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Vertical-cavity surface-emitting lasers for compact atomic sensors

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Abstract. The design features of 8XX nm-range vertical-cavity surface-emitting lasers for providing single-mode and polarization-stable lasing, narrowing the spectral linewidth of laser emission and achieving high modulation bandwidth are considered The special intra-cavity contacted design and the rhomb-shaped oxide-confined aperture can simultaneously provide single-mode output optical power above 1 mW, fixed polarization direction, emission linewidth below 50 MHz and modulation bandwidth more than 5 GHz.

Keywords: vertical-cavity surface-emitting laser, single-mode, polarization, linewidth, modulation bandwidth

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Вертикально-излучающие лазеры для компактных атомных сенсоров

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Аннотация. Рассмотрены особенности конструкций вертикально-излучающих лазеров спектрального диапазона 8XX нм с целью обеспечения одномодового режима генерации с фиксированным направлением поляризации излучения, заужения ширины спектральной линии излучения и реализации высокой частоты эффективной модуляции. Специальная конструкция микрорезонатора с внутрирезонаторными контактами и оксидная токовая апертура ромбовидной формы позволяет одновременно обеспечить оптическую мощность более 1мВт в одномодовом режиме генерации с фиксированным направлением поляризации, шириной линии изучения менее 50 МГц и частотой эффективной модуляции более 5 ГГц.

Ключевые слова: вертикально-излучающий лазер, одномодовое излучение, поляризация, ширина линии, частота модуляции

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Introduction

Recently, increased attention has been paid to the issue of minimizing the size and power consumption of various types of atomic sensors, and the only possible solution is to replace gas discharge lamps, which are used for optical pumping and/or detection, with injection laser diodes [1]. In such devices, alkali metal atoms are used either as a working medium that senses macroscopic magnetization due to the optical orientation of atoms (quantum magnetometers [2]); or as an intermediate medium for the nuclear paramagnets optical orientation due to the spin-exchange interaction (nuclear magnetic gyroscopes [3]); or as a medium for the registration of the so-called dark resonance (formation of a non-absorbing superposition of two states of alkali metal atoms under bichromatic light) due to the effect of coherent population trapping (atomic clocks [4]). As for laser sources for compact atomic sensors, they must simultaneously satisfy several specific requirements: the exact correspondence of the lasing frequency to a certain energy transition of the used alkali atom (^{133}Cs, ^{85}Ru, or ^{87}Ru isotopes); single-mode lasing and narrow spectral width of the emission line; fixed direction of linearly polarized laser emission; large modulation bandwidth; reliable operation at elevated operating temperatures; low power consumption; the possibility of compact installation of the laser emitter and the optical focusing scheme on the gas cell. External cavity lasers, which are widely applied in spectroscopy, can be used to demonstrate an effect or to test one or another design of atomic sensors, but to a large extent, they are a limiting factor in the compact design. The characteristics of the existing edge-emitting lasers are not optimal for creating real devices because the presence of mode-hopping (due to different temperature shifts of the gain maximum and the cavity mode) even with the precise stabilization of the laser temperature and with current and optical means for linking the laser frequency to atomic resonance. And as for a distributed feedback laser, accurate tuning to the required wavelength is the main problem in their practical implementation.

A unique opportunity for compact atomic sensors is provided by vertical-cavity surface-emitting lasers (VCSELs), which have single-mode lasing without external feedback, sub-milliampere threshold currents, increased temperature stability, high spatial symmetry of the output emission, and are manufactured in a planar technology [5]. In this paper, various aspects of the VCSEL design are analyzed in order to meet the above requirements for laser emitters for use in compact atomic sensors.

Results and Discussion

The modern design of the VCSEL is comprised of a vertical optical Fabry-Perot microcavity with an active region, which is confined on both sides by distributed Bragg reflectors (DBRs) based on alternating quarter-wave layers of materials with refractive index contrast. As an active region, several quantum wells (QWs) located at the maximum of the longitudinal distribution of the electromagnetic field of the standing wave are usually used. There are various ways to inject charge carriers into the active region: through doped DBRs, through intracavity contacts, or a combination of both, which have their own advantages and disadvantages [6]. To reduce the threshold current, the region of charge carrier injection and radiative recombination is spatially limited by current apertures, formed mainly either within the concept of buried tunnel junction (BTJ) when the local region of the p^+n^+-junction is usually created, surrounded by the blocking reverse biased p^+n-structure; or by the technology of ion (usually protons) implantation when highly-resistive regions are obtained, or by the selective oxidation technology of AlGaAs layers with a high content of Al in water vapor when a current-blocking layer is created.

To narrow the VCSEL emission linewidth, it is crucial to either increase the output optical power or increase the photon lifetime in the cavity. In the first case, the maximum output optical power of VCSEL is limited by self-heating (increase in the laser internal temperature with an increase in operating current). So, enhancement of the output optical power could be achieved for the VCSELs with higher mirror losses (higher slope efficiency), however, it simultaneously leads to a decrease in photon cavity lifetime and undesirable laser emission line broadening (see Fig.1, *a*). Moreover, with the rise of the carrier and photon density in the microcavity, it becomes necessary to take into account the effects of gain nonlinearity, which lead to an increase of α-factor [7] and, eventually, to the saturation and broadening of the laser emission line with the increasing output optical power [8]. In addition, the optimal current aperture size should be carefully chosen, as it strongly affects the thermal resistance of the VCSEL. Thus, a decrease in the size of the current aperture leads to an earlier (i.e., at smaller output optical power) transition to an anomalous behavior of the spectral linewidth not only due to an increase in scattering losses (and, as a consequence, a drop in the photon cavity lifetime and an increase in the threshold current), but also due to a faster rise of the laser internal temperature and the observable self-heating even at a low optical power (see Fig. 1,*b*). In the latter case, the photon lifetime can be increased either by reduction of mirror losses (see Fig. 1,*a*), which leads to an undesirable drop in slope efficiency and limits the maximum output power, or by increase of the optical cavity length, which leads to an increase in free-carrier absorption in the case of a monolithic VCSEL design and/or a complication of the manufacturing technology in the case of an external cavity implementation (so-called VECSELs).

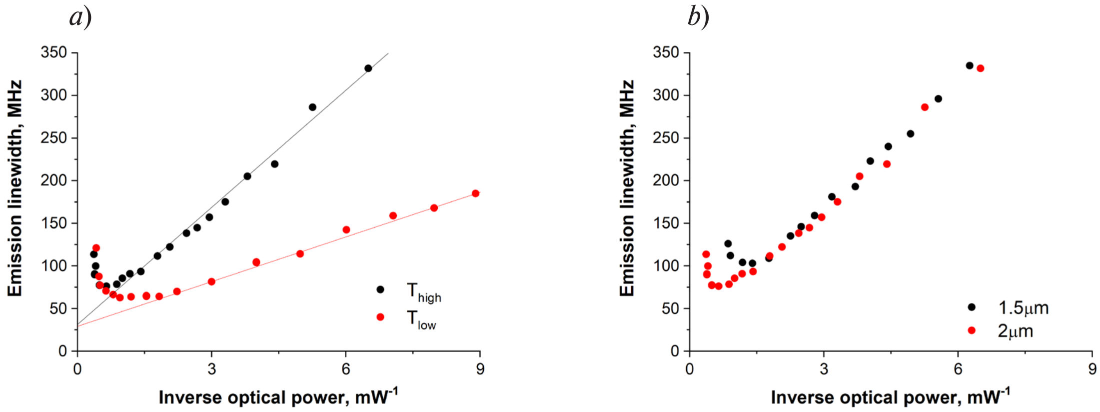

Fig. 1. Emission linewidths of oxide-confined VCSELs based on doped DBRs as functions of inverse optical power for the 2-μm devices with high and low mirror losses (*a*) and for the devices with different aperture size at fixed mirror loss (*b*). The heatsink temperature is 20 °C

A promising solution is to increase the effective cavity length by using the VCSEL design with intracavity contacts and low-Q doped DBRs [9]. As shown in Fig. 2,*b*, incorporation of low-Q doped AlGaAs DBRs between AlGaAs intracavity contact (IC) layers and AlGaAs microcavity with the active region based on InGaAs QWs, along with the modulated doping profile, allows to redistribute electromagnetic mode field. It could also be seen that fine adjustment of the latter allows to substantially increase effective cavity length L_{eff} and decrease the level of intrinsic optical losses, which are usually associated with the free carrier absorption in *p*-doped layers. This approach can simultaneously provide the laser emission line of less than 50 MHz and relatively high (above 2 mW) optical power (see Fig. 2,*b*).

In contrast to edge-emitting lasers, in VCSELs light propagates perpendicular to the active region, which imposes strict requirements on the DBR reflectivity in order to achieve the necessary gain and overcome the lasing threshold. Due to a vertical microcavity, lasing is possible only via one longitudinal mode, while the number of transverse modes is determined by the type of current and/or optical confinement. The most obvious way to achieve single-mode lasing is to reduce the area of carrier injection into the active region. However, in the case of proton-implanted apertures, transverse optical confinement is realized by both the gain guiding and the thermal lensing, which leads to unstable current-dependent mode behavior. BTJ-based apertures and oxide-confined apertures introduce fewer optical losses and provide effective optical confinement due to the built-in index guiding effect (effective index step at the BTJ mesa or oxide-semiconductor boundary). Note that the first one is most widely used for creating long-wavelength InAlGaAsP/InP-based VCSELs, while the second one is for short-wavelength InAlGaAs/GaAs-based VCSELs. The effective index step for the oxide-confined aperture depends on the oxide layer thickness and its positions relative to the maximum of the longitudinal distribution of the electromagnetic field of the fundamental mode. However, even if the oxide layer would be placed in the field minimum, the strong waveguiding effect would be present (since the lowest possible thickness of the oxide layer is limited by the rate of the AlGaAs layer oxidation [10]), which ultimately limits the aperture size at which single-mode laser generation could be obtained. To increase the output optical power in the single-mode regime, various methods have been proposed to insert additional optical losses for high-order transverse modes in inherently multimode VCSELs (with the larger aperture) by varying mirror losses, absorption losses, scattering/diffraction losses, or their combination [6].

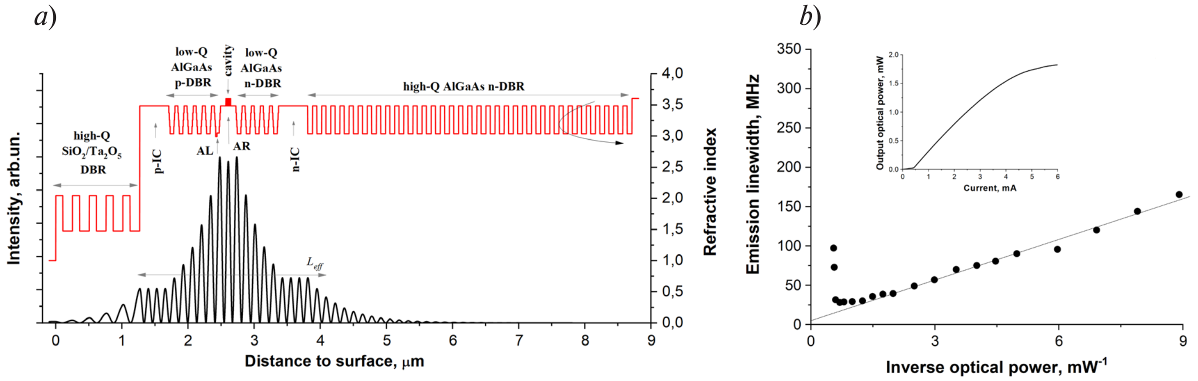

Fig. 2. Oxide-confined VCSELs with intra-cavity contacts: longitudinal distribution of electromagnetic mode field intensity along the refractive index profile (*a*), the inset shows zoom-in of longitudinal distribution of doping concentration along with the refractive index profile in the VCSEL cavity (AR, AL denote active region and aperture layer, respectively) emission linewidth as functions of inverse optical power for the 2-μm devices (*b*), the inset shows light-current characteristic at 20 °C

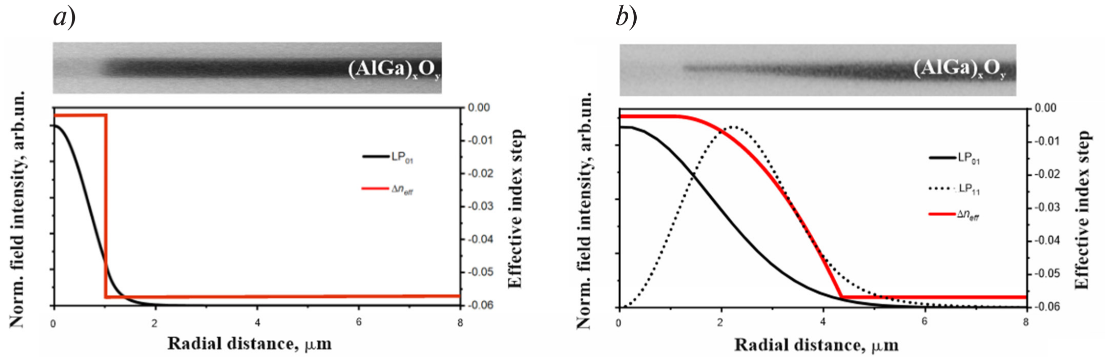

Fig. 3. Effective index step and transverse profiles of the first allowed mode as a function of radial distance for 2-μm oxide-confined VCSELs with the abrupt aperture (*a*) and the tapered aperture (*b*)
The inset shows the scanning electron microscopy images both apertures

Nevertheless, the simplest solution is to use a tapered oxide-confined aperture, which makes it possible to smooth the effective index step (due to the gradual reduction of the oxide thickness towards the current aperture) and form a gradient effective waveguide in which higher-order modes become allowed and spread under oxide taper (see Fig. 3). However, the region of charge carrier injection is defined by the tip of the oxide taper, hence, these modes have a lower transverse optical confinement factor (transverse overlap of the pumped active region with the mode field distribution) compared to the fundamental mode [11]. As a results, single-mode lasing can be achieved at larger oxide-confined aperture sizes (see Fig. 4,*a*).

Unfortunately, the intrinsic mechanism of polarization gain anisotropy does not exist for VCSELs (except for the growth on vicinal substrates), and partial removal of degeneracy due to internal electro-optical and/or elasto-optical effects does not provide reliable polarization stability of laser emission. Therefore, several methods to increase the polarization mode dichroism could be implemented: the formation of a subwavelength diffraction grating on the surface of the output mirror, the use of high-contrast gratings as an output mirror, and the formation of gain anisotropy due to asymmetric charge carrier injection or mechanical stresses [6]. Also, an interesting solution is the use of a rhomb-shaped oxide-confined current aperture formed due to the anisotropy in the selective oxidation process of AlGaAs layers. Our studies revealed that for the emission from 8XX nm-range intra-cavity contacted oxide-confined VCSELs based on InGaAs QWs polarization is typically fixed along the short axis (crystallographic direction $[\bar{1}10]$) of the rhomb-shaped oxide-confined aperture [12]. We believe that the rhomb-shaped oxide-confined aperture simultaneously introduces asymmetry into the optical microcavity and forms an asymmetric mechanical stress field near the active region, which provides suppression of the orthogonal polarized fundamental mode (see Fig. 4,*b*).

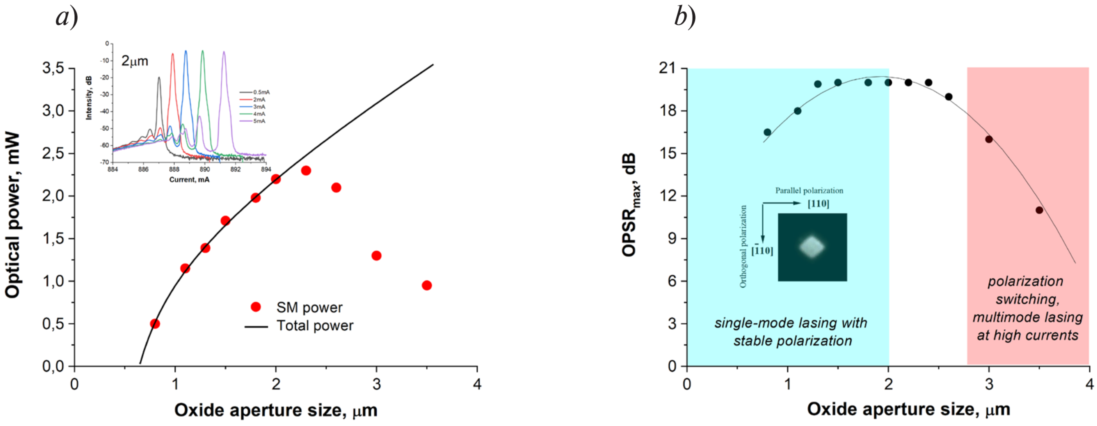

Fig. 4. Intra-cavity contacted oxide-confined VCSELs: total and maximum single-mode output power versus the oxide aperture size, the inset shows spectra for 2-μm device (*a*); dependence of the orthogonal polarization suppression ratio (OPSR) on the size of the oxide aperture (*b*)

The inset shows a subthreshold near-field pattern for 2-μm device; the heatsink temperature is 20 °C

For injection lasers, modulation bandwidth under direct current modulation is determined by three mechanisms: damping of relaxation oscillations, thermal effects and the parasitic cut-off frequency of the low-pass filter (formed by the elements of the equivalent electrical circuit of the laser) [6]. The influence of thermal effects could be reduced by increasing the thermal conductivity of the lower part of the microcavity (via using AlAs layers in the bottom DBR instead of low-index AlGaAs layers) as well as by choosing the optimal gain-to-cavity detuning to provide the high differential gain in the wide temperature range. To increase resonance frequency, the differential gain of the active region should be increased, which could be achieved not only by increasing the strain in the InGaAs QW-based active region (by increasing the mole fraction of In), but also by decreasing total optical loss (see Fig. 5,*a*), this, however, leads to a lower output power and a broader emission line. Resonance frequency could also be enhanced by the reduction of the mode volume, but in the case of intra-cavity contacted VCSELs this can be obtained only by reducing the size of the current aperture, since the larger effective cavity length is needed for narrow linewidth. To reduce damping, the photon lifetime in the cavity should be decreased by increasing the mirror loss and/or the effective cavity length, which, however, again leads to broadening of the emission line, so a compromise between damping and linewidth must be found.

In the case of small-aperture VCSELs, the parasitic cut-off frequency could significantly impact the high-speed performance. According to the analysis of the laser equivalent electrical circuit, the parasitic cut-off frequency is mainly defined by the parasitic capacitance of the laser, where the main contribution is associated with the oxide-blocking layer region. However, the most common approach to increase the parasitic cut-off frequency by increasing the oxide-confined aperture thickness [6] will lead to an increase in the waveguide effect and an earlier switching to the multimode lasing. So one of the possible solutions is the minimization of the topological sizes of the intra-cavity contacted oxide-confined VCSELs to decrease the oxide region capacitance (see Fig. 5,*b*). The combination of the mentioned approaches made it possible to obtain a modulation bandwidth of more than 5 GHz at relatively low (~1 mA) currents (see Fig. 5,*a*).

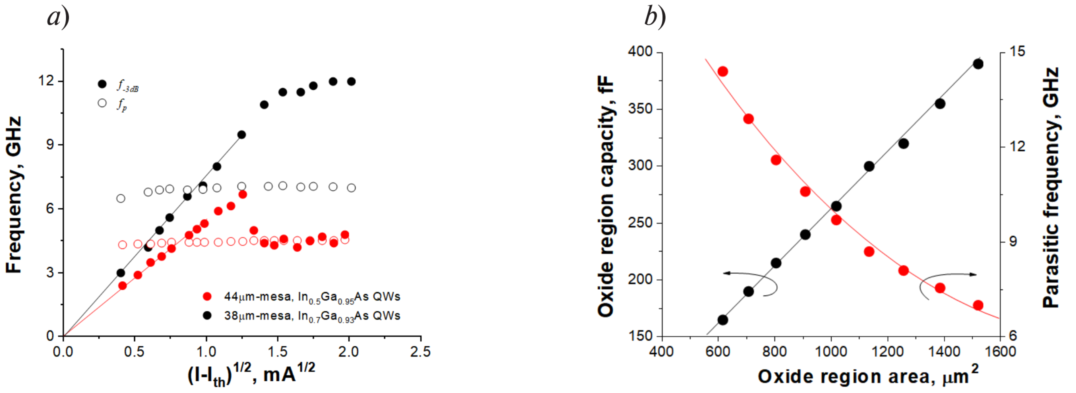

Fig. 5. Intra-cavity contacted oxide-confined VCSELs with 2-μm aperture: modulation bandwidth f_{-3dB} (●) and parasitic cut-off frequency f_p (○) as function of current above threshold for 2-μm oxide-confined VCSELs with different design (*a*); capacitance of the oxide-blocking layer region and the calculated parasitic cut-off frequency (at other fixed elements of the equivalent electrical circuit extracted from S_{11} data for the maximum operation current, when self-heating can be neglected) as function of oxide region area (*b*). The heatsink temperature is 20 °C

Conclusion

In this paper, various features of the VCSEL design that meets the requirements for laser emitters for use in compact atomic sensors were discussed and analyzed. Presented 8XXnm-range intra-cavity contacted VCSEL with the rhomb-shaped oxide-confined aperture simultaneously demonstrated single-mode output optical power above 1 mW, fixed polarization direction, emission linewidth below 50 MHz and modulation bandwidth more than 5 GHz.

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