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# Linewidth of 89X nm-range intra-cavity contacted VCSELs

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The influence of the oxide aperture diameter on static and spectral characteristics of 89X nm-range VCSELs with the carrier injection through the intracavity contacts and composite bragg reflectors was studied. Studied devices with apertures smaller than $2\,\mu$m had stable single-mode lasing with the fixed direction of polarization, however for the larger apertures the lasing through multiple transverse modes was registered. It was shown that the increase in laser internal temperature led to the anomalous spectral linewidth broadening. Since active area overheating occurs faster for the devices with smaller aperture sizes, increasing the aperture size allows to reduce the spectral linewidth to 30 MHz with an output optical power of $\sim 1$ mW

**Keywords:** vertical-cavity surface-emitting laser, spectral linewidth, atomic sensors.

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Vertically-emitting lasers (VELs) of near IR band are of interest for design of optical interconnections of short length and systems of image recognition, as well as are highly promising for development of compact quantum sensors based on alkali metal atom vapors [1]. High requirements are imposed to laser emitters for use in compact atom sensors, one of which is a small width of the spectral line in the mode of single-mode laser generation [2]. According to the Schawlow-Townes-Henry theory, the width of the injection laser emission line is inversely related to both output optical power and the squared time of photon line in a resonant cavity [3]. On the one hand, in virtue of relative high heat resistance of VEL, the increase of the output optical power is related to drastic growth of the laser's inner temperature due to laser self-heating, which limits the maximum output optical power [4]. Besides, VEL operation in the mode of higher current density negatively impacts its reliability. On the other hand, VELs are characterized by relatively small time of photon life in a resonant cavity due to short length of a vertical optical resonant cavity, which makes the reduction of the width of the spectral emission line below 100 MHz for a classic VEL design with injection of charge carriers through the doped distributed Bragg reflectors(DBR) [5,6] a non-so-trivial task. Therefore, the narrowing of the spectral emission line in single-mode VELs is possible either by increase of the geometric length of the optical resonant cavity or effective length of the resonant cavity, or at the expense of lower losses to the emission output by increasing the reflective capacity of the output mirror. However, reduction of the level of optical losses to the emission output causes a drop in the output optical power (which is critical for quantum magnetometers and nuclear magnetic gyroscopes) and is associated with increased instability of VEL emission polarization under the conditions of the mild polarization dichroism (i. e. without external methods of polarization stabilization). The most evident decision to increase the time of photon life in a resonant cavity is increase of the effective length of the microcavity by using intracavity contacts, which is associated with a risk of increased internal optical losses [7].

Relatively recently we proposed and successfully tested the hybrid design of VEL with spectral range of 89X nm and injection of carriers via intracavity contact layers to ensure a single-mode generation mode with a fixed direction of the linear polarization of emission [8]. The feature of this VEL design is use of composite Bragg lattices, which make it possible to effectively redistribute the standing wave electromagnetic field in a microcavity and to simultaneously provide the low level of internal optical losses [9] and to increase the effective length of the resonant cavity by more than two times compared to the classic VEL design [10].

This paper presents the results of the studies on the impact of the current oxide aperture size at the spectral line width in such type of VEL with spectral range of 89X nm.

By design, the studied lasers are a vertical microcavity limited with a lower semiconductor $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ and an upper dielectric $SiO_2/Ta_2O_5$ DBR. The active area is represented by stressed quantum wells InGaAs/AlGaAs. Current and optical restrictions are provided by selectively oxidized aperture. Design details are given in [8,9].

Fig. 1, *a* presents watt-ampere characteristics for VEL with various diameter of the current oxide aperture measured at 20°C. Instruments demonstrate laser generation with submilliampere threshold currents and differential efficiency of more than 0.55 W/A.

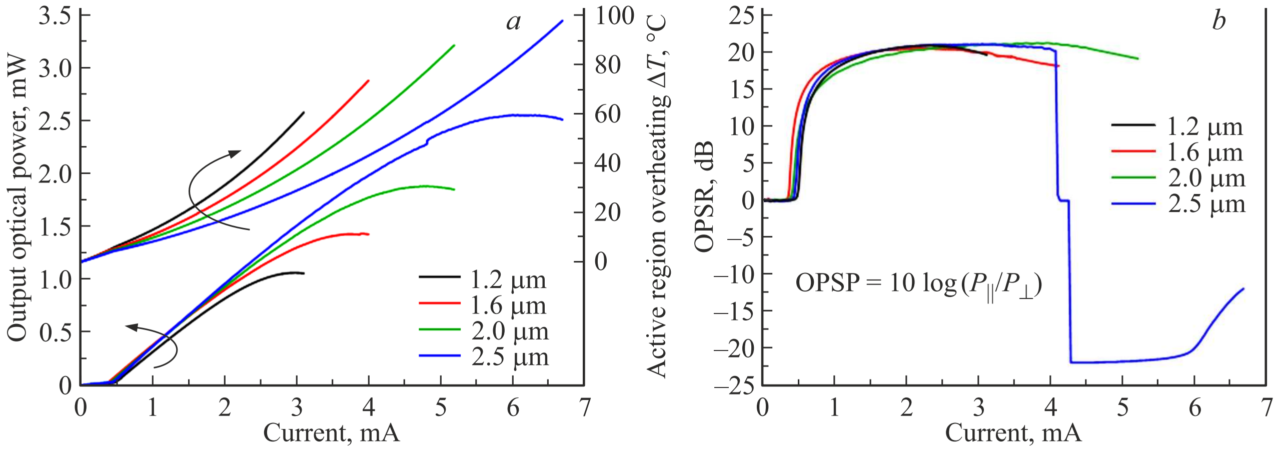


**Figure 1.** (*a*) Watt-ampere characteristics and dependences of active area temperature on current; (*b*) dependences of OPSR (as the ratio of the values of laser output optical power measured along and perpendicularly to the main axis of the polarizer) on the current force. Temperature 20°C.

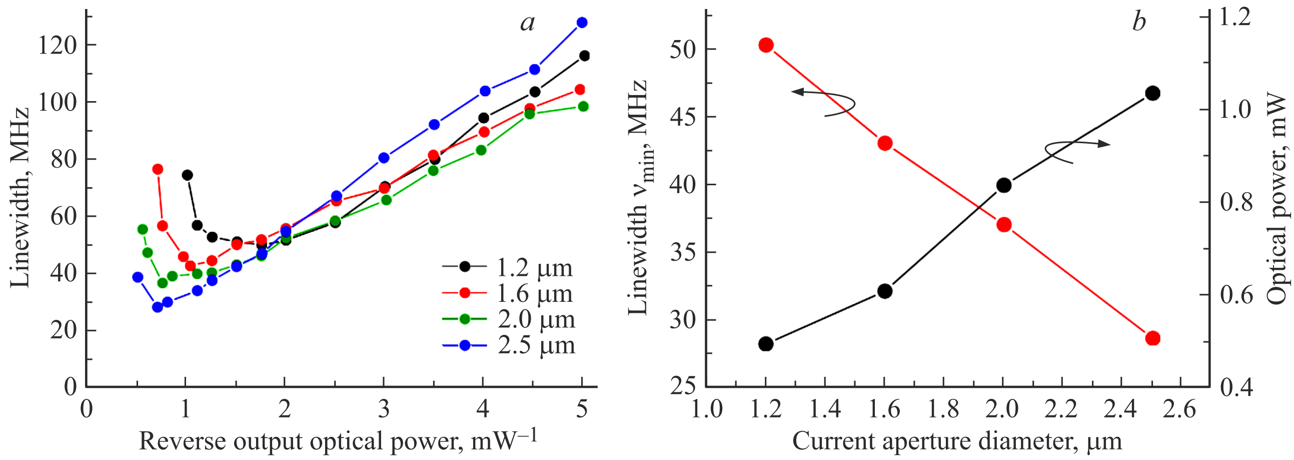


**Figure 2.** (*a*) Dependences of $\Delta\nu(P)$ spectral line width for VELs with various diameters of current oxide aperture. (*b*) Dependences of minimum $\Delta\nu_{min}$ line width and corresponding output optical power on specific size of current oxide aperture. Temperature 20°C.

The analysis of the emission spectra showed that a single-mode laser generation mode near range of 89X nm with the factor of side mode suppression of more than 30 dB in the entire range of currents is implemented for VEL at specific size of the current oxide aperture up to 2 $\mu$m. It should be noted that the output optical emission of VEL is linearly polarized with the orthogonal polarization suppression ratio (OPSR) of more than 15 dB up to the currents of the output optical power saturation (fig. 1, *b*). Fixation of the polarization direction and absence of the polarization switching effect are provided through anisotropy of mechanical stresses near the active area that arise in the diamond-shaped oxide aperture [11]. For a large-sized aperture (more than 2.5 $\mu$m), laser generation becomes possible through the transverse modes of the highest order, accompanied with the jump-like increase in the output optical power and switching of the emission polarization direction.

Fig. 2, *a* presents experimental dependences of the emission line width for line $\Delta\nu$ on the level of the output optical power of the line $P$ for different sizes of the current oxide aperture, obtained using a Fabry-Perot scanning interferometer with the resolution of 7.5 MHz. At the initial section $\Delta\nu(P)$ the line width narrows down along with the growth of power $P$, and the extrapolation of the dependence provides the residual width of the spectral line $\sim 10-20$ MHz, which is due to the flicker noise and/or competition of transverse modes [3]. At the second section $\Delta\nu(P)$ there is an abnormal behavior present, which manifests itself in broadening of the spectral line regardless of the further growth of power $P$, which limits the minimum achievable value of the spectral line width $\Delta\nu_{min}$. The assessment of the internal temperature of the active area in the studied VELs by the value of heat resistance of instruments (fig. 1, *a*) found correlation by current between the area of transition to the second section of the dependence $\Delta\nu(P)$ and drastic growth of the internal temperature.

Therefore, the found abnormal behavior of the dependence $\Delta\nu(P)$ is due to the laser self-heating, which causes growth of $\alpha$-factor [12] and broadening of VEL spectral line.

It should be noted that for lasers with the smaller-sized aperture a stronger overheating of the active area is observed compared to the wide-aperture lasers at the comparable output optical power (fig. 1, *a*), which is due to the higher heat resistance and growth of additional optical losses due to scattering/diffraction of light at the interface of oxide-semiconductor [9], causing growth of the threshold current and reduction in the differential efficiency of VEL. As a result, as the specific size of the current oxide aperture increases, the minimum value $\Delta\nu_{\min}$ drops from 50 MHz at output optical power $\sim 0.5$ mW for an instrument with aperture $1.2\,\mu$m to 30 MHz at output optical power $\sim 1$ mW for an instrument with aperture $2.5\,\mu$m (fig. 2, *b*). Further increase of the aperture size requires use of additional methods for selection of transverse modes and generation of polarization-selective losses.

Therefore, studies were carried out on the impact of the size of current oxide aperture at the width of the spectral line of single-mode VELs of spectral range 89X nm with injection of carriers via intracavity contact layers and composite Bragg lattices. The possibility in principle to narrow the spectral line down to 30 MHz is shown without substantial change in the level of internal optical losses and losses to the emission output.

The data obtained in process of the study are only slightly inferior to the record-low values: 23 MHz at output optical power $\sim 0.45$ mW for VEL of spectral range 85X nm with the broadened optical resonant cavity [7] and 23 MHz at output optical power $\sim 0.91$ mW for VEL of classic geometry of a vertical microcavity of spectral range 89X nm with a subwavelength lattice in the output DBR [13]. The obtained results are critical for design of compact quantum sensors based on alkali metal atom vapors.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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