Modeling of thermal phenomena in structures of diode lasers and diode-laser arrays

Włodzimierz Nakwaski
Laboratory of Computer Physics
Institute of Physics, Technical University of Łódź
ul. Wólczańska 219, 93-005 Łódź, Poland
e-mail: nakwaski@p.lodz.pl

Abstract

With an increase in general availability and high-performance quality of personal computers, an increasing interest in computer modeling of various physical phenomena is observed in many areas of science and technology. Nowadays modern methods of construction designing and structure optimisation of various devices, including diode lasers, are often based on computer experiments. In particular, these new designing approaches are definitely less expensive and less troublesome than traditional ones which usually require costly and time-consuming technological procedures followed by some experimental testing. On the other hand, computer experiments enable us in a relatively simple way to better understand complex physics of many interrelated physical phenomena crucial for an operation of diode lasers, to design new diode-laser devices, to simulate their anticipated performance characteristics and to optimise their structures for various applications, to name the most important applicability areas.

An operation of diode laser is based on mutual interactions of many physical phenomena taking place within their volumes, mostly optical, electrical, mechanical, and thermal ones [1]. Very simplified diode-laser models usually consist only characterisation of optical phenomena; somewhat more advanced models include also electrical ones. However, thermal phenomena should be included in all comprehensive simulations of a diode-laser operation because practically all physical phenomena crucial for this operation are dependent on temperature. Besides, a complex network of many, usually non-linear interactions between individual physical phenomena taking place within a diode-laser volume should be additionally included in complete models of these devices [1], because simpler non-self-consistent approaches are giving very often erroneous results. Therefore comprehensive fully self-consistent simulation methods are strongly recommended for simulation of an operation of diode lasers and arrays of diode lasers.

The key parameter used often in very simplified treatments of steady-state thermal problems in electronic devices (and sometimes even given as an operation parameter of a device) is the thermal resistance (in K/W). It is defined simply as the ratio of the average active-region temperature increase to the total dissipated thermal power [2]. However, it should be emphasized that in fact the above thermal resistance is not constant, as it is often claimed. With an increase in an operation current, all Joule heat generation is proportional to a square of the current density whereas the active-region heat generation is directly proportional to this density. Then a relative influence on temperature profiles of differently located heat sources (and the device thermal resistance itself) become dependent on an operation current [2]. Besides, thermal resistance may sometimes give misleading information. Theoretically, better device should be characterized by lower thermal resistance. But it is not always the case. Consider, for example, a device with a very poor electrical contact between the device chip and the heat sink. The resultant heat flux, generated at the laser chip/heat sink interface, would be very efficiently extracted by the high-thermal-conductivity heat-sink material, so its influence on the active-region temperature would be relatively small. However, the heat generated near the heat sink would still contribute to the total heat power. Therefore such a device would have lower thermal resistance than a well mounted device with low-electrical resistance contact [2].

A detailed analysis of thermal phenomena in a device needs a careful examination of distribution and intensity of generation of all possible heat sources as well as a full knowledge of a device thermal structure and of all posible heat-abstraction mechanisms [3]. Generally, heat is generated within a diode-laser structure as a result of non-radiative carrier recombination and absorption of radiation (both mostly within an active region, with a possible exception of absorption of some part of spontaneous emission) as well as generation of volume (within all current paths) and barrier (at contacts and heterojunctions) Joule heating. Besides, in in-plane (edge-emitting) diode lasers, a transfer of spontaneous radiation and its possible absorption in distant laser regions is of importance.

An influence of the above transfer of spontaneous radiation may be explained as follows [4,5]. Spontaneous radiation is emitted within the active layer isotropically in all directions. All radiation, propagated within the active region outside the cone of the apex angle equal to $2\alpha_{cr}$ with respect to the normal to the heteroboundary between the active-layer medium and the surrounding medium, is reflected, where α_{cr} is the critical angle of the total internal reflection at this heteroboundary. On the other hand, a considerable part of radiation propagated inside the above cone is penetrating the surrounding medium. Therefore spontaneous radiation may sometimes reach distant regions of a device and its absorption may occur in many different and sometimes unexpected places.

Heat conduction throughout a device structure, from its heat-sources locations to heat-abstraction places, depends on a device structure and thermal conductivities of all used materials. Generally, thermal resistances of ternary and quaternary $A^{III}B^{V}$ compounds are drastically higher than those of binary ones [6], which should be taken into account in designing diode-laser devices. Besides, in graded layers, where their composition is gradually changed, thermal conduction becomes anisotropic [7], because radial and axial components of thermal conductivities are different. This effect should be carefully included in comprehensive thermal anaalyses of diode lasers.

Let us now consider possible heat-abstraction mechanisms in diode lasers [3]. In a typical packaging scheme, the outer surfaces of a diode laser are exposed to interactions with an external ambient medium (usually air). In principle, this may result in some heat transfer to this medium via the direct contact of air particles with the device walls and a subsequent diffusion and convection processes. In natural convection, the flux of heat from the surface is approximately proportional to the (5/4)*th* power of a difference between the surface temperature and the ambient temperature. In VCSELs, however, considerable temperature increase occurs only in the close vicinity of the active region, buried deep inside the device. The temperature at the outer VCSEL surfaces is usually only slightly higher than that of the surrounding medium. In the case of in-plane diode lasers, on the other hand, the external surfaces of higher temperatures are confined only to a close surrounding of their small emission areas. So an influence of a diffusion of air particles on a process of heat extraction from a diode-laser volume is negligible. Similar conclusion may be formulated for the radiation condition. Although, according to the Stefan-Boltzmann law, radiation intensity is proportional to the fourth power of absolute temperature, it is still negligible at room temperature. Thus, taking together both the above phenomena, we may conclude, that heat transfer through the outer diode-laser surfaces is very small compared to a very efficient heat conduction through the diode-laser base and its heat sink and therefrore can be completely neglected. Consequently, the outer surfaces of the diode-laser chip can be assumed in thermal analyses to be thermally isolated. Heat flux conduction through the device base, on the other hand, produces a temperature increase inside the contact and solder layers as well as within the heat sink and needs an involved three-dimensional thermal approach to be determined. Some simplified approaches may be also used [8,9]. In the case of arrays of diode lasers, strong mutual thermal interactions between individual array emitters taking place via their common heat sink should be additionally taken into account.

In conclusion, modern, based on a computer experiment, methods of investigation of physics of an operation of diode lasers, additionally enabling their designing, optimisation, and simulation anticipated operation characteristics, have been presented and some general principles necessary to model correctly thermal phenomena in diode lasers and arrays of diode lasers have been given.

References:

[1] M. Osiński and W. Nakwaski, [Chapter 5 in] H. Li and K. Iga (Eds.), "Vertical-Cavity Surface-Emitting Laser Devices", Springer, Berlin 2003.

[2] W. Nakwaski and M. Osiński, Opt. Quant, Electron., **29** (1997) 883.

[3] W. Nakwaski and M. Osiński, [Chapter III in] E. Wolf (Ed.), "Progress in Optics", **38** , North Holland, Amsterdam 1998.

[4] T. Kobayashi and Y. Furukawa, Jpn. J. Appl. Phys., **14** (1975) 1981.

[5] W. Nakwaski, Sov. J. Quantum Electron., **9** (1979) 1544.

[6] W. Nakwaski, J. Appl. Phys., **64** (1988) 159.

[7] M. Osiński, W. Nakwaski, and A. Leal, SPIE Proc., **2147** (1994) 85.

[8] W. Nakwaski and A.M. Kontkiewicz, IEEE Trans. Electron. Dev., **32** (1985) 2282.

[9] M. Osiński and W. Nakwaski, Electron. Lett., **29** (1993) 1015.