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Analysis of the low-frequency noise of 89X nm-range single-mode VCSELs

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Abstract. This paper presents the results of experimental investigations of low-frequency relative intensity noise and phase noise of single-mode 89X nm-range vertical-cavity surface-emitting lasers (VCSELs) with different photon lifetimes. The lasers are based on a hybrid vertical microcavity design with carrier injection through intracavity contact layers and composite Bragg gratings. Analysis of the low-frequency amplitude noise of the VCSELs showed that the noise spectrum in the frequency range from 100 Hz to 10 kHz has a $1/f$-noise trend, transitioning to white noise at frequencies above 10 kHz. The dependence of the amplitude noise on the laser's optical power has a W-shaped form. An increase in temperature leads to growth in both amplitude and phase noise, both at a fixed operating current and at comparable optical power of laser radiation. In the frequency range of 1–100 kHz, the achieved amplitude noise level does not exceed –120 dB/Hz. Meanwhile, in the 10–100 kHz frequency range, the phase noise level saturates at $0.6–1.1 \cdot 10^9$ Hz^2/Hz (depending on temperature and optical power) for devices with a characteristic photon lifetime of ~ 8.5 ps. The obtained results allow the use of the developed VCSELs in compact quantum sensors of various types.

Keywords: vertical cavity surface emitting laser, relative intensity noise, amplitude noise, phase noise, frequency noise, quantum sensors

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Исследование низкочастотных шумов одномодовых вертикально-излучающих лазеров диапазона 89X нм

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Аннотация. В работе приведены результаты экспериментальных исследований низкочастотных шумов относительной интенсивности и фазовых шумов одномодовых вертикально-излучающих лазеров спектрального диапазона 89X нм с различными временами жизни фотонов в резонаторе на основе гибридной конструкции вертикального микрорезонатора с инжекцией носителей заряда через внутрирезонаторные контактные слои и композиционные брэгговские решетки (ВИЛ). Анализ низкочастотных амплитудных шумов ВИЛ показал, что спектр шумов в частотном диапазоне от 100 Гц до 10 кГц имеет вид 1/*f*-шума, а при частотах выше 10 кГц переходит в белый шум. Зависимость амплитудных шумов от оптической мощности лазера имеет W-образный вид. Повышение температуры ведет к росту амплитудных и фазовых шумов как при фиксированном рабочем токе, так и сравнимой оптической мощности излучения лазера. В частотном диапазоне 1–100 кГц достигнутый уровень амплитудных шумов не превышает –120 Дб/Гц, тогда как в диапазоне частот 10–100 кГц уровень фазовых шумов насыщается на уровне $0{,}6–1{,}1 \cdot 10^9$ Гц^2/Гц (в зависимости от температуры и оптической мощности) для приборов с характерным временем жизни фотонов в резонаторе ~ 8,5 пс. Полученные результаты позволяют использовать разработанные ВИЛ в компактных квантовых сенсорах различного типа.

Ключевые слова: вертикально-излучающий лазер, шумы относительной интенсивности, амплитудные шумы, фазовые шумы, частотные шумы, квантовые сенсоры

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Introduction

VCSELs are a promising type of injection laser for use in compact atomic sensors based on alkali metals (quantum frequency standards, quantum magnetometers, and gyroscopes) [1]. These lasers must meet a specific set of obligatory requirements: precise tuning of the radiation wavelength to the line of atomic transitions of alkali metals in the gas cell, single-mode generation, emission linear polarization in a fixed direction, small spectral linewidth, high speed at low operating currents, low phase and amplitude noise, and the ability to operate at elevated temperatures. In the overwhelming majority of studies devoted to VCSELs operating in the 79X nm [2 – 4] and 89X nm [5 – 7] spectral ranges, attention is primarily focused on the issues of stabilizing the polarization state of the radiation, ensuring the required optical power in single-mode regime, and/or laser response time at a given temperature. However, the issue of analyzing the relative intensity noise (RIN, amplitude noise) and phase noise (frequency noise) in the low-frequency region has received very little attention.

This paper presents the results of experimental studies of the RIN and phase noise of single-mode polarization-stable VCSELs operating in the 89X nm spectral range (hereinafter, 89X nm-range VCSELs), implemented within the framework of a hybrid design of a vertical microcavity with carrier injection through intracavity contact layers and composite Bragg gratings. The influence of temperature and photon lifetime on the noise characteristics of the VCSEL is considered.

Materials and Methods

The studied single-mode 89X nm VCSELs are implemented based on a previously proposed design with intracavity contacts, an optical resonator with InGaAs/AlGaAs quantum wells as the active region, and a diamond-shaped oxide current aperture. A more detailed description of the aforementioned VCSEL design is provided in [8]. Variation of the photon lifetime in the resonator was achieved by controlling the output mirror losses through modification of the top dielectric distributed Bragg reflector (DBR) reflectivity (by varying the number of DBR layer pairs and/or the thickness of the phase-matching layer). Details of the method for determining the photon lifetime are presented in [12].

Investigations of the 89X nm VCSELs relative intensity noise (RIN) were performed using a digital lock-in amplifier (SRS SR830 Lock-In Amplifier) operating in a mode measuring the noise power spectral density within a 1 Hz bandwidth at a specified frequency offset from the carrier. To improve the signal-to-noise ratio, low-noise components were used in the measurement setup, including a Hamamatsu S3584 photodetector and a transimpedance amplifier. To account for the nonlinearity of the electrical path and transimpedance amplifier, the corresponding frequency-dependent transfer function was measured. The use of a low-noise power supply with an additional low-pass filter minimized the contribution of technical noise. The noise level was calculated by subtracting the thermal noise, measured in the absence of an optical signal, from the total noise RMS signal, calculated based on the time-averaged in-phase and quadrature noise components, followed by normalization to the transfer function. Variation of the frequency offset from the carrier frequency yielded the frequency dependence of the amplitude noise, while the operating current and the laser temperature were additionally changed to obtain RIN dependence on output optical power or temperature.

Phase noise measurements of the 89X nm VCSELs were conducted using an optical frequency discriminator which converted laser frequency fluctuations into intensity fluctuations. A gas cell containing the cesium isotope ^{133}Cs vapors and buffer gas N_2 was used as an optical frequency discriminator. The linear part of the cell's absorption profile ensured proportional conversion of frequency noise into amplitude noise. The gas cell parameters were chosen to ensure not only complete conversion of phase noise into amplitude noise (discriminator slope), but also the complete dominance of the converted phase noise contribution over the direct contribution of the laser's amplitude noise. A wide-aperture lens was introduced into the optical setup to form a low divergent beam. In order to measure laser phase noise, individual 89X nm VCSEL chips, mounted in TO packages, were tuned to the edge of the gas cell's absorption line to the point of maximum discriminator slope. The position of this point was determined by the maximum of the detected amplitude noise. The procedure for recording such amplitude noise is similar to the methodology described above. It was carried out in an analogous manner – variation of the frequency offset from the carrier frequency and measurement of the noise power spectral density in a 1 Hz bandwidth yielded the frequency dependence of the phase noise.

Results and Discussion

Fig. 1 shows the current-optical power characteristics of 89X nm-range VCSELs with a selectively-oxidized current aperture diameter of 2.5 μm and different photon lifetimes in the resonator, selected for the investigation of noise properties. It is evident that an increase in the photon lifetime in the resonator leads to a reduction in the current threshold value and a decrease in the differential efficiency. Analysis of the emission spectra and polarization state showed that the devices operate in a single-mode lasing regime with a side-mode suppression ratio (SMSR) exceeding 30 dB and a fixed polarization direction with an orthogonal polarization suppression ratio (OPSR) above 17 dB at operating currents up to ~3.2–3.4 mA (the current range corresponding to a multimode lasing regime is highlighted in gray).

Fig. 2, *a* shows the RIN dependence on optical power at different detection frequencies, using Laser 4 as an example. The dependence of the amplitude noise on the laser's output optical power exhibits a W-shaped form. Specifically, as the output optical power increases in the spontaneous emission regime, an initial decrease in the RIN level is observed, followed by a sharp increase in noise as the laser approaches threshold. In the stimulated emission regime, a pronounced drop in RIN is evident, reaching a local minimum (which slightly exceeds the shot noise level) which is consistent with the results reported in [7, 9]. However, for optical powers exceeding 0.5 mW, this trend reverses despite the continued increase in optical power. An increase in the laser temperature does not fundamentally alter the characteristic behavior of the RIN; however, it leads to an increase in the RIN level both at a given output optical power and at a fixed operating current

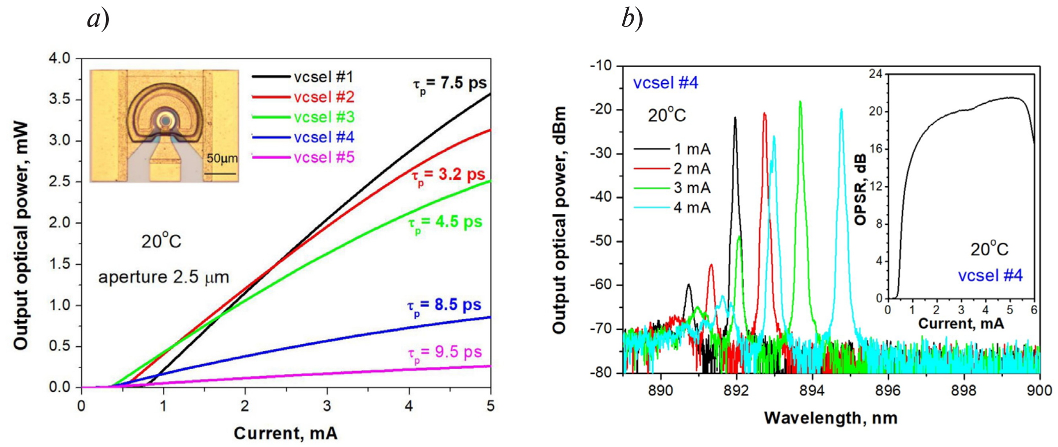

Fig. 1. Evolution of output optical power as functions of current (*a*) and optical spectra for different operating currents (*b*) measured at 20 °C, the inset in panel (*b*) shows the OPSR

(see Fig. 2, *b*). This observed behavior could be attributed to both thermal effects due to laser self-heating and the noise from higher-order transverse modes at elevated operating currents. Nevertheless, in the frequency range of 1–100 kHz, the RIN level does not exceed –120 dB/Hz. This result correlates with findings from studies on single-mode, polarization-stable 89X nm VCSELs with a classical vertical microcavity design [7, 9].

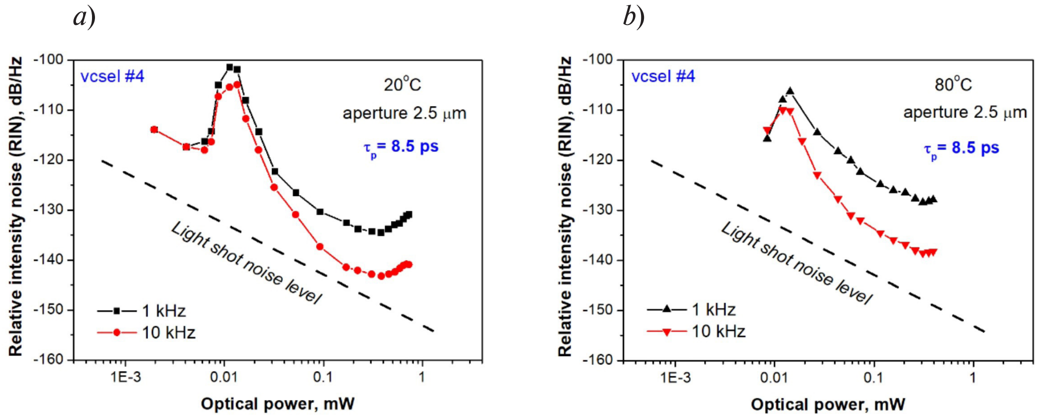

Fig. 2. RIN noise as a function of output optical power for VCSEL 4 with a 2.5 μm current oxide aperture, measured at 20 °C (*a*) and 80 °C (*b*).

The dashed straight line shows the calculated shot noise level as a function of the detected radiation level

Fig. 3, *a* shows a RIN as a function of photon lifetime in the resonator for single-mode 89X nm-range VCSELs. The devices featured a characteristic selectively-oxidized current aperture size of 2.5 μm and were measured at a temperature of 20°C with a fixed output optical power of 0.3 mW. The characteristic behavior of the laser's RIN in the low-frequency region follows a $1/f$ noise (flicker noise) trend with a roll-off rate of ~11 dB/decade, transitioning to white noise at frequencies above 10 kHz. The level of this white noise significantly exceeds the detectable shot noise level of the photodetector. With an increase in photon lifetime from 1.7 ps to 8.5 ps, a reduction in the amplitude noise of the 89X nm VCSELs is observed: the white noise level decreases from –130 dB/Hz to –145 dB/Hz. However, a further increase in photon lifetime above 9.5 ps leads to an increase in amplitude noise. This observation can be explained by the fact that to maintain the specified output optical power level (~0.3 mW) with a sharp drop in differential efficiency, a significant increase in the operating current is required. Narrow-aperture VCSELs are characterized by stronger self-heating of the active region (higher internal laser temperature) compared to broad-aperture lasers at comparable output power levels, due to their higher thermal resistance. This increased self-heating leads to the observed rise in RIN.

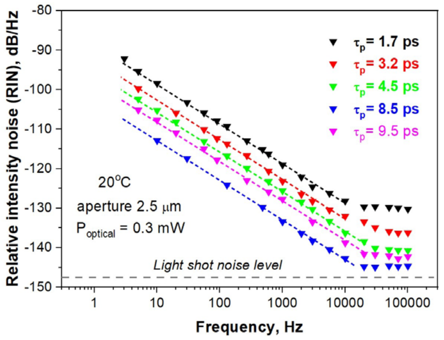

Fig. 3. Frequency dependences of RIN for a VCSEL with a 2.5 µm current oxide aperture and different photon lifetimes, all measured at an output optical power of 0.3 mW and a temperature of 20 °C.

The dashed horizontal line shows the calculated shot noise level corresponding to a detected optical power of 0.3 mW

Direct measurement of phase noise across a wide range of operating currents and output optical powers presents a non-trivial challenge, and in the case of employing the method of laser frequency fluctuation conversion into intensity fluctuations using an optical frequency discriminator, it is not feasible. The issue is that the emission wavelength of the laser under investigation must coincide with the absorption wavelength of the chosen optical discriminator. Fig. 4, *a* illustrates the influence of photon lifetime on the phase noise for 89X nm-range VCSELs with a 2.5 µm characteristic selectively-oxidized current aperture size. The characteristic behavior of the phase noise in the 1–1000 Hz frequency range follows a 1/*f* noise trend, whereas in the 10–100 kHz frequency range, saturation occurs at a level of 0.5–1.1·10^7 Hz^2/Hz, depending on the degree of current exceeding the threshold current. This result correlates with findings reported in [7, 9]. A reduction in the photon lifetime within the resonator leads to an expected increase in the phase noise level, which correlates well with the data from direct measurements of the spectral linewidth of 89X nm VCSELs using a scanning Fabry–Pérot interferometer [8]. The reason is that the white phase noise is closely related to the instantaneous fundamental laser linewidth; however, since the phase noise spectrum in a real laser is enriched by flicker noise, the integral of the phase noise spectral density contains information about the actual laser linewidth [10]. Fig. 4, *b* shows the frequency dependence of the phase noise for a device with a characteristic selectively-oxidized current aperture size of 2.5 µm and a photon lifetime of ~8.5 ps, measured at a laser temperature of 60°C. The fundamental characteristic behavior of the phase noise does not change with increasing temperature; however, an additive increase in noise is observed. This correlates well with the broadening of the spectral linewidth of 89X nm VCSELs with rising temperature [11]. Consequently, the white phase noise at frequencies above 10 kHz reaches a level of 0.6–1.1·10^9 Hz^2/Hz.

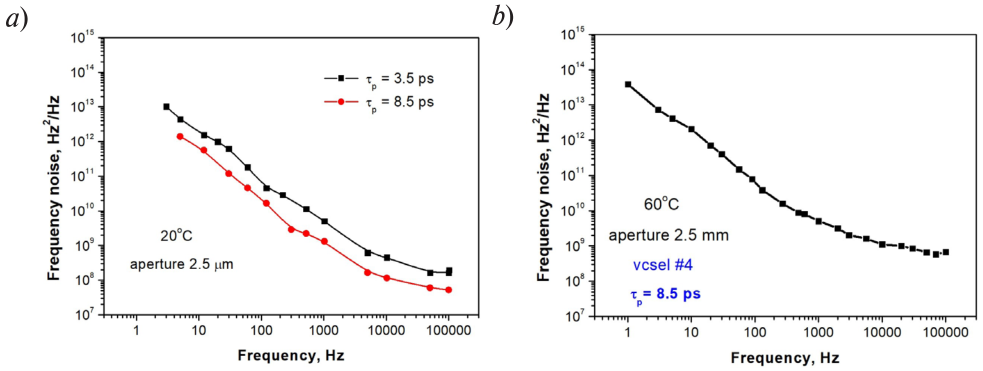

Fig. 4. Frequency dependences of phase noise for 89X nm-range VCSELs with a 2.5 µm characteristic current oxide aperture: influence of the VCSEL photon lifetime at a measurement temperature of 20 °C (*a*); influence of the measurement temperature for the VCSEL with a photon lifetime of 8.5 ps at 60 °C (*b*)

Conclusion

Thus, a comprehensive study of the amplitude and phase noise of an 89X nm-range VCSEL with intracavity contacts was conducted. Increasing temperature leads to an increase in the amplitude and phase noise levels. Increasing the cavity lifetime reduces the amplitude and phase noise levels, but a sharp drop in differential efficiency ultimately leads to an increase in internal temperature and, consequently, an increase in both noise levels.

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