thermal rollover and thermal crosstalk effects [2], which limit output power of single edge-emitting lasers and their one-dimensional arrays, have been described. Lastly, a possibility of wavelength switching in semiconductor disk lasers (SDLs) using temperature increases within their volumes has been discussed.

## 2. Heat generation within broad-area semiconductor structures

For a possible laser action within broad-area semiconductor structures, a separation between the quasi-Fermi levels of the conduction and the valence bands, $F_C - F_V$, should be larger than the semiconductor energy gap $E_G$

$$F_C - F_V > E_G \tag{1}$$

where, for the first semiconductor lasers made of GaAs, their energy gap at room temperature (300 K), $E_G = 1.424$ eV. At temperature $T$, the conduction-band carrier concentration $n$ is related to the Fermi level $E_F$

$$n = n_i \exp\left(\frac{E_F - E_i}{k_B T}\right) \tag{2}$$

where $n_i$ and $E_i$ stand for the intrinsic carrier concentration and the impurity energy level, whereas $k_B$ is the Boltzmann constant. It is known from measurements that for GaAs at room temperature $n_i = 1.8 \times 10^6$ cm$^{-3}$ [3]. Then assuming the impurity level at half of the energy gap

$$F_F - F_i > \frac{E_G}{2} \tag{3}$$

the conduction-band carrier concentration determined using Eq. (2) is approximately equal to $2 \times 10^{18}$ cm$^{-3}$, which is in agreement with experimental data and is of the order of the threshold carrier concentration. Now we may estimate the radiative carrier lifetime $\tau_r$ from the following relation:

$$\tau_r = \frac{1}{Bn} \tag{4}$$

Then, for the GaAs radiative recombination coefficient $B = 2.5 \times 10^{-10}$ cm$^3$/s [4], the radiative lifetime is approximately equal to $\tau_r \approx 2$ ns, which is also in agreement with experimental data.

Let us consider a typical uniform GaAs homojunction broad-area cuboidal structure of the width $W = 200$ μm, the length $L = 500$ μm and the thickness $H = 100$ μm. Then the uniform current density $j = I/WL$, where $I$ is the operation current, through the layer of thickness $d_A$ may be expressed as

$$j = \frac{end_A}{\tau_r \eta_i} \tag{5}$$

where $e$ is the unit charge and $\eta_i$ is the internal quantum efficiency. At room temperature, for typical GaAs homojunctions, characterized by $d_A = 2$ μm, $\eta_i = 0.65$ and the carrier concentration $n = 2 \times 10^{18}$ cm$^{-3}$, Eq. (5) gives $j = 50$ kA/cm$^2$ [5], which for the above structure gives an enormous current $I = jWL = 50$ A. So such a strong current injected into the considered homojunction structure would be then necessary to start the lasing action. It corresponds to the giant heat power $Q$ generated within the active region

$$Q = I(E_G/e) \tag{6}$$

This strong active-area heat generation would lead to an enormous active-region temperature exceeding the melting GaAs temperature of about 1500 K. Therefore the room-temperature continuous-wave (CW) lasing action in not-modified standard homojunction GaAs diode lasers is impossible.

For a one-dimensional heat-flux within the considered broad-area semiconductor structure, the temperature increase $\Delta T$ induced by the above current $I$ may be expressed as follows:

$$\Delta T = \frac{QH_T}{S\lambda} = ejUR_\lambda \frac{S_A}{S} \tag{7}$$

where $\lambda$ is the material thermal conductivity (in Wm$^{-1}$K$^{-1}$), $U$ is supplied voltage, $S_A$ stands for the area of the heat-generation region, $S = LW$, and $R_\lambda = H_T/\lambda$ is the laser thermal resistance (in m$^2$K/W) for considered here a one-dimensional heat-flux flow, where $H_T$ is the distance between the heat generation and the heat-sink. For a uniform heat-flux generation within the semiconductor active region, $S_A = S$, which is followed by a simple one-dimensional flow of an uniform heat-flux towards the laser heat-sink.

It is well-known that generally lasing threshold current in a semiconductor diode laser is proportional to a thickness $d_A$ of its active region. Therefore, during earlier development of diode-laser technology, an improvement of laser performance (mostly connected with a decrease in both its lasing threshold and heat generation within a laser volume) was usually achieved with the aid of reduction of this thickness $d_A$ using heterostructures [6].

Temperature increases (see Eq. (7)) within such simple semiconductor structures may be also reduced by decreasing $R_\lambda$, strictly speaking – by an application of the *p*-side down structure instead of the *p*-side up one [7]. Then $H_T$ is drastically reduced because the heat-generation region becomes located much closer to the laser heat-sink.

As one can see in Eq. (7), temperature increases are generally directly proportional to the ratio $S_A/S$. In first broad-area diode lasers $S_A = S$, which is followed by a one-dimensional heat flux flowing from the laser active region to the heat sink. Let us consider now the case, for which a width of the above heat-generation region is reduced as compared with the width of the semiconductor structure, so $S_A/S < 1$. Such laser structure is called a stripe-geometry diode laser. Then, the heat-flux flow towards the heat-sink is no longer one-dimensional, its flow becomes two-dimensional. Efficiency of such a two-dimensional heat-flux spreading is much better than the previous one-dimensional one, which leads to lower temperature increases. Besides, the temperature increases within diode-laser structures may be also reduced by an additional lateral expansion of the heat-flux flow with the aid of high-thermal-conductivity diamond layers below or even above their active regions [8]. Then much broader heat flux towards the laser heat sink takes place, which induces reduction of laser thermal resistances. However such an approach would be very troublesome in the case of nitride lasers. Therefore, another laser structure is proposed in this case.

## 3. Heat-flux spreading in more advanced semiconductor structures

It may be easily concluded from the above analysis that the improved development of diode lasers would be impossible without an application of stripe-geometry edge-emitting laser structures introduced first only to cope with a filament radiation distribution.

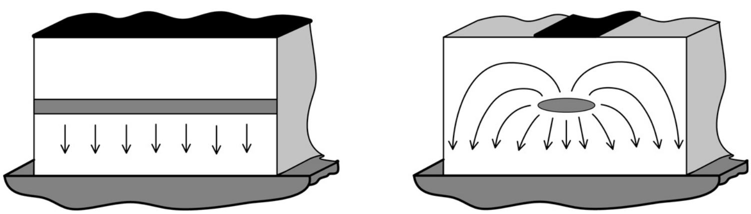

Fig. 1. Comparison of one-dimensional heat-flux spreading in broad-area devices with two-dimensional spreading in stripe-geometry ones.

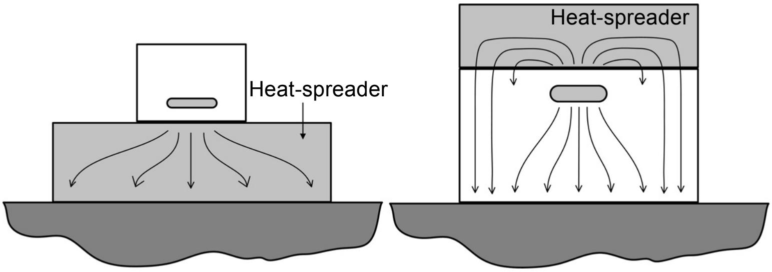


Fig. 2. Influence of a localization of high-thermal-conductivity heat-spreaders on a heat-flux spreading.

From a thermal point of view, the most important consequence of the above stripe structure of a heat-generation region is much higher efficiency of two-dimensional heat-flux spreading from its generation place (Fig. 1) of reduced sizes as compared with previous one-dimensional one. As it was mentioned in the previous Section, even better improvements may be also achieved using additionally special heat-flux spreaders made of materials of high thermal conductivities and applied below or above heat-generation regions (Fig. 2). In the case of such devices, their thermal resistance $R_{th}$ (in K/W) may be expressed as

$$R_{th} = \frac{\Delta T_{max}}{P_{in} - P_{out}} \tag{8}$$

where $\Delta T_{max}$ is the maximal temperature increase within a device and $P_{in} = UI$ and $P_{out}$ stand for the supply power and the emission power, respectively.

Threshold current density $j_{th}$ of a semiconductor laser is increased with temperature, which is usually described by the following relation:

$$j_{th}(T + \Delta T) = j_{th}(T)\exp(\Delta T / T_0) \tag{9}$$

where $T_0$ is a laser parameter. As one can see, threshold current density within a laser volume is increasing nonlinearly with a supplied current $I$ (Fig. 3**a**). Two values $R_{th,1}$ and $R_{th,2}$ of the laser thermal resistances are considered in this figure. Laser emission is possible for $j = I/S_A > j_{th}$ only, *i.e.*, between two intersections of plots of an operation current and that of the threshold current (Fig. 3**a**), the first one for the lasing threshold and the second one for the operation current equal to an increasing threshold one following Eq. (9). Figure 3**a** shows also points of the thermal roll-over, *i.e.*, for the operation currents giving maximal values $P_{max}$ of the emitted power, determined here for both considered thermal resistances $R_{th,1}$ and $R_{th,2}$. In the above analysis, a possible catastrophic degradation of laser mirrors is neglected. For an operation current $I$ only slightly higher than its threshold value, the output power $P_{out}$ is directly proportional to a current increase over its threshold, *i.e.*, to $I - I_{th}$ (Fig. 3**b**). For higher currents, the

$P_{out} = f(I)$ plot is becoming curved reaching the highest $P_{max}$ value for the so-called thermal roll-over point. For even higher currents, $P_{out}$ is monotonically reduced to zero. Figure 3**b** presents also an obvious dependence of an operation voltage $U$ on a current $I$.

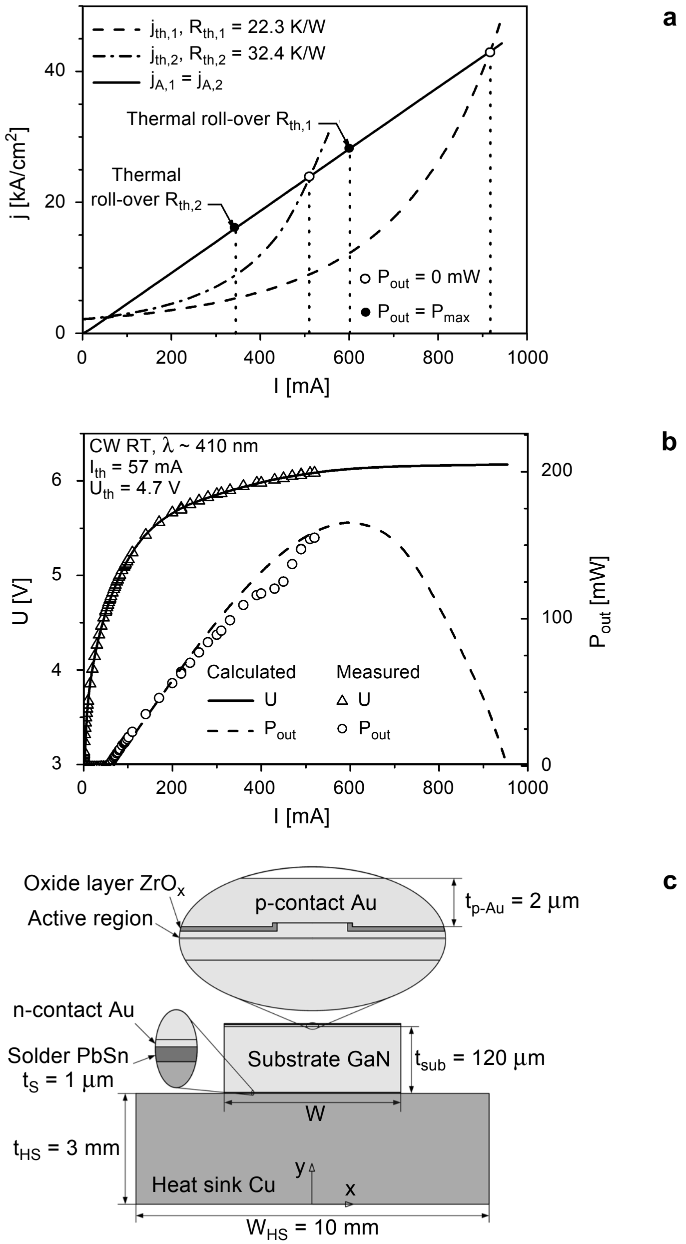


Fig. 3. Typical operation characteristics for a typical stripe-geometry diode laser (**a**, **b**) and schematic structure of a ridge-waveguide (RW) laser with an upper Au contact used also to enhance a radial heat -flux spreading (**c**).

## 4. Ridge-waveguide nitride laser

Reduction of a temperature increase in lasing thresholds of semiconductor lasers with the aid of high-thermal-conductivity (*e.g.*, diamond) layers [7] below or over their active regions is technologically troublesome in nitride devices. Therefore let us consider a new structure of the nitride edge-emitting ridge-waveguide (RW) laser (Fig. 3**c**) whose upper *p*-side Au contact is used not only to supply a biased voltage but also to enhance the 2D heat-flux spreading from the central active region [9]. It is well-known that RW laser structure is considered as one of the best stripe-laser designs because of its relatively simple one-step technology (as in gain-guided stripe lasers) and its built-in waveguiding effect (as in index-guided stripe lasers). The RW lasers will be used here to examine a two-dimensional heat-flux spreading from the central active region, to investigate an influence of various construction details on temperature increases within their volumes and to compare results of our computer simulations with experimental ones. Details of our self-consistent simulation approach are given in [2, 8].

As it is seen in Fig. 3**c**, the upper *p*-side Au contact layer is separated from an internal semiconductor part of the above RW laser by the low-thermal-conductivity $ZrO_x$ oxide

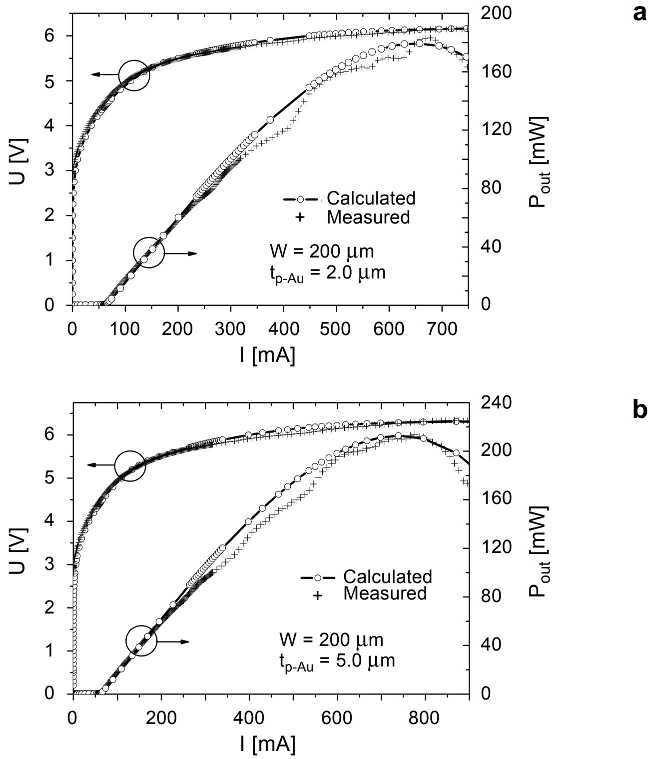


Fig. 4. Calculated (lines) and measured (points) current-voltage and output-current characteristics of the nitride RW laser for the GaN substrate width $W = 200$ µm and the 2 µm thickness (**a**) and the 5 µm thickness (**b**) of the *p*-side Au contact.

layer with an exception of the central laser region. Therefore a lateral heat-flux flow within the above oxide layer seems to be strongly reduced because of its very low thermal conductivity. However, using relatively thick Au layer enhancing this lateral spreading within it, a perpendicular heat-flux flow through the above oxide layer has been found to be quite intense. It brings about an essential reduction of the total laser thermal resistance.

Figures 4**a** and 4**b** present a comparison between calculated (lines) and measured (points) [10] current-voltage and output-current characteristics of two RW laser designs for the GaN substrate width $W = 200$ μm and, respectively, with two thicknesses, 2 or 5 μm, of the *p*-side Au contacts. As one can see, experimental results agree with theoretical ones, which means that our simulation procedure is confirmed by an experiment.

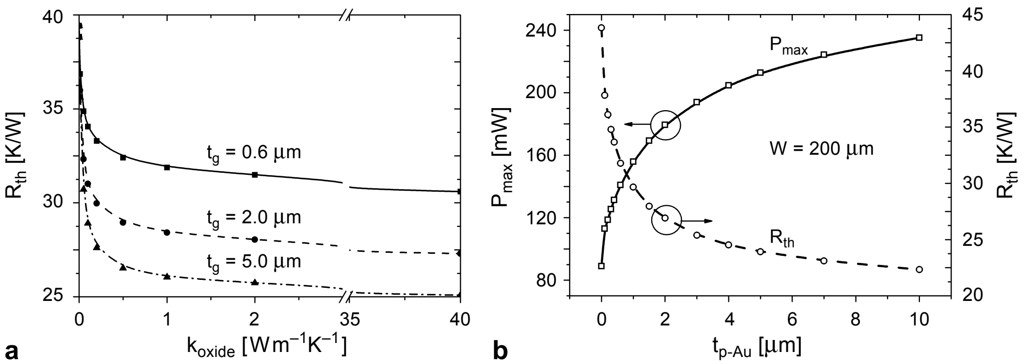


Fig. 5. The nitride RW laser (Fig. 3**c**): an impact of the thickness $t_g$ and the thermal conductivity $k_{oxide}$ of the oxide layer on the thermal resistance $R_{th}$ (**a**), an impact of the thickness of the Au layer, $t_{p\text{-Au}}$, on the maximal output $P_{max}$ and the thermal resistance $R_{th}$ (**b**).

Unwanted temperature increase within the laser volume depends not only on the efficiency of heat generation within it but also on the efficiency of its extraction. An impact of both a thickness $t_g$ of the upper Au layer and of the thermal conductivity $k_{oxide}$ of the upper oxide layer (separating the laser volume from the above top gold layer) on the laser thermal resistance $R_{th}$ is illustrated in Fig. 5**a**. As it has been explained earlier, the upper Au layer is here used not only as an electric contact but also to enhance the lateral heat-flux spreading from the central laser part containing the active region. It is clearly seen that, for standard oxide layers of thermal conductivities about 2 Wm$^{-1}$K$^{-1}$, an increase in a thickness $t_{p\text{-Au}}$ of the Au layer is followed by a quite significant laser thermal resistance decrease. An impact of $t_{p\text{-Au}}$ on the maximal laser output $P_{max}$ and on the laser thermal resistance $R_{th}$ is shown in Fig. 5**b**. As expected, to avoid high temperature increases, the Au layer should not be too thin, however its thickness of about 2–3 μm seems to be already sufficiently appropriate.

## 5. One-dimensional array of nitride edge-emitting lasers

The output of individual edge-emitting diode lasers is mostly limited by excessive temperature increases within their volumes. Significantly higher outputs [11, 12] are possible in their one-dimensional arrays (Fig. 6**a**). But temperature increases within array volumes depend not only on heat generation within individual array emitters, as in individual diode lasers, but also on interactions within a common heat-sink between heat fluxes generated by all of them [2, 7]. Let us consider the array of nitride RW lasers shown in Fig. 6**a**. For $n = 2$ array emitters, Fig. 6**b** presents the theoretically determined array active-area temperature increase $\Delta T_A$ and the output power $P_{out}$ *versus* operation current $I$ for two axis-to-axis distances $d$ between array emitters of 10 and 150 µm. As expected, because of the above interaction, in the array with more dense laser emitters,

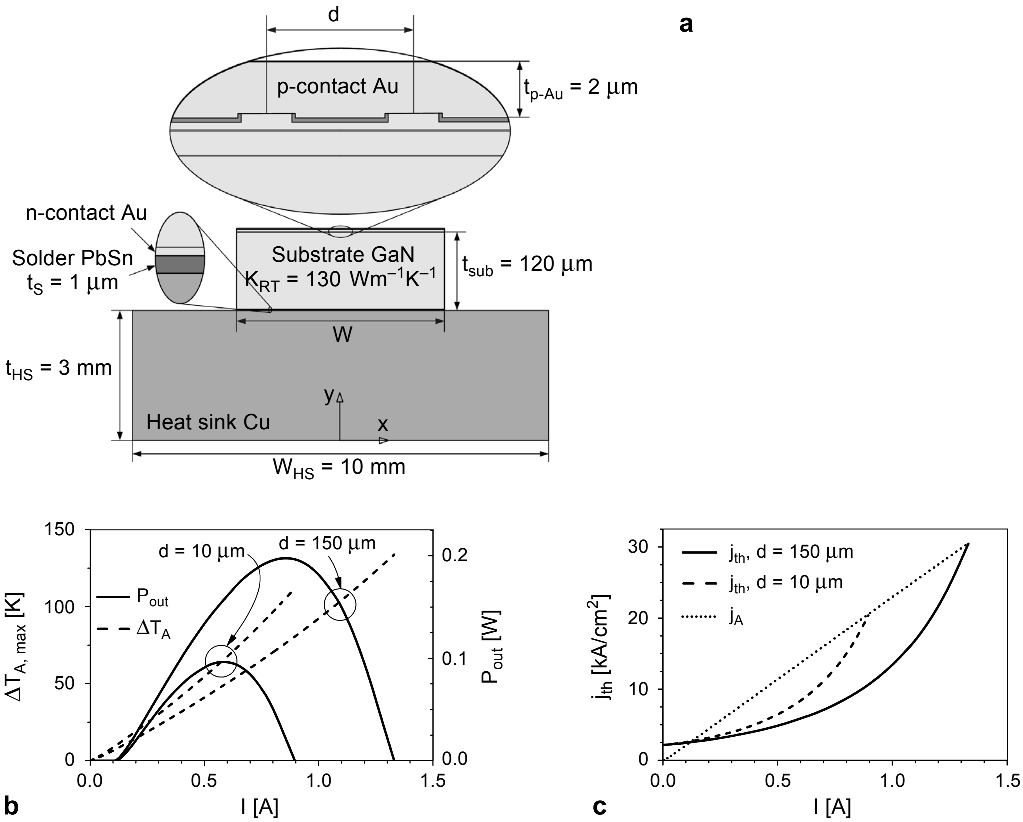


Fig. 6. The array of two RW nitride edge-emitting lasers: construction details (**a**), the maximal active-area temperature increase $\Delta T_{A,max}$ and the output power $P_{out}$ *versus* the array operation current $I$ (**b**), the threshold current density $j_{th}$ as a function of the array operation current $I$ (**c**); $d$ is a distance between laser emitters (for both the above $d$ values, $W = 300$ µm).

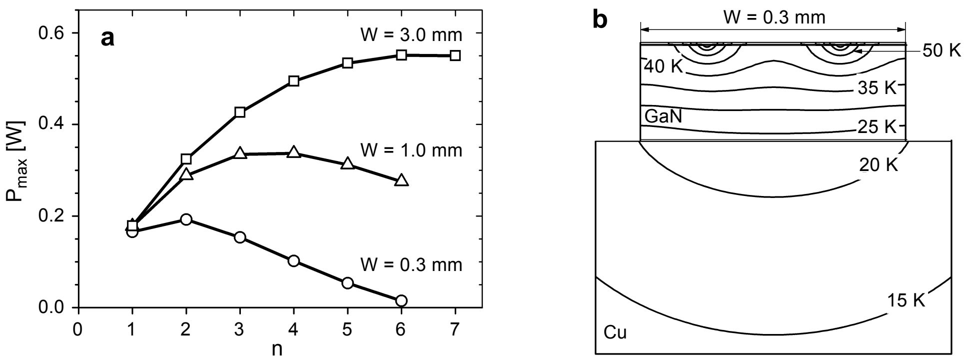


Fig. 7. The one-dimensional array of RW emitters (Fig. 6**a**): maximal output power as a function of a number $n$ of its emitters for three substrate widths $W = 0.3$ mm, 1.0 mm and 3.0 mm (**a**), temperature increases within the array for the substrate width $W = 0.3$ mm, the number $n = 2$ array emitters and the total current $I$ of 0.86 A (**b**).

the temperature increase is higher and the output power lower than in the array with more distant emitters. Besides, the later array may operate for higher currents $I$ (Fig. 6**c**). However, it is also seen in Fig. 6**c** that, in the considered case, the output power of this two-emitter array is lower than the maximal output of a single diode laser of 165 mW for both the emitter-to-emitter distances $p$. This means that the array width $W = 0.3$ mm is too small for a two-emitter array. Because of interactions between heat fluxes generated by individual array emitters, an increase in their number $n$ is not always followed by an increase in the array output (Fig. 7**a**). For dense arrays, their maximal outputs may be even decreased for too large $n$. Figure 7**b** presents for: $n = 2$ and $W = 0.3$ mm two-dimensional mostly radial heat-flux spreading (perpendicular to isotherm lines) within the array substrate.

## 6. Thermal wavelength switching in semiconductor disk lasers

Generally, a temperature increase is an important factor limiting the performance of diode lasers. However, it can be turned to good use for some special purposes. A good example is a switchable semiconductor disk laser where a change in structure temperature is used to switch laser emission between two different wavelengths. Such a structure operating at 967 and 1018 nm has been previously reported in [13]. The wavelength switching was induced by the change of the pump power.

Semiconductor disk lasers are special kinds of diode lasers, which can generate high-power radiation with high-quality output beams. They are also known as vertical -external-cavity surface-emitting lasers (VECSELs). In contrast to typical diode lasers, they are optically pumped and act as active mirrors in external cavities which enable placing an additional optical element within laser resonators for frequency doubling, short pulse generation, advanced transverse-mode control and so on. However, also in this case, a temperature increase is the main reason which limits laser performance [14, 15]. This results from the fact that the spectrum of a laser material gain shifts faster towards longer wavelengths due to temperature increase than the structure resonance peak. When the overlap of these two quantities is too low, the laser switches off. In a typical SDL structure there is only one resonance peak within the DBR stopband. In the switchable SDL there are at least two of them. This can be achieved by a special design of the laser active region. Figure 8 shows spectra of the DBR reflectivity, confinement factor [16] and material gain of the InGaAs/GaAs switchable SDL designed on the basis of the structure presented in [13]. One can see two peaks of the confinement factor within the DBR stopband. The confinement factor has been calculated for longitudinal modes of the structure in the external cavity – this is why the resonance peaks are so wide. At 293 K the spectrum of the material gain is adjusted to the first of these peaks and laser operates at wavelength about 962 nm. When increasing a temperature within a laser volume, the gain spectrum is shifting towards longer wavelength faster than the spectrum of the confinement factor. For high temperatures it becomes enough tuned to the second resonance peak to switch laser emission to longer wavelength at about 1020 nm.

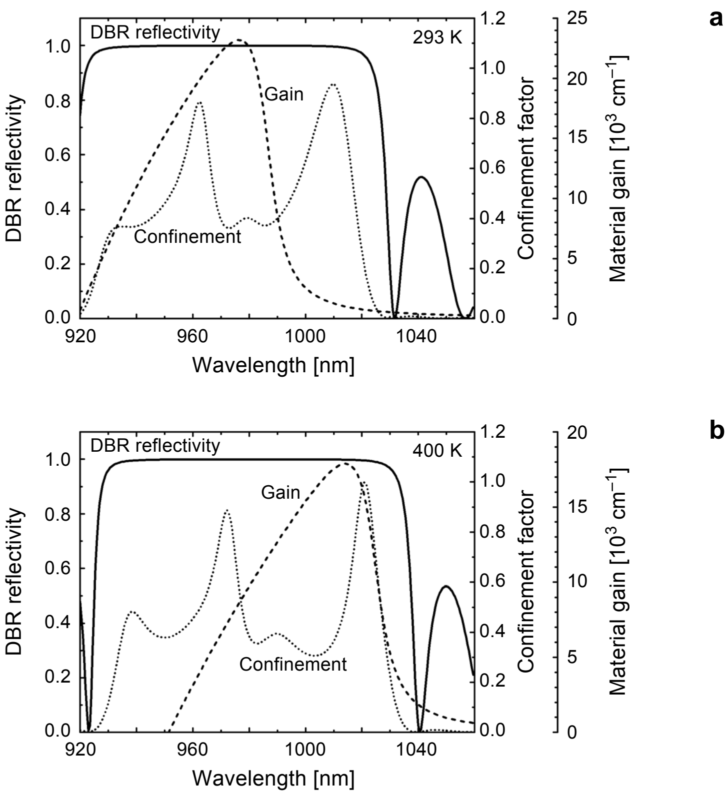


Fig. 8. Spectra of reflectivity, confinement factor and material gain for the switchable SDL structure at 293 K (**a**) and 400 K (**b**).

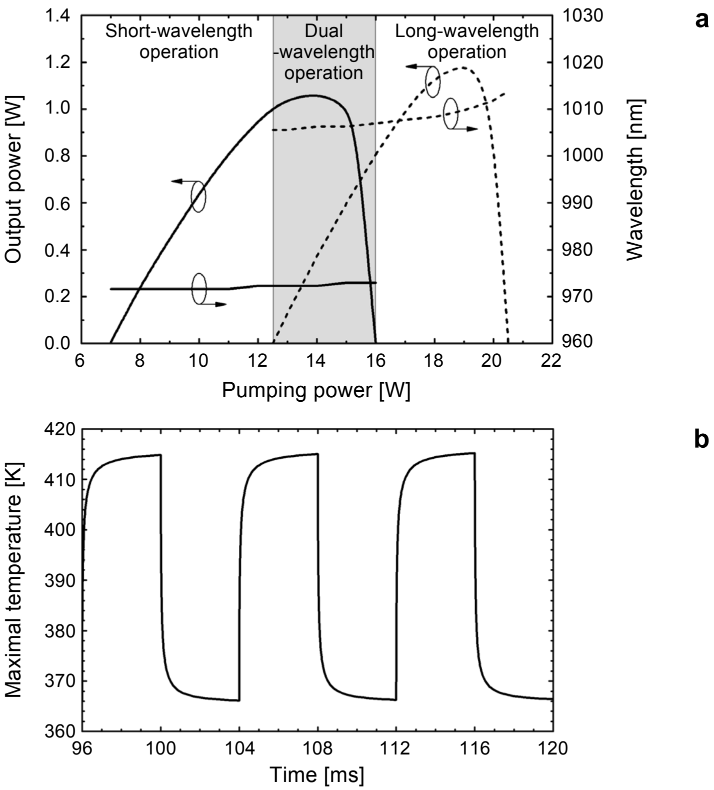


Fig. 9. Power transfer characteristic of the switchable SDL for short- and long-wavelength operation (**a**), change of maximal temperature in the SDL structure due to switching of pumping power between 12 and 17 W with 2-ms interval (**b**).

The simplest way to change a temperature within the SDL structure is to change the power of pumping radiation. Figure 9**a** shows a calculated power transfer characteristics of the modelled SDL. One can see that for pumping powers from 7.0 to 12.5 W laser operates only at shorter wavelengths. For higher pumping power the emission at higher wavelengths also occurs. Within the 12.5–16.0 W range the laser operates at both of these wavelengths. For higher excitation the emission at short wavelengths switches off and laser operates only at higher wavelengths. This means that by changing the pumping power, for example from 12 to 17 W, it is possible to change emission between short and long wavelengths. Time required to switch the laser emission between these two wavelengths is determined mainly by the time required for stabilization of a temperature distribution within the laser structure. Figure 9**b** shows the calculated change of the maximal temperature in the considered SDL structure due to switching of pumping power between 12 and 17 W. It seems that the 2-ms interval is long enough to achieve a quite good temperature stabilization. The laser with such a short switching time and output power higher than 0.5 W can be an attractive source for an application in position meters. Moreover, such lasers optimized for bigger spectral separation between the emission wavelengths, combined with a nonlinear crystal, could be attractive two-colours sources in RGB projectors.

## 7. Conclusions

Temperature increases within active areas of diode lasers obstruct their efficient radiative emission. These increases depend not only on an intense heat-flux generation within and outside their active areas but also on the efficiency of its extraction from laser volumes. Heat-flux extraction depends on a specified diode-laser design and used materials. Laser designers in technological centres are still looking for new materials to produce more efficient new diode-laser constructions. Therefore, the competition between those centres is still a driving force for diode-laser technology improvement. In the paper we show that properly designed Au contact layers in RW lasers may strongly improve the heat extraction efficiency. This approach seems to be an interesting alternative for diamond heat spreaders. In the presented GaN-based structure, a 2-μm-thick Au layer decreases laser thermal resistance by over 60%. We also show that the output power of diode-laser arrays depends strongly on thermal interaction between individual emitters. In the extreme case, the thermal crosstalk effect causes that the array produces less power than the single emitter. For each array width, the number of emitters and distance between them should be properly adjusted to minimize the impact of the thermal crosstalk and to achieve the best array performance. On the other hand, the temperature increases within diode lasers can be beneficial for some special purposes. A good example is the switchable semiconductor disk laser, where a temperature increase is used to switch laser emission between two different wavelengths.

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