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Investigation of the noise characteristics of vertical-cavity surface-emitting laser with a rhomboidal oxide current aperture for use in a Cs-based compact atomic magnetometer

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The possibility of using vertical-emitting lasers with intracavity contacts (IC-VCSEL) and a rhomboidal oxide current aperture for creating a non-zero magnetic field optically pumped atomic magnetometers (OPM) with a ^{133}Cs vapor cell for magnetoencephalographic (MEG) systems were demonstrated. Relative intensity noise (RIN) and polarization resolved RIN of the IC-VCSEL in the 895 nm range with different mirror losses (linewidth) in the frequency range from 1 Hz to 100 kHz were experimentally investigated. Lasers with low mirror loss (narrow linewidth) have polarization resolved RIN comparable to amplitude noise. For IC-VCSEL with an output optical power of 0.8 mW and a linewidth of 55 MHz, the noise level measured is 148 dB/Hz in 1 Hz bandwidth at 40 kHz frequency. The ultimate sensitivity of OPM based on two-beam M_Z-scheme with studied VCSELs was estimated as $\sim 11\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$.

Keywords: vertical-cavity surface-emitting laser (VCSEL), magnetoencephalographic (MEG) systems, optically pumped atomic magnetometers (OPAM), relative intensity noise (RIN), polarization-resolved RIN.

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Currently, the rapidly developing noninvasive magnetoencephalography (MEG) [1] technology is increasingly being used to register ultra-small magnetic fields generated by the electrical activity of the brain. The characteristic magnitudes of the ultra-small magnetic fields created by the brain do not exceed several hundred fT. In traditional MEG systems that allow registering such ultra-small magnetic fields with a sensitivity of $\sim 3\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$, an array of magnetic sensors based on superconducting quantum interference devices is used [2]. The significant disadvantages of such MEG-systems include the need to create a magnetically shielded room (units nT) and to ensure constant cooling of magnetic sensors to liquid helium temperatures (-270°C), which leads to a significant increase in the cost and size of the system itself. The use of a fixed-shape Dewar helmet with an array of sensors designed for the maximum size of the patient's head significantly complicates brain research in mobile patients, which leads to a drop in spatial resolution.

Recently, an alternative version of an optically pumped MEG system has been demonstrated that does not require cooling and a stationary patient position, which uses commercially available optically pumped quantum magnetometers (optically pumped atomic magnetometer, OPAM) [3] operating in a spin-free mode-exchange broadening (spin exchange relaxation-free, SERF) and having a sensitivity of $\sim 10\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in the frequency band $1-130$ Hz [4]. The principle of operation of such magnetometers is based on optically detectable magnetic resonance in alkali metal atoms in the gas phase. The essential advantages of the OPAM using the SERF scheme are the high sensitivity limit and the small size of the sensor itself, which makes it possible to increase the recorded signal and improve the spatial resolution. At the same time, the disadvantages of such a sensor are the need to provide an ultra-weak homogeneous magnetic field (units nT) and a strong mutual influence of nearby sensors (low-frequency range of operation).

In recent work [5], the possibility of obtaining a sensitivity comparable to that achieved in the SERF mode in the OPAM for an optically pumped magnetometer implemented in a bi-beam M_X scheme [6] was shown. In this magnetometer, the effect of narrowing the magnetic resonance line was used under conditions of high optical pumping power and high concentrations of alkaline atoms at nonzero magnetic fields (units μT) [7]. The advantages of a MEG system based on such a sensor include a significant reduction in the requirements for screening the room for research (reducing the size and cost of the system) and the shift of the operating frequency from the low-frequency region (OPAM in SERF mode) to the kilohertz

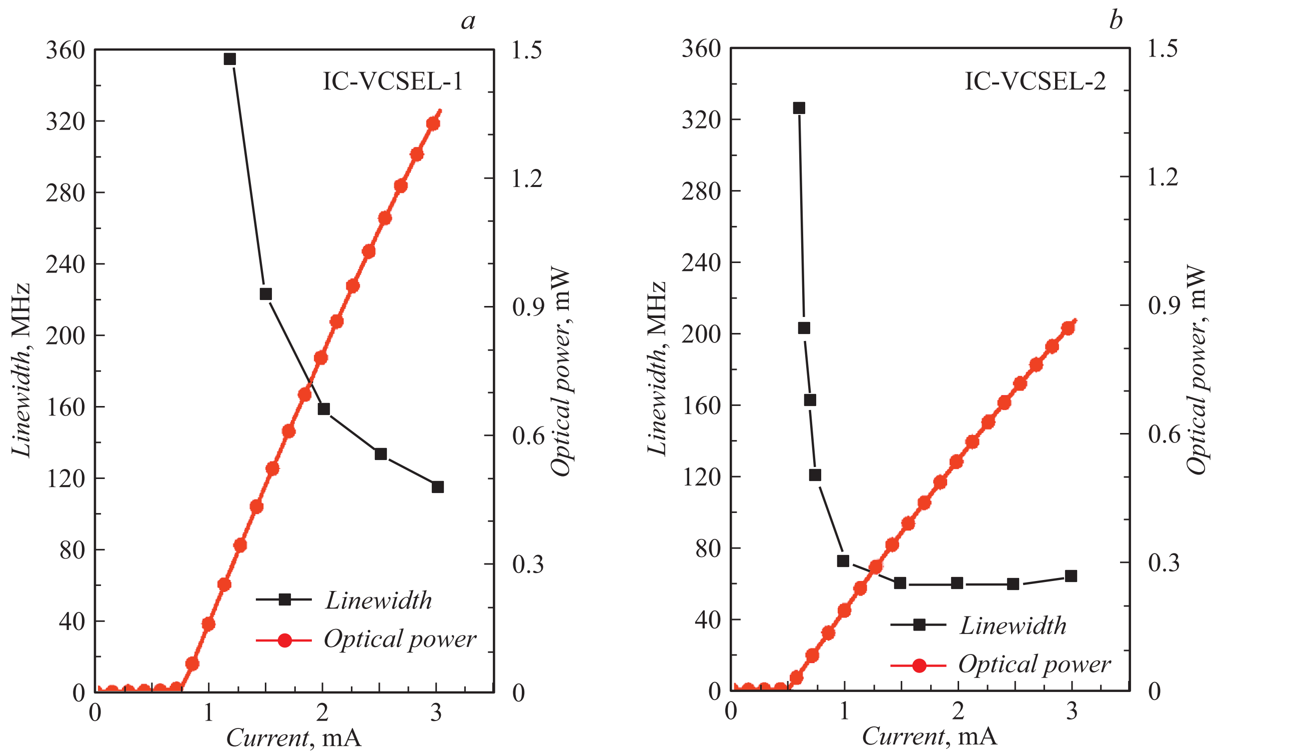

Figure 1. Watt-ampere characteristics and spectral line width of radiation for IC-VCSEL-1 (IC-VCSEL-1) (*a*) and IC-VCSEL-2 (IC-VCSEL-2) (*b*) with characteristic the size of the diamond-shaped current oxide aperture is $\sim 2.5\,\mu$m depending on the pumping current. The measurements were performed at a temperature of 20°C.

range (reducing the influence of low-frequency noise of the surrounding equipment and laser source). The key components of such devices are an injection single-mode laser source and a miniature gas cell with an alkali metal (for example, K, Rb or Cs). Along with lasers with distributed feedback (DFB-lasers) vertical-cavity surface-emitting lasers (VCSEL) [8] can be used to implement OPAM, which potentially allow to improve the compactness of MEG systems. Other potentially important applications of VCSEL with a radiation wavelength tuned to one of the resonances of the alkali metal are compact gyroscopes based on the effect of nuclear magnetic resonance and compact atomic frequency standards based on the effect of coherent population trapping [8]. The laser under consideration must have the ability to precisely adjust the wavelength to the spectral line of the alkali metal used, spatially single-mode radiation with a small spectral width of the radiation line (less than 100 MHz), a fixed direction of linear polarization and a low level of laser radiation noise. At the same time, any instability of laser radiation, for example, the amplitude noise (relative intensity noise, RIN) of the laser, an abrupt change in polarization (polarization-hop) and/or a jump of modes in the spectrum (frequency mode-hop) if the pump current changes directly affect the metrological characteristics of OPAM (on the signal ratio/noise/magnetic resonance width). In this regard, a detailed study of the noise characteristics of VCSEL is extremely important for further improvement of the characteristics of the OPAM [9,10].

In this paper, the intensity of amplitude and polarization noise of the developed VCSEL of the spectral range 895 nm is experimentally investigated. The influence of the spectral width of the radiation line, depending on the losses on the output of laser radiation, on the noise characteristics of VCSEL is considered.

The investigated single-mode VCSEL of the spectral range of 895 nm are implemented on the basis of the previously proposed VCSEL design with intracavity contacts and a diamond-shaped oxide current aperture (IC-VCSEL), its main features and the laser manufacturing process are presented in the works [11,12]. To study the effect of the level of losses on the output of radiation on the noise characteristics of VCSEL, they manufactured devices with a different number of pairs in the upper dielectric distributed Bragg reflector. The watt-ampere characteristics of IC-VCSEL with various radiation output losses A_m, measured in continuous mode at 20°C, are shown in Fig. 1. The values of A_m are obtained within the framework of the transfer matrix method in the approximation of the absence of internal losses in mirrors. IC-VCSEL with high radiation output losses — $A_m \sim 0.71\%$ for a full pass (round trip) of the laser resonator (hereinafter IC-VCSEL-1, in the figures IC-VCSEL-1) — has a threshold current ~ 0.8 mA, with a differential efficiency of ~ 0.65 W/A and an optical output power of ~ 1.4 mW at a pump current of 3 mA. Whereas

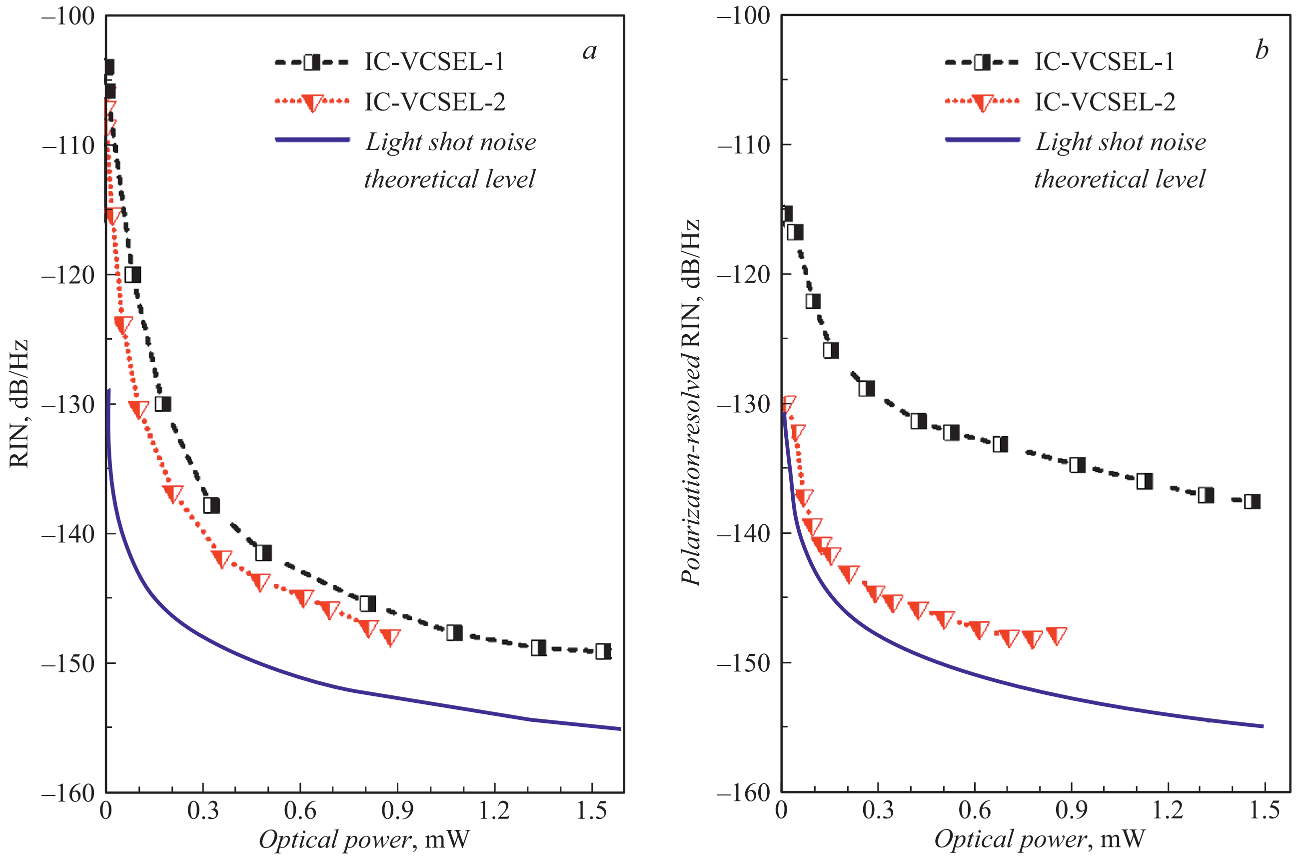

Figure 2. Dependences of amplitude (RIN) (a) and polarization (*polarization-resolved* RIN) (b) noises on the output optical power for two types of IC-VCSEL with different radiation output losses, measured in band 1 Hz at a frequency of 40 kHz. The measurements were performed at a temperature of 20°C. Solid curve — calculated shot noise level of detected radiation.

IC-VCSEL with a lower level of radiation output losses — $A_m \sim 0.23\%$ (hereinafter IC-VCSEL-2, in the figures IC-VCSEL-2) — has a threshold current ~ 0.5 mA, differential efficiency ~ 0.37 W/A and optical output power 0.9 mW at a pump current of 3 mA. An estimate of the level of internal losses obtained from the dependence of the efficiency of radiation output on the level of losses on radiation output T_m, for the two lasers under study gives a value of $\sim 0.35 \pm 0.05\%$. The relatively high level of internal losses is due to an increase in optical losses due to scattering and/or diffraction of light at the oxide current aperture with a decrease in the size of the aperture [10]. According to the data of the analysis of laser radiation spectra, the level of suppression of higher-order modes with respect to the fundamental mode in the current range under consideration for both lasers exceeds 30 dB. The polarization characteristics of the studied devices demonstrate the dominance of one direction of radiation polarization with an orthogonal polarization suppression factor of more than 20 dB at pumping currents of more than 2 mA. The spectral width of the laser radiation was also measured depending on the laser injection current at a temperature of 20°C using a scanning interferometer Fabry–Perot Thorlabs SA-200 (with a resolution of 7.5MHz). An increase in radiation output losses leads to a broadening of the radiation line. So, with an injection current of more than 2 mA for both lasers, the spectral line width for IC-VCSEL-1 was 120–160 MHz, and for IC-VCSEL-2 — 60–70 MHz (fig. 1). It should be noted that the non-classical behavior of the radiation line width for IC-VCSEL-2 at an output optical power of more than 0.3mW is apparently due to a drop in differential gain and, as a consequence, an increase in the α-factor of the torus under conditions of high density of carriers and photons in the microresonator [13].

The level of amplitude and/or polarization noise (polarization-resolved RIN) of the laser has a significant effect on the ultimate variational sensitivity of the atomic magnetometer. At the same time, the OPAM implemented according to the classical single-beam M_Z scheme are less sensitive to the instability of laser radiation polarization, unlike atomic magnetometers implemented on the basis of double-beam M_X schemes. The amplitude noise of the IC-VCSEL was measured using a low-noise Hamamatsu S3584 photodetector and a Lock-in SR830 synchronous detector in the mode of measuring the noise density in the 1 Hz band. Fig. 2, a presents experimental dependences of the amplitude noise level on the output optical power of lasers, measured at a temperature of 20°C and a frequency of

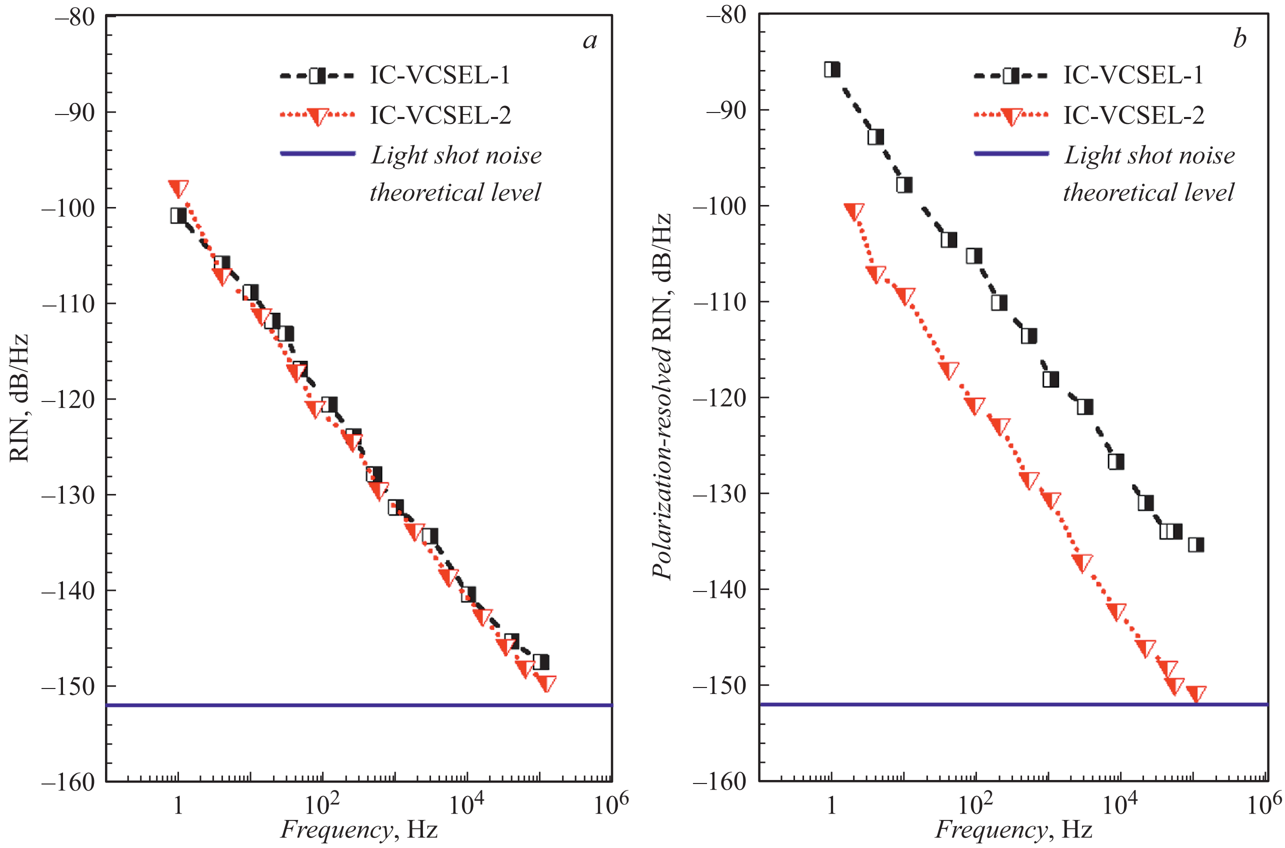

Figure 3. Frequency dependences of amplitude (RIN) (*a*) and polarization (*polarization-resolved* RIN) (*b*) noises for two types of IC-VCSEL with different radiation output losses measured in band 1 Hz at the optical power of the laser radiation 0.8 mW. The measurements were performed at a temperature of 20°C. Solid curve — calculated shot noise level of detected radiation.

40 kHz (due to the measurement scheme of the cesium magnetic resonance [5]). For both types of lasers, if the generation threshold is exceeded with an increase in the output optical power, an almost identical drop in amplitude noise is observed with their subsequent saturation at the level of −148 dB/Hz with an optical power of more than 0.5 mW.

Measurements of the polarization noise of lasers were carried out at a temperature of 20°C and a frequency of 40 kHz using a balanced detection scheme. The radiation of the laser under study was directed to a polarizing beam-splitting cube and collected by two photodetectors connected to a balanced detection circuit. The laser radiation fell on the polarization beam-splitting cube at an angle of 45° for the possibility of registering the angle of inclination of the polarization plane, i.e., measuring the second Stokes parameter. Next, the difference signal was sent to a synchronous detector and in the mode of measuring the noise density in the band 1 Hz, the intensity of the polarization noise of the laser, consisting of the noise of two orthogonal modes, was recorded. As shown in Fig. 2, *b*, the level of polarization noise for IC-VCSEL-1, measured at an optical output power of 0.8 mW, exceeds the expected calculated level of shot noise of the detected radiation by 18 dB/Hz. At the same time, for IC-VCSEL-2, this difference is 4 dB/Hz, and the level of polarization noise is reduced to the level of amplitude noise. A significant increase in the polarization noise of IC-VCSEL-1 compared to those in the case of IC-VCSEL-2 is apparently associated with a larger spectral width of the laser radiation line and, as a consequence, an increase in the jitter of the polarization plane of the laser output radiation. The search for the reason of such behavior requires more detailed research, which is beyond the scope of this work.

To determine the frequency-noise characteristics of the studied lasers, measurements of amplitude and polarization noise were carried out depending on the frequency in the range from 1 Hz to 100 kHz. According to Fig. 3, for the IC-VCSEL-2 laser, the dependences for polarization and amplitude noise on frequency are practically the same and close to the curve for the amplitude noise of the IC-VCSEL-1 laser. The amplitude noise is almost the same for both lasers studied, their level in the frequency range of 40 kHz is below −145 dB/Hz. It should be noted that the magnitude of the amplitude noise of IC-VCSEL-2 in the frequency range of 10 kHz is comparable to the results obtained for VCSEL of the spectral range of 895 nm with an external cavity and a subwavelength array on the surface of an upper distributed Bragg reflector (for polarization fixation) having a line width of 23 MHz and optical power 0.15 mW [14]. At the same time, the frequency-dependent polarization noise of IC-VCSEL-1 is ~ 13 dB/Hz higher than the polarization noise of IC-VCSEL-2, which should be taken into account when choosing a OPAM implementation scheme.

The evaluation of the maximum variational sensitivity of OPAM was carried out according to the criterion of the signal steepness ratio, i.e., the ratio of the signal amplitude to the width of the resonant line, to the spectral noise density of the detecting radiation [15]. The measured parameters of a compact cubic ($0.125\,\mathrm{cm}^3$) gas cell with vapors were used to estimate the achievable variational sensitivity of a nonzero field atomic magnetometer implemented on the basis of the studied IC-VCSEL ^{133}Cs and nitrogen under pressure of 100 Torr, heated to 85°C, having a magnetic resonance line width of 1 kHz [16]. According to estimates, an atomic magnetometer based on a single-beam M_Z circuit with an operating frequency of 40 kHz, when using any investigated IC-VCSEL, can potentially have a maximum variational sensitivity of about 16 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$. In the case of using a two-beam M_X scheme, the maximum variation sensitivity for IC-VCSEL-1 reaches $57\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$, whereas for IC-VCSEL-2 the sensitivity can be improved to the level of $11\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$. For comparison, the measured sensitivity of a compact magnetometer in the M_X scheme using a cesium cell of VCSEL with a power of 0.15 mW in the detection channel and VCSEL with a power of 0.35 mW in the pumping channel was $300\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in scalar mode and $16\,\mathrm{fT/cm}/\sqrt{\mathrm{Hz}}$ in the gradiometric scheme [17]. The results obtained confirm the potential possibility of using the developed IC-VCSEL in the creation of magnetic sensors for MEG systems implemented through OPAM based on M_X- or M_Z-circuits on cells with pairs ^{133}Cs. It should be noted that the low level of polarization noise of IC-VCSEL allows them to be used inside compact OPAM without additional filtering of polarization noise in the detection channel, for example, using a polarizer or a polarizing beam-splitting cube (English polarizing beamsplitter cube).

In this paper, studies of amplitude and polarization noise of vertically emitting lasers with intracavity contacts and a diamond-shaped current aperture with various radiation output losses were carried out. It was found that for IC-VCSEL with low radiation output losses and a spectral line width of 50−60 MHz at an optical power of 0.5−1.0 mW, polarization noise becomes comparable with amplitude noise, which makes it possible to use these lasers in various optical OPAM schemes. The use of such IC-VCSEL in the two-beam M_X-OPAM circuit without the use of additional filtering of polarization noise in the detection channel potentially allows us to obtain the maximum variational sensitivity at the level of $\sim 11\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ (with an output optical power of 0.8 mW). The developed IC-VCSEL are potentially suitable for creating compact electronic magnetometric sensors for use in MEG systems.

Conflict of interest

The authors declare that they have no conflict of interest.

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