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Vertical-cavity surface-emitting lasers with intracavity contacts and a rhomboidal current aperture for compact atomic clocks

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Abstract. **Single-mode vertical-cavity surface-emitting lasers (VCSELs) with intracavity contacts, composite distributed Bragg reflectors, and a rhomboidal selectively-oxidised current aperture are studied. It is shown that the use of a rhomboidal current aperture allows the light output polarisation to be fixed without using a special surface relief and leads to efficient narrowing of the emission line with retaining a high slope efficiency. The developed VCSELs have a high output power (exceeding 1 mW), a threshold current below 1 mA, an effective modulation frequency exceeding 5 GHz, and a linewidth smaller than 60 MHz at increased (65–75 °C) temperatures and are promising for application in compact Cs vapour cell atomic clocks.**

Keywords: *vertical-cavity surface-emitting laser, current aperture, compact atomic clock.*

In recent years, extensive studies have been performed on compact atomic frequency and time standards (so-called atomic clocks), whose principle of operation is based on the coherent population trapping effect in alkali metal (usually rubidium or caesium) vapour atoms [1]. As a light emission source, these devices often use compact semiconductor vertical-cavity surface-emitting lasers (VCSELs), which provide a high operation speed in a single-mode regime with low energy consumption. In addition to the requirement for precision wavelength tuning to a used spectral line (794.8 and 780 nm for the D_1/D_2 line of the ^{87}Rb isotope or 894.3 and 852.1 nm for the D_1/D_2 line of the ^{133}Cs isotope), the laser should satisfy some specific requirements, namely, it should emit single-frequency emission with a side-mode suppression ratio exceeding 20 dB and linearly polarised emission with an orthogonal polarisation suppression ratio exceeding 15 dB, its linewidth should be smaller than 100 MHz, and its modulation bandwidth should be larger than 3.4 GHz for Rb and 4.6 GHz for Cs [2]. These requirements must be fulfilled at high temperatures corresponding to the working temperatures of compact gas cells (60–90 °C).

The single-mode operation of VCSELs is traditionally achieved using small oxide current apertures, which simultaneously provide current and optical confinement and thus cause an increase in the series resistance and limiting of the output optical power. Under conditions of laser operation at temperatures of 60–90 °C, one of the key problems for these single-mode VCSELs is to achieve an output power exceeding 0.2 mW. A narrow laser linewidth is usually achieved by decreasing the output coupling losses [2], which leads to a decrease in the slope efficiency, or by increasing the microcavity length [3], which is accompanied with an increase in the internal optical losses. Simultaneous achievement of low internal optical losses and a moderate electric resistance in classical-geometry VCSELs with doped distributed Bragg reflectors (DBRs) seems to be a difficult task. Nevertheless, we have previously demonstrated that both problems can be solved within a modified geometry of VCSELs with intracavity contacts (IC-VCSELs) [4].

A key requirement for the considered devices is fixation of the polarisation direction. The fundamental mode of VCSELs based on InAlGaAs quantum wells (QWs) is usually polarisation degenerate due to the symmetry of the current and optical confinements. It was proposed to use different methods to fix the VCSEL polarisation, in particular, to produce lateral optical gain anisotropy due to asymmetric current injection, to obtain transverse gain anisotropy due the cavity asymmetry or mechanical stresses, and to form anisotropy of the output mirror reflection by using mirrors based on high-contrast gratings or by formation of a subwavelength diffraction grating on the output DBR surface [5]. The last approach also makes it possible to perform additional selection of transverse modes in the initially multimode laser, which allows one to increase the output optical power at relatively low output

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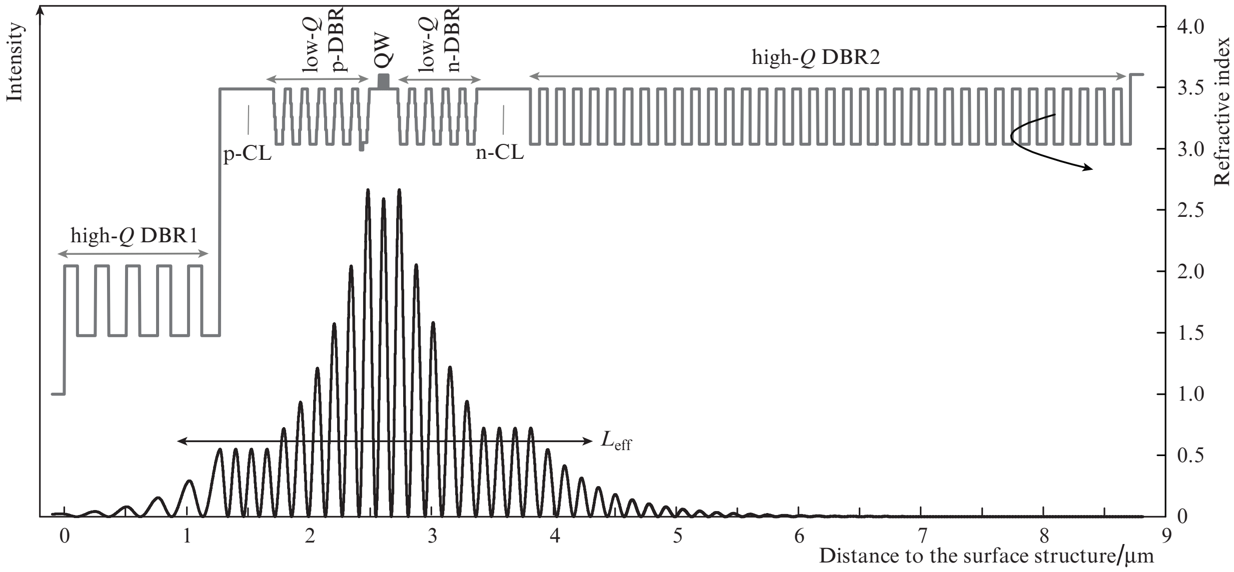

Figure 1. Calculated distribution of a standing-wave electromagnetic field and refractive index profile in an IC-VCSEL: (high-*Q* DBR) high-*Q* distributed Bragg reflector with a high reflectance; (QWs) quantum wells; (CL) intracavity contact layer; (low-*Q* DBR) composite Bragg grating with a low reflection coefficient (low-*Q* Bragg reflector).

coupling losses [6]. We have recently proposed a technologically simpler method to control the polarisation of the output IC-VCSEL emission in the region of 850 nm by forming a rhomboidal oxide current aperture using an $AlAs/Al_{0.9}Ga_{0.1}As$ aperture layer [7]. This approach can also be used for the spectral region near 895 nm owing to the retention of the anisotropy of selective oxidation of AlGaAs layers with high Al concentrations.

Below we present the results of development of an original IC-VCSEL scheme with a rhomboidal current aperture for application in compact Cs atomic clocks.

The IC-VCSEL for the Cs D_1 line (Fig. 1) includes a high-*Q* SiO_2/Ta_2O_5 DBR (high-*Q* DBR1), a p-$Al_{0.15}Ga_{0.85}As$ intracavity contact layer (p-CL), a low-*Q* p-$Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ composite Bragg grating (low-*Q* p-DBR), a single-mode AlGaAs microcavity with an active region based on $In_{0.08}Ga_{0.92}As$ QWs, a low-*Q* n-$Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ composite Bragg grating (low-*Q* n-DBR), an n-$Al_{0.15}Ga_{0.85}As$ intracavity contact layer (n-CL), and a high-*Q* $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ DBR (high-*Q* DBR2). The IC-VCSEL epitaxial structure was synthesised by molecular beam epitaxy of the InAlGaAs material system on a GaAs substrate. One can see from Fig. 1 that the introduction of composite Bragg gratings with a low reflection coefficient between the intracavity contact layers and the microcavity makes it possible to redistribute the electromagnetic field and not only to decrease the internal optical losses related to the absorption at free carriers but also to considerably increase the effective cavity length L_{eff}, which allows narrowing of the laser line retaining the high slope efficiency [8]. The details of the technological process of IC-VCSEL fabrication are presented in [9]. Analysis of the near-field spontaneous emission patterns of the lasers and observation of the optical contrast in the lateral direction between the AlGaAs semiconductor layer and AlGaO oxide upon IR illumination revealed a distinct rhomboidal oxide current aperture with a diagonal ratio of 0.8–0.85. The anisotropy of the selective oxidation process fixes the following rhomb orientation: the major diagonal corresponds to the [110] crystallographic direction, and the minor diagonal corresponds to the [110] direction. Below, we will use the major diagonal length as the characteristic size of the oxide current aperture.

Figure 2 presents the voltage–current and power–current characteristics of an IR-VCSEL with a characteristic size of the oxide current aperture of 2.5 μm, which were measured in the cw regime at different temperatures. Due to the small area of the oxide current aperture, these VCSELs have high thermal resistances (as a rule, 7–8 K mW^{-1}) and current densities (tens of kA m^{-2}). Taking into account a considerable acceleration of degradation processes in semiconductor lasers with increasing current density and temperature, the characteristics of the IC-VCSEL crystals were studied within the range of maximum working currents not exceeding 50%–70% of the current corresponding to the power–current characteristic saturation due to strong self-heating. With increasing temperature, one observes a noticeable increase in the threshold current, which is accompanied by a decrease in the slope efficiency due to deviation of the resonance wavelength of the IC-VCSEL microcavity from the peak of the gain spectrum. Nevertheless, the studied lasers demonstrate operation with a slope efficiency exceeding 0.5 W A^{-1} and a submilliampere

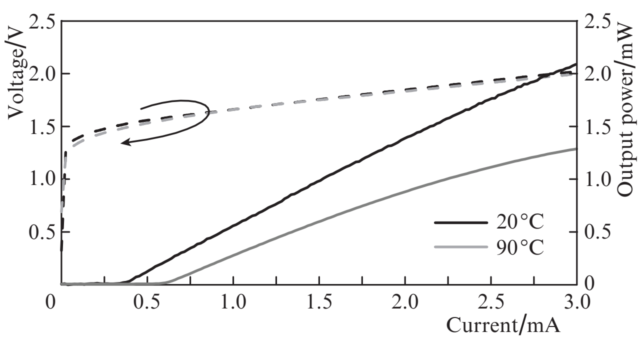

Figure 2. Voltage–current and output power–current characteristics of an IC-VCSEL with a characteristic size of the rhomboidal oxide current aperture of 2.5 μm measured at different temperatures.

threshold current at higher temperatures, which makes it possible to achieve a higher optical power (exceeding 0.5 mW at currents of 2–3 mA) than that of commercially available VCSELs for the Cs D_1 line [6, 10]. The total energy consumption of these lasers does not exceed 6 mW.

According to the results of polarisation studies of the fabricated lasers, the polarisation of IC-VCSELs with a characteristic size of the rhomboidal oxide current aperture of 2.5 μm was fixed along the minor aperture diagonal coinciding with the [110] crystallographic direction, which correlates with the previous results for single-mode 850-nm IC-VCSELs [6]. Figure 3 presents the dependences of the orthogonal polarisation suppression ratio (OPSR) on the pump current. The OPSR slightly decreases with increasing temperature, which is obviously caused by an increase in the relative fraction of spontaneous emission at high output coupling losses. It should be noted that the OPSR exceeds 15 dB in the entire working current range even at a higher temperature.

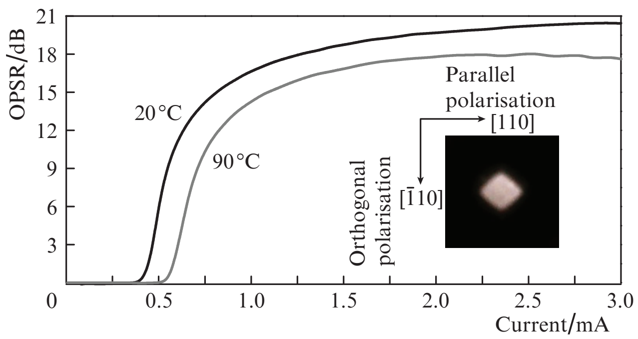

Figure 3. Dependences of the orthogonally polarised mode suppression ratio (OPSR) on the pump current for an IC-VCSEL with a characteristic size of the rhomboidal oxide current aperture of 2.5 μm. The inset shows a near-field pattern in a subthreshold regime and typical crystallographic directions.

Analysis of the spectra of IC-VCSELs with a characteristic size of the oxide current aperture of 2.5 μm at different pump currents and temperatures revealed the single-mode character of laser emission with the side mode suppression ratio (SMSR) higher than 35 dB in the entire working range of pump currents (Fig. 4). Wavelength tuning by the pump current and control of the laser temperature allow operation exactly at the wavelength of the Cs D_1 line. For example, the working point of the considered device corresponds to a current of 2 mA and a temperature of 70 °C.

The working current of IC-VCSELs in compact Cs atomic clocks must be modulated at a frequency of 4.596 GHz to provide, at simultaneous pumping of two optical transitions, hyperfine splitting of spectral lines in a magnetic field by 9.192 GHz. Figure 5 shows the results of small-signal frequency analysis of an IC-VCSEL near the working point. The effective modulation frequency at a level of –3 dB increases with increasing pump current with a rate of 6.2 GHz $mA^{-1/2}$ (see the inset in Fig. 5) and exceeds 5 GHz even at comparatively low (∼1.2 mA) pump currents. It should be noted that the maximum effective modulation frequency exceeds 8 GHz and is limited by two factors, i.e., by saturation of the resonance frequency with increasing pump current due to a strong self-heating and by a relatively low parasitic frequency of the low-frequency filter formed by the elements of the laser electric circuit (due to a large capacity of passive regions and a relatively high series resistance of the devices).

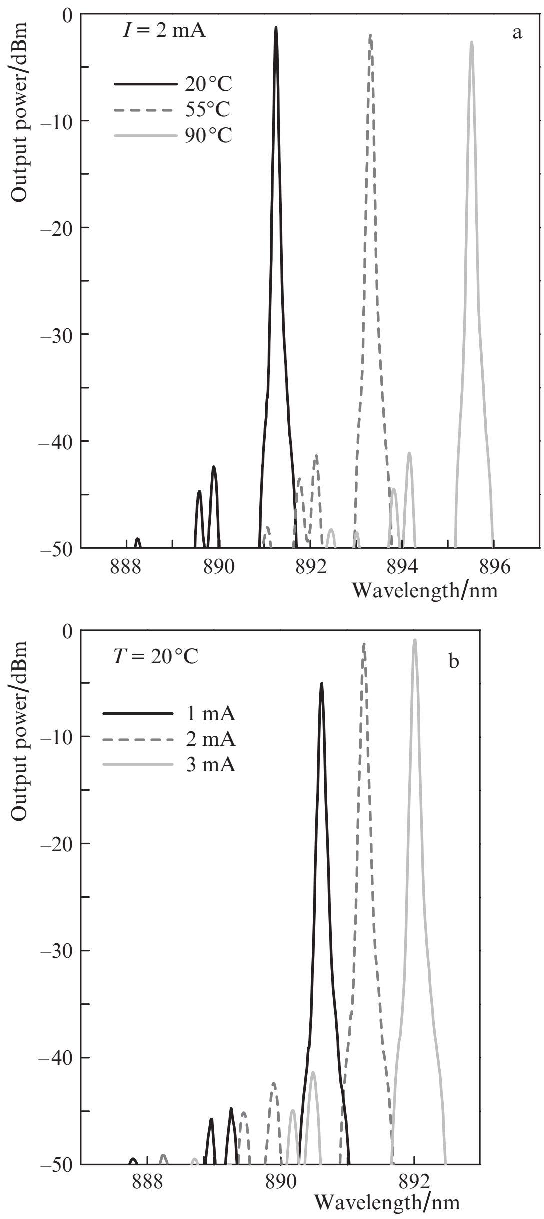

Figure 4. Laser spectra of an IC-VCSEL with a characteristic size of the rhomboidal oxide current aperture of 2.5 μm at different (a) temperatures and (b) pump currents.

Figure 6 presents the dependence of the linewidth of an IC-VCSEL with a characteristic oxide current aperture size of 2.5 μm on the reciprocal optical power P^{-1} at a temperature of 20 °C, which was measured using a Thorlabs SA-200 scanning Fabry–Perot interferometer. As the pump current increases, one first observes a decrease in the emission linewidth inversely proportionally to the output optical power, but, at a reciprocal power below 1 mW^{-1}, this dependence saturates with subsequent broadening of the laser line, which is obviously caused by increasing α factor at higher densities of carriers and photons in the microcavity [11]. Nevertheless, due to an increase in the effective microcavity length, the laser linewidth within the pump current region of 1–3 mA does not increase 45 MHz, which correlates with the data for VCSELs with a classical microcavity geometry, doped DBR, and low output coupling losses [2]. It should be noted that further

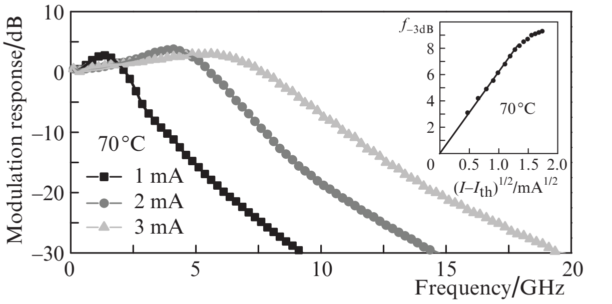

Figure 5. Amplitude–frequency characteristics of an IC-VCSEL with a characteristic size of the rhomboidal oxide current aperture of 2.5 μm measured at a temperature of 70 °C. The inset shows the dependence of the effective modulation frequency f_{-3dB} on the current excess over the threshold current I_{th}.

decrease in the output coupling losses allows considerable narrowing of the IC-VCSEL line to 20–25 MHz. Due to the compact atomic clock design, the laser has to operate at a temperature close to the gas cell temperature, which may by accompanied with a spurious increase in the α factor [12] due to a decrease in the differential gain in the active region with increasing temperature and, as a result, with broadening of the laser line [13]. According to the measured emission spectra of the studied IC-VCSELs at a higher temperature, the emission linewidth does not exceed 60 MHz near the working point (see the inset in Fig. 6).

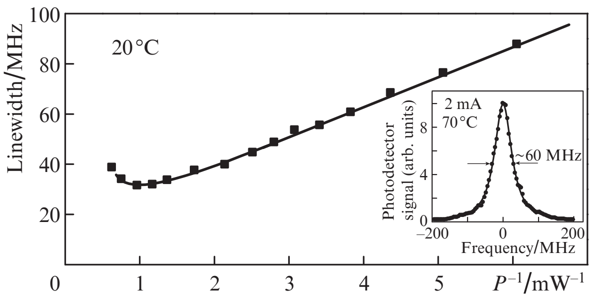

Figure 6. Dependences of the emission linewidth of the pump current for an IC-VCSEL with a characteristic size of the rhomboidal oxide current aperture of 2.5 μm measured at a temperature of 20 °C. The inset shows a characteristic laser linewidth measured at the working point.

Thus, we have successfully tested a scheme of a VCSEL with intracavity contacts, low-Q composite Bragg gratings, and a rhomboidal current aperture, which allows single mode lasing with a fixed polarisation of emission near the Cs D_1 line. The output optical power of the laser at the working point reaches 1 mW, the effective modulation frequency exceeds 5 GHz, and the emission linewidth does not exceed 60 MHz. According to the entire set of achieved characteristics, the developed IC-VCSELs are promising for application in Cs atomic clocks, as well as for various optical spectroscopy problems requiring ultranarrow optical emission lines.

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