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Performance characteristics of variously detuned VCSELs

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A comprehensive model of an operation of vertical-cavity surface-emitting diode lasers (VCSELs) is used to simulate the operation of modern GaAs-based oxide-confined double intra-cavity contacted GaInNAs/GaAs quantum-well VCSELs emitting the 1.3-μm radiation. An impact of various detuning of the cavity mode with respect to a maximal active-region optical gain on VCSEL performance characteristics is examined. In particular, high-temperature VCSEL operation is investigated. Properly detuned VCSELs have been found to exhibit nearly constant lasing threshold within quite a wide range of ambient temperatures. In such temperature-insensitive VCSELs with relatively small 4 μm active regions, threshold currents change from 0.84 mA to 1.10 mA, *i.e.*, only by 22%, within quite a wide range of ambient temperatures between 300 K and 360 K.

Keywords: VCSEL lasers, VCSEL detuning, simulation of VCSEL performance.

1. Introduction

Stable single-fundamental-mode operation is required in many laser applications. It means that emitted laser radiation should only consist of a single longitudinal mode as well as a single fundamental transverse mode. Spectral differences between wavelengths corresponding to successive longitudinal modes are inversely proportional to cavity lengths. Therefore, in edge-emitting (EE) diode lasers, the radiation of which usually contains only one transverse mode, there is a problem of reducing a number of longitudinal modes. It happens because of relatively long cavities of these lasers, which results in excitation of many neighbouring longitudinal modes of similar wavelengths corresponding to similar values of the active-region optical gain. In vertical-cavity surface-emitting diode lasers (VCSELs) of much shorter cavities, on the other hand, the wavelength separation between successive longitudinal modes is much larger, which means that their radiation contains only a single longitudinal mode (if any) of the wavelength contained within the active-region gain spectrum. In imperfect VCSELs, the wavelength of the cavity longitudinal mode may be relatively far from a maximum of the active-region optical gain spectrum, then such a VCSEL cannot reach its lasing threshold.

In EE lasers, any change of an active-region temperature leading to a spectral shift of its optical gain results in a change of the dominating longitudinal mode for another one closer to the new spectral position of a maximal active-region optical gain. In VCSELs, on the other hand, the wavelength of only one longitudinal mode may be contained within the gain spectrum. Then, a change in the active-region temperature leads only to a better or worse VCSEL detuning. Consequently, cavities of EE lasers are always tuned to maxima of their gain spectra but those of VCSELs may be intentionally detuned, which gives an additional degree of freedom in VCSEL designing. As a result, designers of EE lasers can propose devices emitting radiation of wavelengths solely associated with their active regions. But in the case of VCSELs, it is possible to design a device emitting radiation of required wavelength, sometimes somewhat different (practically always longer) from that connected with a maximal optical gain of their active-region structure.

Both the cavity modes and the whole optical gain spectrum are shifted with temperature towards longer wavelengths (red shift) [1]; modes – because of temperature dependences of both refractive indices and cavity sizes, gain spectrum – because of a temperature-dependent energy gap. However, the gain spectrum is shifted distinctly more rapidly than the cavity modes, therefore it is possible to obtain in VCSELs at higher temperatures the desired longer-wavelength emission in active regions of the gain spectrum with its maximal value corresponding, at room temperature (RT), to a shorter wavelength. However, to keep the high-temperature long-wavelength lasing threshold relatively low, the cavity mode should be appropriately blue shifted at RT with respect to the RT maximum of the gain spectrum.

An impact of various detuning of VCSEL cavity modes with respect to its active--region gain spectrum on its performance at room and higher temperatures is examined in this paper with the aid of a comprehensive self-consistent VCSEL model.

2. Model

Following the principles given by NAKWASKI [2], a comprehensive optical-electrical-thermal-gain self-consistent VCSEL threshold model has been developed to simulate a room-temperature (RT) continuous-wave (CW) operation of the diode laser under consideration. The model consists of four mutually interrelated parts:

1. A three-dimensional (3D) optical model (the effective-frequency method proposed by WENZEL and WÜNSCHE [3]) describing, for successive radiation modes, their modal gain and losses, lasing thresholds, emission wavelengths and optical field distributions within the laser cavity;

2. A 3D finite-element-method (FEM) electrical model characterizing the current spreading between the top and the bottom annular contacts through the centrally

located active region, the injection of carriers of both kinds into the QW active region and their subsequent radiative or non-radiative recombination after radial 2D out-diffusion within the active layer;

3. A 3D FEM thermal model characterizing generation of the heat flux (non-radiative recombination, re-absorption of spontaneous radiation as well as volume and barrier Joule heating), its flow from the heat sources towards the heat sink and its spreading within the heat-sink;

4. A gain model (Fermi's Golden Rule) furnishing information about an optical gain process within the QW active region to enable determination of its optical-gain spectra.

In this theoretical approach, all important, usually non-linear, interactions between optical, electrical, thermal and recombination phenomena are taken into account with the aid of the self-consistent approach (Fig. 1), including:

– thermal focusing, *i.e.*, the temperature dependence of refractive indices,

– self-focusing, *i.e.*, dependence of refractive indices on carrier-concentration decrease stimulated by radiation intensity,

– gain-induced waveguiding, *i.e.*, the temperature, carrier-concentration and wavelength dependences of extinction coefficient,

– temperature dependence of thermal conductivities,

– temperature and carrier-concentration dependences of electrical conductivities,

– temperature, carrier-concentration and wavelength dependences of optical gain and absorption coefficients,

– temperature and carrier-concentration dependences of energy gaps.

Accordingly, in each loop of the self-consistent calculation algorithm, new 3D profiles of all model parameters within the whole device volume are determined not only on the basis of various chemical compositions of its structure layers but also taking into account current 3D profiles of temperature, current density, carrier concentration and the mode radiation intensity. Therefore, we consider our model as

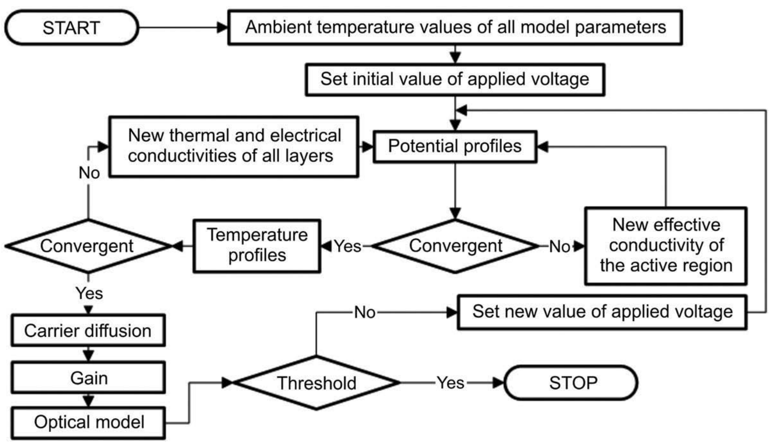

Fig. 1. A flowchart of the iteration algorithm used in our self-consistent threshold VCSEL simulation.

a fully self-consistent one. More details of the model have been reported by SARZAŁA and NAKWASKI [4] and SARZAŁA [5].

Diffraction losses associated with light scattering at oxide apertures are not taken into account in our scalar optical model, which leads to somewhat underestimated lasing thresholds, whereas exactness of our electrical model is additionally improved by introducing the effective electrical resistivity of the active region extracted from experimental current–voltage characteristics. We believe that accurate taking into consideration numerous mutual and usually strongly non-linear interactions between various physical phenomena, *i.e.*, between various optical, electrical, thermal and recombination processes, taking place within a VCSEL volume, which requires a fully self-consistent iterative approach and which is included in our model (see Fig. 1), is much more important for model accuracy than some of its shortcomings of probably minor importance. Besides, validity of our model has been confirmed experimentally [6].

Our model has been prepared following the general principle [2] that exactness of all model parts should be of the same order, because the model is as exact as its less exact part (analogously to a chain which is as strong as its weakest link).

3. Structure

The present analysis has been carried out assuming the modern GaAs-based oxide--confined double intra-cavity contacted double-quantum-well (DQW) GaInNAs/GaAs VCSEL (Fig. 2) emitting the 1.3-μm radiation as a typical VCSEL example. The laser structure is similar (but not identical) to the one reported by RAMAKRISHNAN *et al.* [7]. The intentionally undoped active region consists of two 6.5 nm (GaIn)(NAs) quantum wells (QWs), each containing 34% indium and 1.7% nitrogen, separated by a 25-nm GaAs barrier. The active region is sandwiched by the GaAs spacers: the *p*-type one

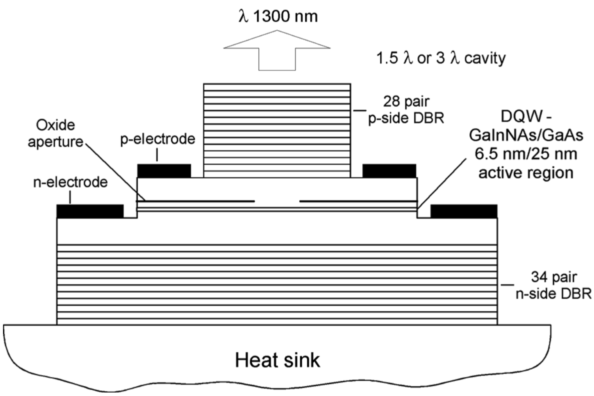

Fig. 2. A typical structure of the standard GaAs-based oxide-confined double-quantum-well (DQW) GaInNAs/GaAs VCSEL with a single oxide aperture located at the anti-node position of the optical standing wave within the VCSEL cavity.

doped to 10^{17} cm^{-3} below the oxide aperture and to 2×10^{18} cm^{-3} over it, whereas the whole *n*-type spacer is doped to 10^{18} cm^{-3}. An increased doping of the upper part of the *p*-type spacer and of the whole *n*-type one has been introduced to reduce their electrical resistivities leading to a more intense radial current spreading from distant annular contact towards centrally located active region. The active region is surrounded by the *p*-type and the *n*-type GaAs contact layers. The Al_xO_y oxide aperture is located at the anti-node position of the optical standing wave within a laser cavity to introduce radial confinements for both the current spreading and the electromagnetic field. The 28-period GaAs/$Al_{0.8}Ga_{0.2}As$ upper and the 34-period GaAs/AlAs bottom quarter-wave distributed-Bragg-reflectors (DBRs), both intentionally undoped, are manufactured as DBR mirrors of the 1.5λ laser cavity. The AuGe/Ni/Au annular *n*-side contact of internal and external diameters equal to 74 μm and 100 μm, respectively, and the Ti/Pt/Au *p*-side one of analogous diameters equal to 54 μm and 70 μm are deposited on both GaAs spacers. The laser is stuck on the copper heatsink with the aid of a 5-μm indium solder.

4. Results

For VCSELs with the cavity mode of about 1.29 μm wavelength tuned at room temperature (RT = 300 K) to a maximal value of the active-region gain spectrum, active-region gain spectra for lasing thresholds at various ambient temperatures T_{HS} are plotted in Figs. 3**a** and 3**b** for the relatively small and large active regions, respectively. As expected, both gain spectra and wavelengths of cavity modes are gradually shifted towards longer wavelengths (red shift) with an increase in temperature. But the spectra are shifted faster which results in an increasing detuning of cavity modes at higher temperatures. For VCSELs with the smaller active regions (r_A = 2 μm), the maximal gain value corresponds to about 1.290 μm at 300 K, but this value is increased to as much as about 1.319 μm for 360 K. At the same time, the wavelength of the cavity mode is increased from 1.2877 μm to only 1.2934 μm. This detuning, together with steadily increasing mode losses at higher temperatures, leads to an increase in the threshold carrier concentrations from its maximal value of 5.07×10^{18} cm^{-3} at 300 K to as much as 7.41×10^{18} cm^{-3} at 360 K. In the case of the larger active region (r_A = 8 μm), the above increases are even more pronounced: the maximum of the gain spectrum is shifted from about 1.287 μm to about 1.320 μm, the cavity mode – from 1.284 μm to 1.290 μm, and the threshold carrier concentration – from its maximal value of 5.66×10^{18} cm^{-3} at 300 K to as much as 9.32×10^{18} cm^{-3} at 360 K.

Analogous plots for VCSELs detuned (red shift) at room temperature with the RT cavity-mode wavelengths of about 1.308 μm (for r_A = 2 μm) and 1.304 μm (for r_A = = 8 μm) distinctly different from wavelengths corresponding to maximal RT optical gain values (in both cases – 1.284 μm) are plotted for both active-region sizes in Fig. 4. This time, for the temperature range considered, the highest lasing threshold happened to be at RT, for which the above detuning is the highest. With an increase in

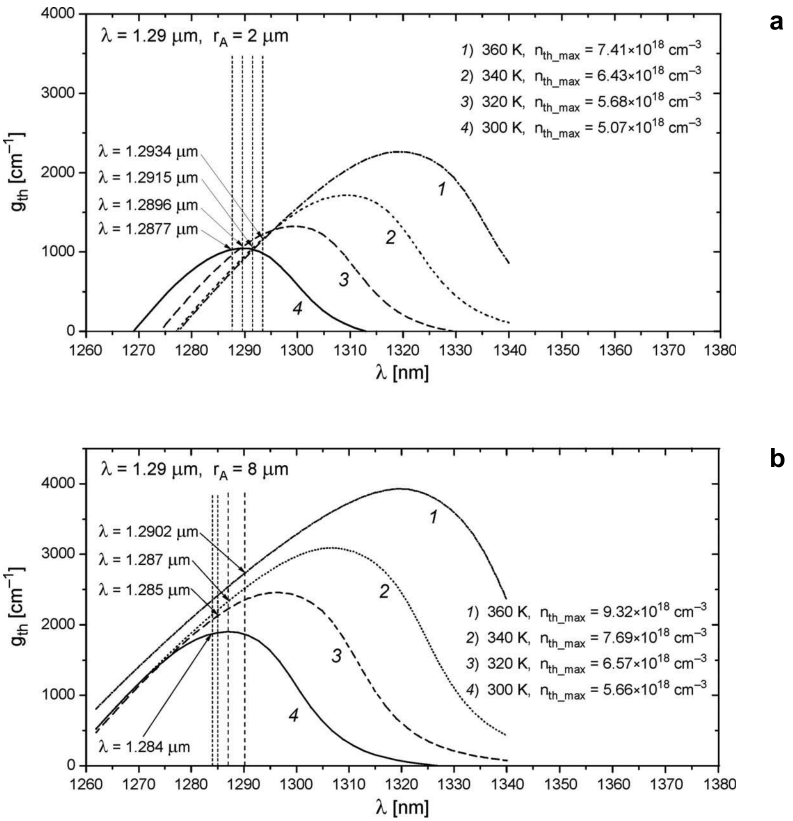

Fig. 3. Active-region gain spectra $g_{\mathrm{th}}(\lambda)$ determined for lasing thresholds at indicated ambient temperatures T_{HS} of the GaAs-based oxide-confined double-quantum-well GaInNAs/GaAs VCSEL with the cavity mode tuned at room temperature to the maximal value of the active-region gain spectrum and with active-region radii r_A equal to: 2 μm (**a**), and 8 μm (**b**). Localizations (straight vertical lines) and wavelengths λ of cavity modes at various temperatures are shown. Maximal values of the threshold carrier concentrations are indicated.

temperature, gain spectrum maxima are initially becoming closer to the mode wavelength, the VCSEL cavity becomes tuned to the VCSEL gain spectrum at about 340 K and then the gain spectrum leaves the cavity mode behind. In the case of the VCSEL with smaller active region, it results in an initial maximal threshold carrier concentration decreasing from as much as 6.75×10^{18} cm^{-3} at 300 K to only 5.88×10^{18} cm^{-3} at 340 K and again to higher value of 6.54×10^{18} cm^{-3} at 360 K. For the VCSEL with larger active region, analogous threshold carrier concentrations are equal to 6.78×10^{18} cm^{-3} at 300 K to 6.80×10^{18} cm^{-3} at 340 K and to 7.89×10^{18} cm^{-3} at 360 K. Nearly identical lasing thresholds at 300 K and 340 K follow from two opposite tendencies: a better overlapping of the cavity mode wavelength with the maximal value of the optical gain spectrum at 340 K and increasing optical losses at higher temperatures.

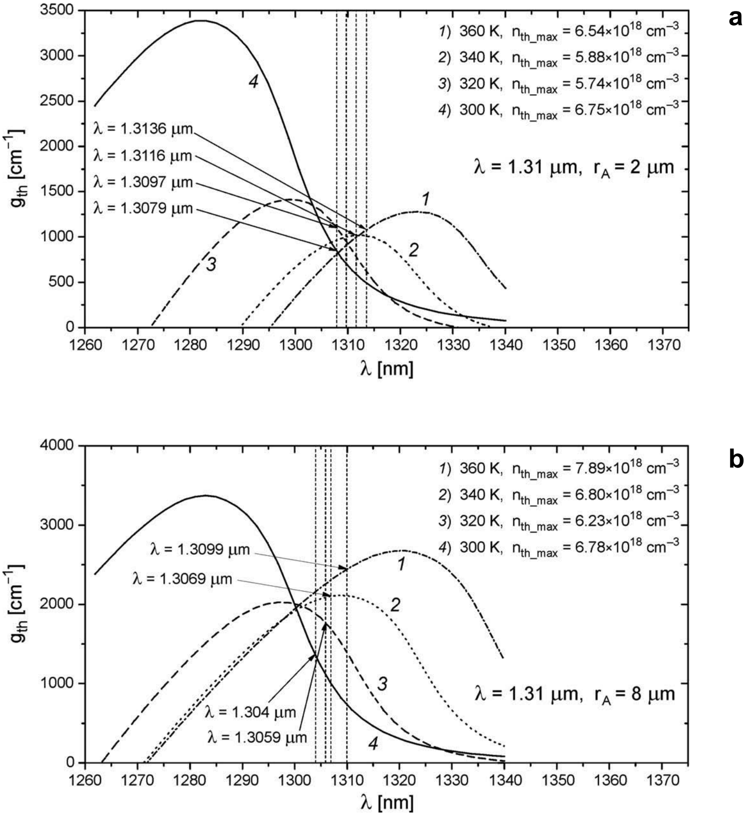

Fig. 4. Active-region gain spectra $g_{th}(\lambda)$ determined for lasing thresholds at indicated ambient temperatures T_{HS} of the GaAs-based oxide-confined double-quantum-well GaInNAs/GaAs VCSEL with the cavity modes detuned at room temperature from the maximal value of the active-region gain spectrum and with active-region radii r_A equal to: 2 μm (**a**), and 8 μm (**b**). Localizations (straight vertical lines) and wavelengths λ of cavity modes at various temperatures are shown. Maximal values of the threshold carrier concentrations are indicated.

The above behaviour of detuned VCSELs may be employed in designing temperature-insensitive VCSELs exhibiting intentionally nearly constant lasing thresholds within an assumed temperature range. In Figures 5**a** and 5**b**, temperature dependences of threshold currents of VCSELs under consideration with the two active regions are plotted for variously detuned cavity modes. For VCSELs with smaller active regions, a perfect tuning of the cavity mode (1290 nm) and the active-region gain spectrum at RT leads to the lowest threshold of 0.65 mA which is more than three times lower than the threshold of 2.0 mA of the detuned VCSEL (λ = 1320 nm). For VCSELs with larger active regions, analogous lasing thresholds are equal to 4.9 mA and 11.1 mA. However, the most interesting plots have been shown for intentionally detuned VCSELs with the wavelength of the cavity mode of 1310 nm. Within quite a wide range of ambient temperatures between 300 K and 360 K, the threshold current

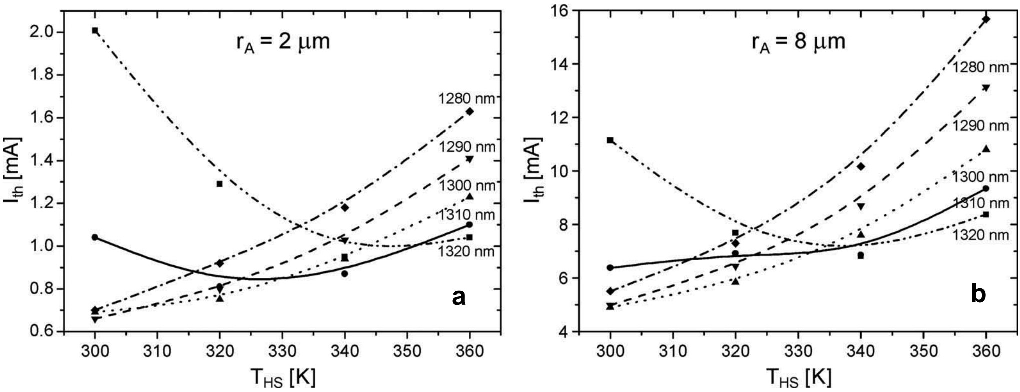

Fig. 5. Temperature dependences of threshold currents I_{th} of VCSELs under consideration with active-region radii r_A equal to: 2 μm (**a**), and 8 μm (**b**) are plotted for variously detuned cavity modes of indicated wavelengths.

of VCSEL with the smaller active region is changing from 0.84 mA to 1.10 mA, *i.e.*, within a 22% range only, and that of VCSEL with the larger active region – from 6.3 mA to 9.3 mA, *i.e.*, within a 32% range.

5. Conclusions

Lasing thresholds of VCSELs with cavity modes intentionally detuned at room temperature towards longer wavelengths with respect to the active-region gain spectrum are changing only moderately within quite a wide range of higher ambient temperatures. Such VCSELs may be regarded as almost temperature-insensitive ones, which may be important in some of their possible applications.

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