*Optica Applicata, Vol. XLI, No. 1, 2011*

# Why is it so difficult to reach the single fundamental transverse-mode operation in detuned oxide-confined VCSELs?

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In most applications of vertical-cavity surface-emitting diode lasers (VCSELs), their stable and efficient single-mode operation is required. In standard VCSEL designs, single-longitudinal-mode operation is assured because of their short optical cavities. There is, however, a real problem, how to reach single fundamental-transverse-mode (SFM) operation, especially in modern intra-cavity contacted VCSELs demonstrating the current-crowding effect close to active-region edges. This problem becomes even more acute in detuned oxide-confined VCSELs, where wavelengths of higher-order transverse modes are distinctly lower than that of the fundamental one. VCSEL structures enable spectral detuning of the cavity modes with respect to the peak value of the optical gain spectrum. Such a red-direction detuning is used in GaInNAs VCSELs designed for the 1300-nm wavelength of the second generation of optical fibre communication. In this case, the above detuning enhances at room temperature the excitation of lower-wavelength higher-order transverse modes spectrally located closer to the peak value of the optical gain than the fundamental one. At elevated temperatures, however, the above detuning is reduced leading to higher values of the optical gain available for the fundamental mode. Then the desired stable and efficient SFM 1300-nm operation may be reached.

Keywords: single-fundamental-mode VCSEL operation, oxide-confined VCSELs, detuned VCSELs.

## 1. Introduction

Currently a vertical-cavity surface-emitting diode laser (VCSEL) offers superior lasing performance to all other semiconductor lasers. Its output beam is low-divergent, circularly symmetric and without astigmatism, its radiation field inherently contains only a single longitudinal mode, its manufacturing makes possible permanent on-wafer monitoring of layer compositions and thicknesses and its structure enables its application as an emitter of two-dimensional arrays. Therefore, the VCSELs are used in many important applications. But in most of them, *e.g.*, in high-speed (over 10 Gbps) data transmission in optical networks, optical interconnects, free-space communication, airborne light detecting and ranging (LIDAR), optical storage, laser printing, equally important is additionally their stable single fundamental transverse mode (SFM) operation. In modern intra-cavity contacted VCSELs, such an operation is usually limited to devices with small active regions emitting relatively low output power [1–4]. Even more difficult is to obtain the SFM performance in highly detuned oxide-confined (OC) VCSELs, whose physics is distinctly different from that of regular VCSELs. Reasons of the above difficulty are explained in the present paper using the detuned OC GaInNAs quantum-well VCSEL emitting the 1.3-μm radiation as a typical example.

## 2. Physics of detuned VCSELs

It is well known that inherently single-longitudinal-mode VCSELs operation is directly connected with their very short optical cavities as compared with those of edge-emitting (EE) diode lasers. Spectral distance $\Delta\lambda_{\rm FP}$ between peaks on a laser spectral characteristic corresponding to successive longitudinal Fabry–Perot cavity modes is inversely proportional to the cavity length $L$ [5]:

$$\Delta\lambda_{\rm FP} = \frac{\lambda^2}{2L\left(n_{R,\,\rm eff} - \lambda\dfrac{\partial n_R}{\partial\lambda}\right)} \tag{1}$$

where $n_{R,\,\rm eff}$ stands for the effective refractive index of the considered mode and $\lambda$ is its emission wavelength. This spectral spacing $\Delta\lambda_{\rm FP}$ in a typical GaAs-based EE laser with $L$ = 400 μm is equal to only about 0.25 nm, whereas the above spacing in an analogous 1.3-μm VCSEL with a typical $\lambda$ cavity is as high as over 270 nm. Hence, the EE lasers may emit radiation containing many longitudinal modes of wavelengths close to that corresponding to the maximal optical gain and only slightly different (by about 0.25 nm) from one another. Therefore, in EE lasers, any change in the active-region temperature leading to the spectral shift of its gain spectrum results in a change of the dominating longitudinal mode for the one closer to the new position of the maximal active-region optical gain. VCSELs, on the other hand, emit radiation of only one (if any) longitudinal mode of the wavelength relatively close to the above optical gain maximum but determined mostly by the cavity design because it corresponds to the standing optical wave within the resonator. Then, a change in the active-region temperature leads only to a better or worse VCSEL tuning. Consequently, the cavities of EE lasers are always tuned to peak values of their gain spectra but those of VCSELs may be intentionally detuned, which gives an additional degree of freedom in VCSEL designing [6]. 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 a required wavelength, sometimes somewhat different (practically always longer) from that connected with the maximal optical gain of their active-region structure. However, it should be remembered, that physics of the detuned VCSELs is a little different from that of the tuned ones [6].

During VCSEL operation, in their resonators there are excited standing optical waves, usually called – cavity modes. For such standing waves, the resonator length $L$ is equal to an integer number of half-wavelengths:

$$L = k\left(\frac{\lambda}{2n_{R,\,\mathrm{eff}}}\right) \quad \text{for} \quad k = 1, 2, 3, \ldots \tag{2}$$

An increase in temperature results in shifting towards longer wavelengths (red shift) both the cavity modes and the whole optical gain spectrum [5]: modes – because of temperature dependences of both refractive indices and cavity sizes, gain spectrum – because of the temperature-dependent energy gap. The gain spectrum is shifted distinctly more rapidly than the cavity modes, therefore, in VCSELs, it is possible to obtain at higher temperatures the desired longer-wavelength emission in active regions emitting at room temperature (RT) radiation of shorter wavelength. Then, to keep the high-temperature long-wavelength lasing threshold relatively low at elevated temperatures, the cavity mode should be appropriately red shifted (detuned) at RT with respect to the RT maximum of the gain spectrum. Thereupon, with an increase in temperature, the above detuning is steadily reduced leading to an increase in the optical gain available for the initially detuned mode in spite of steadily reduced maximal (peak) value of this gain. Higher temperatures result also in higher optical losses, but, for detuned VCSELs, increase in temperature leads initially to their lower lasing thresholds. Besides, scrupulous designing may even result in obtaining so-called temperature-insensitive VCSELs with threshold currents nearly independent of temperature within some of its range. The above designing possibility is impracticable in EE diode lasers, for which an active-region temperature increase results in a jump of the lowest-threshold longitudinal mode towards the next one, closer at elevated temperatures to the maximal gain.

Fundamental-mode operation is enhanced for a uniform current injection into VCSEL active regions [4]. However, most of designs of modern VCSELs has the intra-cavity contacted structure. Then, approximately uniform current injection is possible only in the case of small active regions. An increase in their diameter leads to increasingly non-uniform current injection favourable for excitation of higher-order transverse modes.

## 3. Performance of detuned VCSELs

Let us consider the modern mesa top-emitting OC VCSEL design reported by YANG *et al*. [7]. Its upper contact is in a ring form whereas the broad-area one is used as the bottom contact. The one-wavelength cavity is placed between two distributed Bragg reflector (DBR) mirrors. The GaInNAs/GaAs double quantum well (DQW) active region is located at the anti-node position of the optical standing wave and the oxide aperture is placed at the second such a position.

GaInNAs/GaAs quantum-well active region creates some problems with reaching at RT the desired 1300-nm emission. Energy gap of $Ga_{1-x}In_xN_yAs_{1-y}$ is reduced with an increase in both indium ($x$) and nitrogen ($y$) amounts. However, $x$ and $y$ values over 36% and over 1%, respectively, may lead to generation of some structure defects. For the "safe" lower values of these mole fractions, the maximal RT optical gain will correspond to the wavelength much shorter than the desired 1300 nm. Then, the VCSEL emission may be shifted towards desired longer wavelengths with the aid of proper red detuning of the $LP_{01}$ mode, *i.e.*, when the cavity mode corresponds to the wavelength of 1300 nm disregarding the gain spectrum.

The comprehensive optical-electrical-thermal-gain self-consistent VCSEL threshold model [4, 6] has been developed to simulate at RT continuous-wave (CW) operation of a diode laser under consideration. Three-dimensional (3D) profiles of all model parameters within the whole device volume are determined in each calculation loop not only on the basis of various chemical compositions of its structure layers but also, with the aid of the self-consistent calculation algorithm, taking into account current 3D profiles of the temperature, the current density, and the carrier concentration.

It is well known, that an increase in the OC VCSEL active-region diameter leads in intra-cavity contacted devices to increasing non-uniform current injection [2] which enhances excitation of higher-order transverse modes. Nevertheless, quite high SFM output of 4.8 mW was reported in 3.5-μm diameter VCSEL emitting the 840-nm radiation [1]. With the aid of special mechanisms suppressing higher-order transverse modes, the SFM operation has been reached even in devices with very large active regions of diameters from 15 μm to even 25 μm [8–10]. However, reaching the SFM operation becomes more difficult in highly detuned VCSELs. For example, in the case of the standard OC (oxide-layer thickness of 20 nm) 6.5-nm $Ga_{0.64}In_{0.36}N_{0.006}As_{0.994}$/GaAs DQW VCSEL properly detuned to reach at RT the 1.3-μm emission for the fundamental mode and equipped with a typical active region of the 10-μm diameter, RT modal optical gain values $g(LP_{ij})$ and threshold gain values $g_{th}(LP_{ij})$ determined for the threshold current of the lowest-threshold $LP_{71}$ mode are presented in Fig. 1. As one can see, the threshold gain of the fundamental $LP_{01}$ mode is distinctly lower than threshold gains of higher-order transverse modes, but, because of considerable detuning at RT between this cavity mode and the gain spectrum, optical gain available for this mode is still lower. Higher-order modes are penetrating the oxide aperture to much more extent than the fundamental one. Therefore, because of very low index of refraction of only 1.61 [11] of this oxide, effective indices of higher-order modes are distinctly lower than that of the fundamental mode. This fact, following Eq. (2), results in considerably lower wavelengths of higher-order modes than the desired 1300 nm of the fundamental one (Fig. 1). Higher-order modes demonstrate distinctly higher threshold gain values than that of the fundamental one but their optical gain values are also higher. Then, for this case, the $LP_{71}$ mode of wavelength equal to only 1291 nm has happened to be the first one reaching the lasing threshold condition. Therefore, in

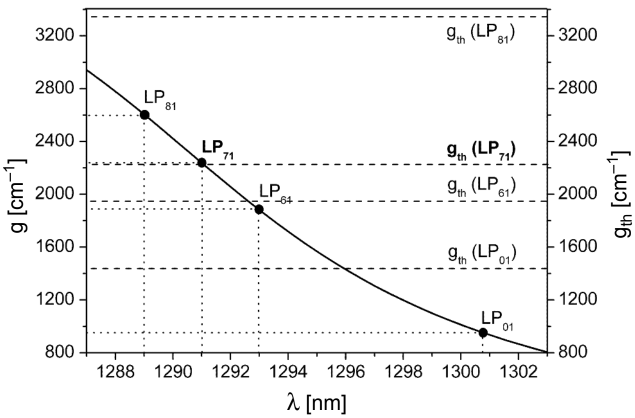


Fig. 1. Modal optical gain values $g(LP_{ij})$ and modal threshold gain values $g_{th}(LP_{ij})$ determined for the threshold current of the lowest-threshold $LP_{71}$ mode for the RT operation of the standard detuned 10-μm diameter GaInNAs QW VCSEL. The cavity is designed for the 1.3-μm operation.

standard large-size detuned OC GaInNAs VCSEL structures, the SFM 1.3-μm emission is very difficult to be obtained at RT.

The wavelength of radiation emitted in QW structures may be increased with an increase in the QW thickness. But then, when this thickness becomes larger than its critical value, some defect generation may appear. Therefore, following suggestions of MISIEWICZ *et al.* [12], it seems to be reasonable to add two intermediate 2-nm $Ga_{0.73}In_{0.27}N_{0.0065}As_{0.9935}$ layers on both the 6.5-nm $Ga_{0.65}In_{0.35}N_{0.0065}As_{0.9935}$ QW sides in the modified step-like QW. Then, the QW thickness is kept below its critical value, the QW levels are distinctly shifted down (followed by a profitable shifting of the gain spectrum towards longer wavelengths) and a proper detuning of the $LP_{01}$ cavity mode is introduced. Temperature dependence of threshold currents of VCSELs with such modified active regions is plotted in Fig. 2 for various active-region

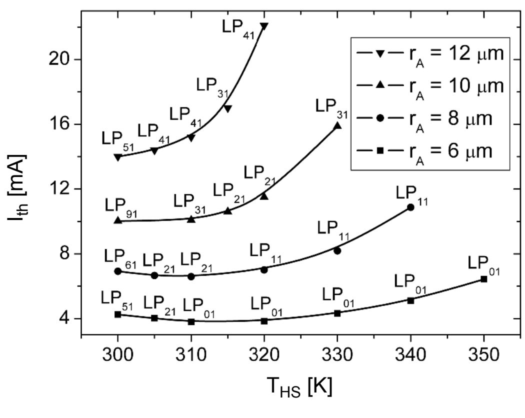


Fig. 2. Temperature dependence of threshold currents $I_{th}$ of VCSELs with modified active regions of various radii $r_A$. $T_{HS}$ – the ambient temperature. The lowest-threshold LP modes are indicated.

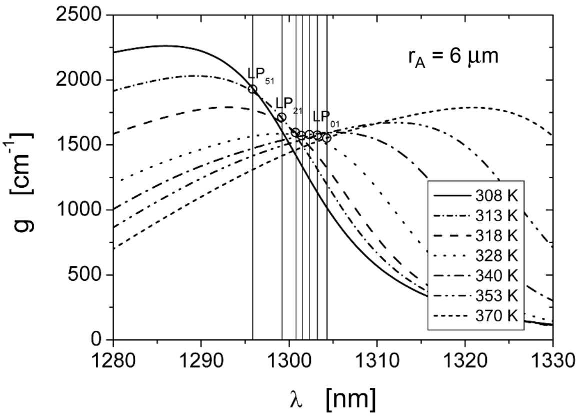


Fig. 3. Gain spectra and cavity-mode wavelengths (perpendicular lines) determined for the indicated lowest-threshold mode and increasing active-region temperatures for the 12-µm diameter VCSEL with the modified active region.

radii $r_A$. As one can see, temperature increase leads to a steady decrease in the order of the lowest-threshold mode and, for 310 K and the 12-µm aperture ($r_A$ = 6 µm) VCSEL, the fundamental mode becomes the lowest-threshold one (Fig. 2). The above behaviour is a result of the gradual detuning of the fundamental mode leading to a decrease in its threshold current. Besides, an increase in the active-region size leads at RT initially to excitation of still higher-order modes $LP_{61}$ and $LP_{91}$. But for the largest considered active region, its relatively high threshold current leads to a considerable active-region temperature increase because of Joule heating. Then, the gain spectrum is additionally shifted towards longer wavelengths, which results in detuning reduction and excitation of the lower-order $LP_{51}$ mode.

A gradual change with temperature of the mode detuning of the 12-µm modified VCSEL is shown in Fig. 3. Successive active-region temperatures correspond to successive ambient temperatures $T_{HS}$ given in Fig. 2. Gain spectra determined for successive lasing thresholds of the indicated lowest-threshold cavity modes are shown as continuous lines whereas spectral positions of these modes are shown with perpendicular straight lines. Larger shifts of the lowest-threshold cavity-modes at lower temperatures result from an additional change of their mode order. For the active--region temperature about 328 K (corresponding to the ambient temperature of 320 K), a perfect spectral match between the fundamental mode $LP_{01}$ and the gain peak is seen. For temperatures higher than that of the above spectral matching, wavelengths of cavity modes correspond to the opposite slope of the optical gain spectrum. Then higher values of optical gain are available for longer-wavelength lower-order transverse modes than for higher-order ones. Anyway, increasing blue-direction detuning at higher temperatures is affecting the threshold gain to less extent than it might be anticipated because of more smooth gain changes on the blue-side of the gain spectrum than those of the red side (Fig. 3).

## 4. Discussion and conclusions

In most VCSEL applications, their single-mode operation is required, which means that its output beam should contain singular both a longitudinal and a transverse mode. In standard VCSEL designs, their single-longitudinal-mode operation is assured inherently because of their short optical cavities. However, it is more difficult to reach their stable single-transverse-mode operation, preferably – the single fundamental--transverse-mode one. This problem becomes even more acute in detuned oxide--confined (OC) VCSELs.

VCSEL structures enable spectral detuning of the cavity modes with respect to the peak value of the optical gain spectrum. With an increase in temperature, the gain spectrum is shifted towards longer wavelengths distinctly more rapidly than the wavelengths of the cavity modes. Therefore proper red-direction detuning of cavity modes at room temperature (RT) with respect to the peak optical gain results in their higher optical gain values at elevated temperatures. Because of the same reasons, blue-direction detuning of cavity modes is not recommended. However, there may be also another reason of the above mode detuning. With its aid, it is possible to design VCSELs emitting radiation of longer wavelength than that of the peak value of their active-region gain spectrum. Such a method is, for example, used in GaInNAs VCSELs designed for the 1300-nm wavelength of the second generation of optical fibre communication.

In OC VCSELs, wavelengths of higher-order transverse modes are distinctly lower than that of the fundamental one. Therefore in this case, red-direction mode detuning enhances at RT excitation of lower-wavelength higher-order transverse modes spectrally located closer to the peak value of the optical gain. At elevated temperatures, however, the above detuning is reduced leading to higher values of the optical gain available for the fundamental mode. Then the desired stable SFM 1300-nm operation may be reached.

*Acknowledgements* – This work has been supported by the COST Action MP0805 and by the Polish Ministry of Science and Higher Education (MNiSzW), grant No. NN 515 417 635.

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*Received September 7, 2010*
*in revised form October 20, 2010*