Heat transport in high power lasers: simulation and experiment

Michał Szymański
Institute of Electron Technology, al. Lotników 32/46, 02-668 Warsaw, Poland
e-mail: mszyman@ite.waw.pl

Broad-area lasers and laser bars are widely used in many applications like solid state laser pumping, telecommunication or material processing. They are prized mainly due to high output powers reaching several watts. However their external quantum efficiencies do not exceed 50% and large amount of energy, supplied by pumping current, is converted to heat. High temperature of semiconductor laser significantly deteriorates its main parameters, namely threshold current, output power, spectral characteristics or lifetime. Therefore deep insight into thermal effects in the broad-area lasers is the main condition of obtaining the improved devices. In this work the analytical solution of the two-dimensional, stationary heat conduction equation is presented. The model yields the relative temperature (the temperature exceeding the ambient temperature) in the laser cross-section in plane parallel to the mirrors. Various heating mechanisms are taken into account and their contribution to the total temperature of the device is considered.

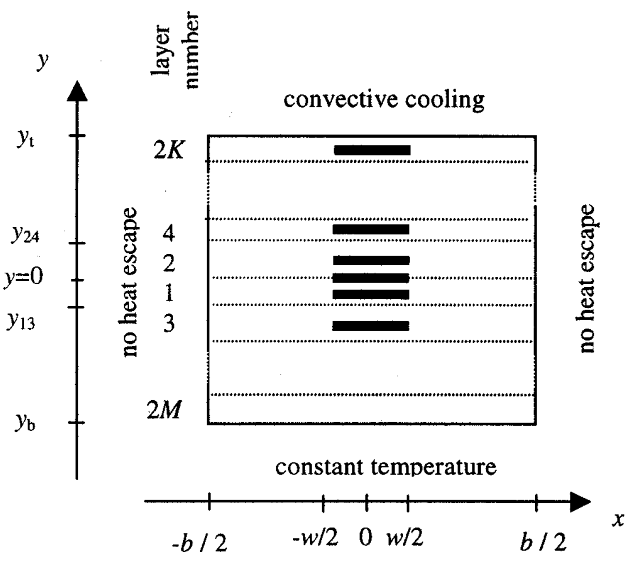
The crucial point in thermal analysis is to identify the heat sources and assess their role in increasing a temperature of the device. The heat can be generated due to the following phenomena occurring in the laser chip: nonradiative recombination, reabsorption of radiation, Joule's effect or radiative transfer [1]. Improper mounting can also lead to heat generation especially because of voids in solder layer [2].

A simplified scheme of the cross-section of the investigated broad-area laser is shown in Fig. 1. In this case the heat conduction equation reduces to the two-dimensional, time-independent form:

$$\nabla\left(\lambda\,(y)\,\nabla T(x,y)\right) = -g(x,y)\,, \tag{1}$$

where T denotes relative temperature (the temperature exceeding the ambient temperature), λ is the thermal conductivity, g - a heat source function, x and y are the lateral and transverse co-ordinates, respectively. The the boundary conditions can be written as follows:

$$T(x,y_b)=0, \qquad \frac{\partial}{\partial x}T\left(-\frac{b}{2},y\right)=\frac{\partial}{\partial x}T\left(\frac{b}{2},y\right)=0, \qquad -\lambda_{2K}\frac{\partial}{\partial y}\,T(x,y_t)=\alpha\,T(x,y_t) \tag{2}$$



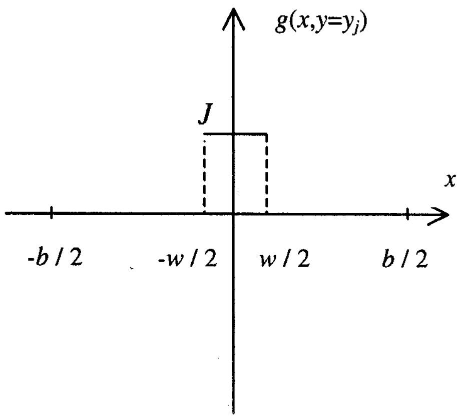


Fig 1. Schematic view of a broad-area laser cross-section. Thick segments mark heat sources.

Fig 2. Function describing a *j*-th heat source.

In the model heat sources are represented by infinitely thin stripes of different efficiency and localization (as it has been symbolically depicted in Fig. 1). All of them are rectangular-shaped functions of lateral co-ordinate (Fig. 2). The most efficient heat source is the active region, where nonradiative recombination and reabsorption of radiation occur. Assuming that $g(x,y) = g(x,y=0)$ and using the separation of variables method the analytical solution of Eq. (1) obeying boundary conditions (2) can be found [3,4]. On the basis of this solution a map of temperature of the laser cross-section has been calculated and compared with the temperature of laser mirror measured experimentally (Fig. 3). The plot shows a good convergence, but it must be stressed that these investigations are provided for the near-threshold regime. Far above the threshold, to obtain correct theoretical results, nonradiative surface recombination at the mirror must be taken into account and 3-dimensional heat conduction equation must be solved [5].

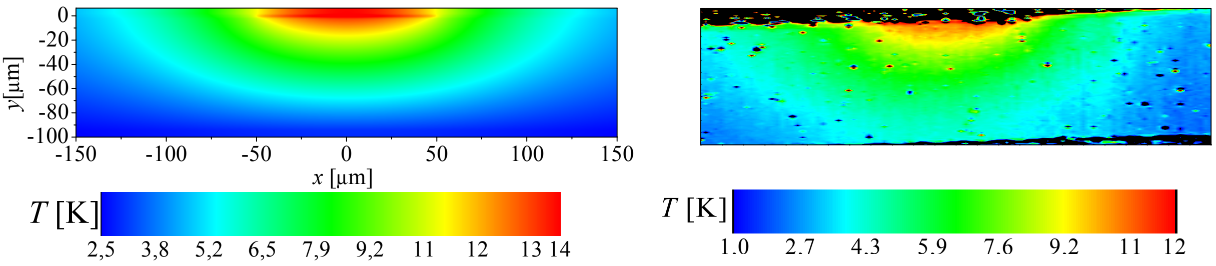


Fig 3. Calculated (left) and measured (right) 2-D maps of the relative *T* temperature distribution in a p-side up mounted broad-area laser.

The described approach can be extended for multiple heat sources due to the following fact. It can be shown that if $T_j(x,y)$ is the solution of Eq. (1) with heat source $g_j(x,y)$ and boundary conditions (2), then the function $T(x,y)=\sum T_j(x,y)$ is the solution of Eq. (1) with heat source $g(x,y)=\sum g_j(x,y)$ and obeys boundary conditions (2) [4].

A *p*-side down mounted QW AlGaAs/GaAs broad-area laser has been assumed. The transverse temperature profiles for $x=0$ have been calculated (Fig. 4). The dotted lines present the additive temperature contributions of the main heat sources to the total temperature of the device, which is plotted by the solid line. Fig. 4 confirms that the quantum well active layer (qw), where non-radiative recombination and re-absorption of light occur, is the main heat source in the device. Joule heating is proportional to electrical resistance *R* of a layer. High value of *R* appears in waveguide layers (wg), substrate (s) and p-doped cladding (pclad) due to lack of doping, large thickness and low mobility of holes [4] , respectively.

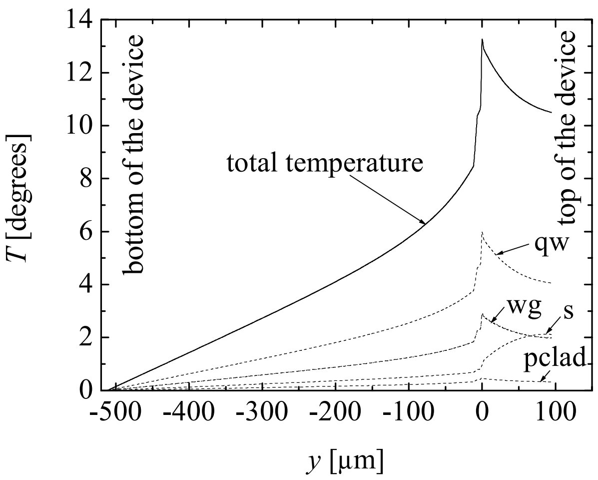


Fig 4. Transverse temperature distribution (*x*=0). Symbols are described in the text.

References

[1] B. Mroziewicz, M. Bugajski, W. Nakwaski, *„Physics of Semiconductor Lasers”*, North-Holland, 1991.
[2] A. Bärwolff et al., *J. Thermal Analysis*, vol. 45, 1995, p. 417
[3] W.B. Joyce and R.W. Dixon, *J. Appl. Phys.,* vol. 46, (2), 1975, p. 855.
[4] M. Szymański, M. Zbroszczyk, B. Mroziewicz, *Proc. SPIE* (in press).
[5] G. Chen and C. L. Tien, *J. Appl. Phys.,* vol. 74, (4), 1993, p. 2167.

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