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The study of the phase noise of 89X nm-range single-mode intra-cavity contacted VCSELs

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The study results of the phase noise spectral density measurements for the 89X nm-range single-mode VCSELs with the carrier injection through the intracavity contacts and low-Q doped DBRs are presented. The frequency-to-intensity fluctuations conversion in the optical discriminator was used to analyze the behavior of phase noise spectral density. Obtained results indicated that in the frequency range of 1−1000 Hz phase noise spectral density has the form of $1/f$ noise, while in the frequency range of 10−100 kHz the noise saturation is achieved at a level of $(0.4-1)\cdot 10^9$ Hz^2/Hz depending on the size of the current oxide aperture and mirror losses.

Keywords: vertical-cavity surface-emitting laser, phase noise, atomic sensors.

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Recently the problem of reducing the dimensions and energy consumption of various quantum sensors based on alkali metal atom vapors have become highly relevant, and it may only be solved using laser emitters for optical pumping and/or detection [1]. Broad perspectives in this area are opened by vertical-cavity surface-emitting lasers (VCSELs) due to the ability to obtain the single-mode generation with a symmetrical directional pattern, high temperature stability and low energy consumption [2]. However, for use in compact quantum frequency standards it is necessary to both provide the single-mode laser generation with linear polarization and fast response time at low pumping currents and the low phase noise. The thing is that phase noise limits both the short-term stability of quantum frequency standards (QFS) via deterioration of signal-to-noise ratio and impact their long-term frequency stability due to light shifts of frequency in process of long-term integration [3,4]. Currently only several design solutions are available for development of single-mode polarization-stable VCSELs with radiation wavelength corresponding to the absorption line of atoms ^{133}Cs, ^{85}Rb or ^{87}Rb, used in the gas cells [5–7]. Relatively recently we proposed an alternative approach for design of VCSELs of the spectral range 85X/89X nm [8,9] and conducted the preliminary assessments of the intensity noise level [10].

This paper presents the results of research on the phase noise spectral density of single-mode polarization-stable VCSELs of spectral range 89X nm (hereinafter referred to as 89X nm VCSELs), implemented within the concept of a hybrid microcavity with carrier injection through intracavity contact layers.

The studied VCSEL is a hybrid vertical microcavity composed of lower semiconductor $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ distributed Bragg reflector (DBR), a lower *n*-type intracavity $Al_{0.15}Ga_{0.85}As$ contact, a low-Q *n*-type $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ DBR an optical resonant cavity with quantum wells InGaAs/AlGaAs as an active area, an upper composite Bragg lattice $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ *p*-type with a selectively-oxidized aperture, an upper *p*-type intracavity $Al_{0.15}Ga_{0.85}As$ contact and an upper dielectric SiO_2/Ta_2O_5 DBR. More detailed description of the 89X nm VCSEL design is given in papers [8,11].

Fig. 1 presents watt-ampere characteristics and dependences of the orthogonal polarization suppression ratio (OPSR) on the operating current for several lasers selected to research the phase noise spectral density (with different

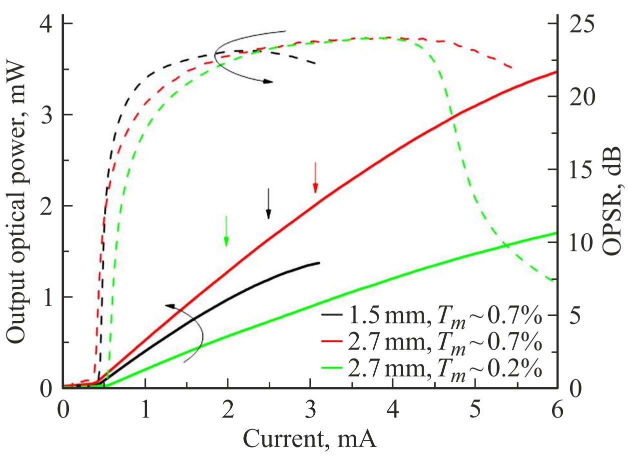

Figure 1. Watt-ampere characteristics and dependences of OPSR on the operating current for VCSELs with different size of current aperture and mirror losses. Measurement temperature 20°C. The arrows indicate the working points for the research of $S(f)$.

size of current aperture and level of mirror losses T_m). The OPSR value was defined as the ratio of the optical power values for two orthogonal directions of polarizations: $\mathrm{OPSR} = 10\log(P_{\parallel}/P_{\perp})$. Analysis of static and spectral characteristics showed that 89X nm VCSELs demonstrate the single-mode laser generation with the fixed direction of polarization in the entire range of the working currents up to the characteristic size of the oxide current aperture $2\,\mu$m [11]. For lasers with the characteristic aperture size above $2.5\,\mu$m depending on the level of mirror losses it is possible to switch from the single-mode generation to the multi-mode one associated with the OPSR reduction. Besides, the further increase in the aperture size causes earlier switching of the mode content of the laser radiation. And reduction of the mirror losses causes amplification of this negative effect due to weakening in the selectivity of the fundamental mode.

The studies of the spectral density of laser phase noise were carried out using an optical frequency discriminator, which converted the 89X nm VCSEL frequency fluctuation into the intensity fluctuation. The optical frequency discriminator was a gas cell with Cs atom vapors. To determine the coefficient for recalculation of the pumping current to the detuning frequency using the available values of the hyperfine splitting frequencies of energy levels of $D1$-line ^{133}Cs, a gas cell #1 was used with low pressure of buffer gas (insert to fig. 2). The working gas cell for measurement of phase noise was cell #2, the parameters of which were selected to provide for the high coefficient of phase noise conversion into amplitude noise with preservation of the symmetrical shape of the absorption profile (relevant steepness of the optic discriminator 0.18 V/GHz). To measure the converted phase noise, a synchoronous amplifier with differential input SR830 was used set for the noise density measurement in a 1 Hz band. The precision tuning of the laser wavelength for the $D1$ ^{133}Cs absorption line was carried out with a working current, whereas the laser temperature was stabilized at the level 20°C. The laser was tuned for the edge of the gas cell absorption line to the point of maximum steepness (the position of this point was determined using the position of the local maximum/minimum of the function of the first derivative from the absorption signal at the loading resistor of the photodetector). To minimize the noise of the power supply source, a chemical power supply source was used in a combination with a splitter based on the tunable low-noise resistors.

Fig. 2 shows the frequency dependences of phase noise $S(f)$ for VCSEL of spectral range 89X nm with different size of the current oxide aperture. The phase noise behavior practically does not depend on the size of the current oxide aperture, and in the frequency range of $1-1000$ Hz has the specific appearance for $1/f$-noise with transition to white noise at frequencies above 10 kHz. The results of calculation of the laser emission spectral linewidth through the integral of phase noise $\Delta\nu_{\mathrm{FN}}$ [12] for all the studied VCSELs were perfectly aligned with the data of the direct measurements of $\Delta\nu_{\mathrm{SI}}$ line width using the Fabry-Perot scanning interferometer (provided in table in fig. 2). At the fixed level of the mirror losses, the reduction of the characteristic size of the current oxide aperture leads to increase in the serial and thermal resistances of the laser and growth of the active area overheating (with the comparable current density), which in a combination with the higher working current (to get into $D1$-line ^{133}Cs) causes growth of α-factor [13] and, in the end, causes the broadening of the spectral line of laser radiation, which is in perfect alignment with the data for a narrow-aperture laser demonstrating the highest phase noise. Reduction of losses T_m from $\sim 0.7\%$ to $\sim 0.16\%$ for passage of the resonant cavity at the fixed characteristic size of the current oxide aperture causes the growth of photon life time in the resonant cavity and leads to spectral line narrowing of the laser radiation, which correlates to the low phase noise for a large-aperture laser.

Therefore, the designed 89X nm VCSELs potentially make it possible to achieve the phase noise of less than 1E9 Hz^2/Hz in the frequency range $1-100$ kHz, where the feedback loops typically work to stabilize the microwave frequency and the laser wavelength in the system of automatic control of compact quantum frequency standards.

Therefore, studies were carried out on the spectral density of phase noise in single-mode VCSELs of spectral range 89X nm with carrier injection via intracavity contact layers and low-Q doped DBRs. The nature of the phase noise behavior in the frequency range $1-1000$ Hz has the appearance of $1/f$-noise, whereas in the frequency range $10-100$ kHz saturation is observed at level $(0.4-1)\cdot 10^9$ Hz^2/Hz depending on the size of the current oxide aperture, mirror losses and working current of laser. The lowest level of phase noise was recorded for the large-aperture single-mode 89X nm VCSELs, besides, the

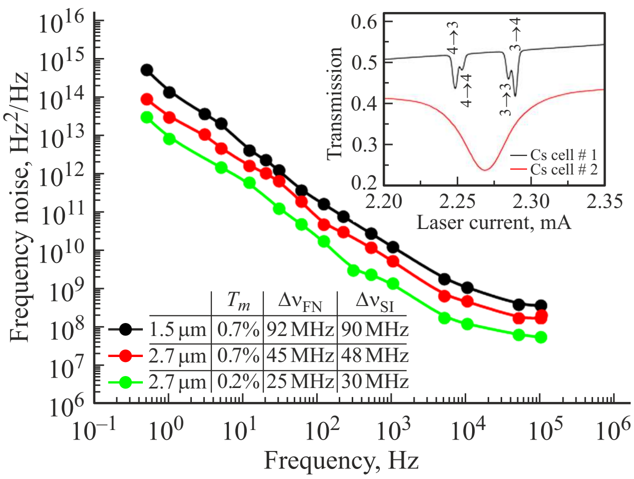

Figure 2. Dependence of spectral density of phase noise $S(f)$ for 89X nm VCSELs with different characteristic size of current oxide aperture and mirror losses. Measurement temperature 20°C. On the insert — transmission curves through Cs-cells when the VCSEL wavelength is retuned with the current near the working point.

reduction of mirror losses causes additional drop in the phase noise level.

The obtained results correlate both with data for 79X nm [6,7] with classic geometry of the microcavity and the data for 89X nm VCSEL [5] with polarization anisotropy and spatial-selective losses that were successfully tested in the quantum frequency standards.

The study results are important to create lasers for the quantum frequency standards based on ^{133}Cs atoms.

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Conflict of interest

The authors declare that they have no conflict of interest.

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