Simulation of Carrier and Power Losses in Semiconductor Disk Lasers

A. K. Sokół and R. P. Sarzała
Photonics Group, Institute of Physics, Lodz University of Technology
ul. Wólczańska 219
90-924 Łódź, Poland, adam.sokol@p.lodz.pl

***Abstract*–We present the self-consistent numerical model for simulation of multi-mode operation of optically pumped semiconductor disk lasers. We use this model to analyze carrier and power losses in GaN-, GaAs- and GaSb-based structures operating at 0.4, 1.3 and 2.8 µm, respectively.**

I. Introduction

Semiconductor disk lasers (SDLs), also known as vertical-external-cavity surface-emitting lasers (VECSELs), combine advantages of vertical-cavity surface-emitting lasers (VCSELs), edge-emitting lasers (EELs) and solid-state disk lasers. They transform high-power pumping radiation with low quality beam into relatively high-power, circularly-symmetric and narrow-divergence output beam. Moreover, their external cavities enable placing additional optical elements within a laser resonator for advanced transverse-mode control, frequency doubling, high repetition rate short pulse generation and so on. Unique properties of SDLs cause that they find many scientific and commercial applications for example in: telecommunication, colour projection displays, broadly defined bioinstrumentation, gas sensing, fingerprint and trace evidence detection or laser shows.

Typical configurations of a semiconductor disk laser in a simple linear cavity are shown in Fig. 1. The laser chip consisting an active region and distributed Bragg reflector (DBR) is mounted on the cooled heat sink with the aid of an In- or Au-based solder. Since an efficient heat extraction is crucial for proper SDL operation, usually an additional heat spreading layers are applied. Fig. 1a shows a configuration with a diamond heat spreader bounded directly to the laser upper surface. This assembly is especially efficient for narrow pumping beams. The second approach, shown in Fig. 1b, consists in mounting the diamond heat spreader between the laser chip (with the removed substrate, if possible) and heat sink. This assembly configuration is efficient for wide pumping beams and is usually used in SDL power scaling.

A deep understanding of complex interactions between physical phenomena underlying a laser operation is essential for designing efficient SDL structures. Indication of processes responsible for main carrier and power losses within SDL volumes is the first step in a proper structure optimization. In this paper we present the numerical model of optically pumped semiconductor disk laser and results of our analysis of loss mechanisms in SDLs based on different material systems.

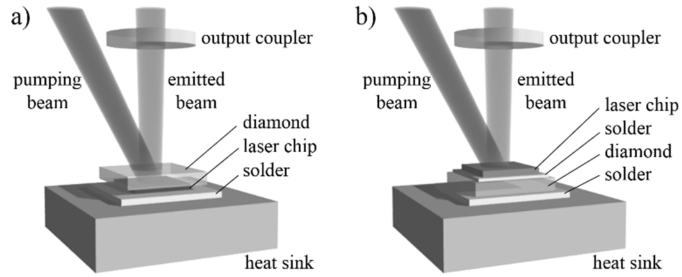

Fig. 1. Typical structure of a semiconductor disk laser with the upper (a) and bottom (b) heat spreader.

II. Numerical model

The numerical model of a semiconductor disk laser has been developed and implemented in the Photonics Group, Institute of Physics, Lodz University of Technology. It consists of four main modules for: carrier transport and recombination, heat flow, gain and optical calculations. It has been previously described in [1]. However, here we use its improved version with the 2D carrier transport model and the algorithm of self-consistency for laser multi-mode operation [2]. To determine the temperature distribution within the laser volume we solve the Fourier-Kirchhoff heat transfer equation with the aid of the finite element method (FEM). Material gain of quantum wells (QWs) in the laser active region is determined using the Fermi's golden rule and parabolic band approximation. Optical module is based on the transfer matrix method (TMM) and the generalized ABCD law for Gauss-Laguerre modes in stable optical resonators. The 2D distribution of carriers generated in the laser active region is determined by solving a set of 1D diffusion equations with no drift contribution in the vertical direction along the active region. The radial diffusion is ignored since its influence on radial carrier distribution is negligible for the considered semiconductor structures [2]. The algorithm of self-consistency for multi-mode operation consists in assuming starting values of output power for each transverse mode and calculating carrier losses due to hole burning in QWs. Hole burning rates are used to determine new values of output power for each mode. Then new values of hole burning rates are calculated. The whole procedure repeats for each transverse mode until its output power is equal to its hole burning power. More detailed description of the self-consistency algorithm can be found in [2].

978-1-4673-8603-6/16/$31.00 ©2016 IEEE

III. Results

The above described model has been used to analyze carrier and power losses in SDLs made of various material systems. Here we present the results of our calculations for the InGaN/GaN, GaInNAs/GaAs and GaInAsSb/AlGaAsSb/GaSb structures operating at 0.4, 1.3 and 2.8 μm, respectively. The InGaN/GaN structure is based on the laser described in [3]. It contains 16 $In_{0.1}Ga_{0.9}N$ QWs separated by $In_{0.02}Ga_{0.98}N$ and GaN barriers and Ta_2O_5/SiO_2 DBR mirror. The structure is pumped through the DBR mirror with 337-nm radiation. The pump spot on the laser surface is 300-μm width. The output coupler transmission is 2.6%. The GaInNAs/GaAs structure is described in [4]. It contains 10 $Ga_{0.63}In_{0.37}N_{0.012}As_{0.098}$ QWs separated by GaAs barriers. The DBR mirror is composed of GaAs/AlAs layers. Over the active region there is a diamond head spreader. The structure is pumped from the upper side with 810-nm radiation. The pump spot on the laser surface is 75-μm width. The output coupler transmission is 2.0%. The GaSb-based structure is presented in [5]. It contains the active region with 10 InGaAsSb QWs separated by $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ barriers and AlAsSb/GaSb DBR mirror. There is also a SiC heat spreader on the laser upper surface. The laser is pumped with 980-nm radiation from the upper side. The pump spot diameter is 300 μm. The output coupler transmission is 0.7%. More details about structures' designs and setups can be found in [3, 4, 5]. In our calculations we have assumed that the external cavity of each structure is adjusted in such a way as to support only a fundamental-mode operation.

Fig. 2 presents distributions of carriers generated in the active regions of the modeled structures. In each case calculations have been carried out for pumping power which provides the maximal value of laser output power. Emission through the output coupler and DBR mirror, surface scattering, free-carrier absorption and monomolecular (A), bimolecular (B) and Auger (C) recombination processes in QWs and barriers are taken into account. The results obtained show that in the GaN-based structure the bimolecular and Auger recombination processes in QWs are the main source of carrier losses (~70% of all carrier losses). For the GaAs-based SDL these losses are almost twofold lower (~38%), however output power is strongly limited by surface scattering.

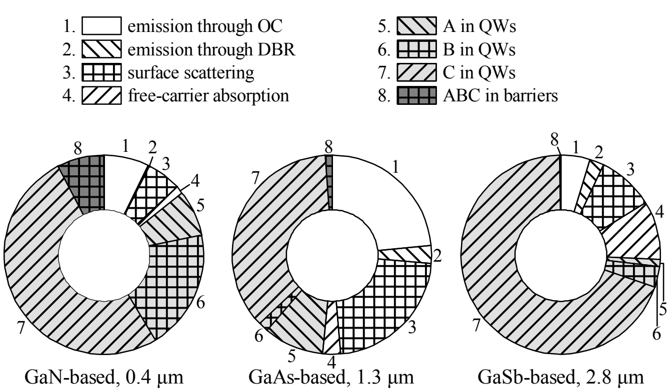

Fig. 2. Distributions of carriers generated in the active regions of the modeled lasers. OC stands for output coupler, A, B, C denote monomolecular, bimolecular and Auger recombination processes, respectively.

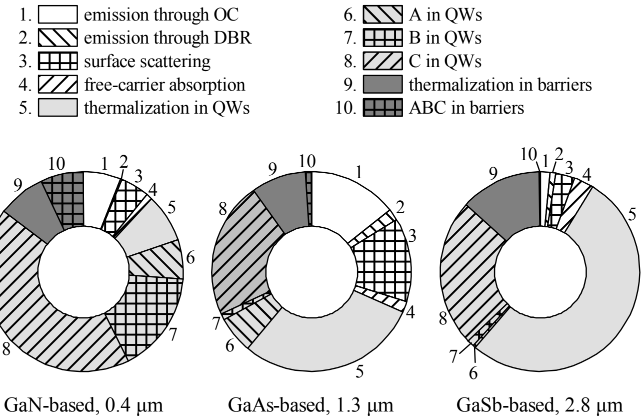

Fig. 3. Distributions of pumping power absorbed in the active regions of the modeled lasers. OC stands for output coupler, A, B, C denote monomolecular, bimolecular and Auger recombination processes, respectively.

In the GaSb-based the carrier loss due to Auger recombination is even higher as compared with the GaN-based laser. In this structure almost ~70% of carriers generated in the active region recombine in this way.

Fig. 3 illustrates distributions of pumping power absorbed in the active regions of the modeled lasers. In the GaN-based SDL the main mechanisms of power losses are bimolecular and Auger recombination. Losses resulting from thermalization of carriers from the pumping photon energy level to energy levels in the QWs are quite small (~16%) due to low relative quantum defect (i.e. the difference between energy of pumping and emitted photons to energy of pumping photon ratio). In turn, in the GaSb-based laser pumped by the 980-nm radiation the relative quantum defect and total power losses due to carrier thermalization reaches 66%. The antimonide structure is also limited by the Auger recombination in the QWs. The GaAs-based SDL has the highest efficiency – more than 14% of absorbed pumping energy is reemitted as laser radiation through the output coupler. The relative quantum defect does not exceed 39%. The main limitations for laser performance in this case is Auger recombination and surface scattering.

Acknowledgment

This work was partially supported by the National Science Centre, Poland under the projects: 2014/13/B/ST7/00633 and 2014/15/N/ST7/05290.

References

[1] A. K. Sokół and R. P. Sarzała, "Influence of pumping beam width on VECSEL output power", *Int. J. Electron. Telecommun.*, vol. 60, pp. 239-245, September 2014.

[2] A. K. Sokół and R. P. Sarzała, "Numerical model of a semiconductor disk laser", *Opt. Appl.*, in press.

[3] R. Debusmann et al., "InGaN–GaN Disk Laser for Blue-Violet Emission Wavelengths", *IEEE Photon. Technol. Lett.*, vol. 22, pp. 652-654, May 2010.

[4] J. M. Hopkins et al., "0.6 W CW GaInNAs vertical external-cavity surface emitting laser operating at 1.32 μm", *Electron. Lett.*, vol. 40, pp. 30-31, January 2004.

[5] B. Rösener et al., "Continuous-wave room-temperature operation of a 2.8 μm GaSb-based semiconductor disk laser", *Opt. Lett.*, vol. 36, pp. 319-321, February 2011.