Int特色 noise characteristics of intracavity contacted VCSELs with rhomboidal oxide current aperture for the magnetometric sensor with Cs$^{133}$ vapor cell used in magnetoencephalography

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Abstract. We demonstrate noise characterization of novel 894.4 nm vertical-cavity-surface emitting lasers with intracavity contacts and a rhomboidal oxide current aperture (IC-VCSELs), dedicated to $^{133}$Cs D1 line compact optically pumped atomic magnetometers (OPM). The laser relative intensity noise, measured to be $-139$ dB/Hz at 10 kHz frequency in 1 Hz bandwidth for a laser optical power of 0.8 mW, is decreased with optical power growth. The IC-VCSELs polarization-resolved relative intensity noise is 143 dB/Hz at 1 kHz frequency in 1 Hz bandwidth for 0.8 mW. The emission linewidth of the VCSEL is about 55 MHz. The IC-VCSEL parameters are determined, such as emission linewidth ~ 50-60 MHz, optical power ~ 0.5-1.0 mW, at which the polarization-resolved RIN becomes close to the RIN, which makes it possible to use these lasers in various OPM $M_z$ and $M_x$ schemes. The ultimate sensitivity of OPM was estimated by the ratio of the magnetic resonance to the signal to noise level. It is shown that a OPM based on the IC-VCSELs, assuming magnetic resonance FWHM ~ 1 kHz, can achieve a shot noise-limited sensitivity around 20 fT in 1 Hz bandwidth without any polarization improvements by polarizer or polarization beam splitter cube (PBC). Developed IC-VCSELs is acceptable for use in compact OPM for magnetoencephalography.

Compact atomic magnetometers are widely used in geophysical equipment [1] and promising systems for magnetoencephalography (MEG) [2] for detecting brain signals. In addition to traditional MEG systems on superconducting quantum interference devices (SQUID), solutions based on optically pumped atomic magnetometers (OPM) operating in a spin exchange relaxation free (SERF) mode were proposed [3]. SERF schemes are characterized by a higher ultimate sensitivity, but operating regime require weak (order of units of nT) uniform magnetic fields. It has been recently shown that a possible candidate to replace OPM SERF schemes is OPM in a two-beam $M_x$ scheme operating in the non-zero magnetic field (units of μT) [4]. Key components of such devices are injection single-frequency laser sources and miniature vapor gas cells with alkali-metal atoms (for example, $^{133}$Cs). To be useful for precision optically pumped quantum magnetometer laser must satisfy some criteria: operate at a single optical frequency with a narrow emission linewidth, a fixed linear polarization direction, temperature...
stability of the characteristic with the ability of fine tuning the emission wavelength to the spectral line being used, a low the laser radiation noise. The laser relative intensity noise, stability of the laser emission and optical power, asymmetry of generation spectrum, appearance of polarization-hop or frequency mode-hop are responsible for signal-to-noise ratio of the magnetic resonance and its shift due to AC Stark effect (light shift). This parameters of VCSEL performance directly reflect on metrological characteristics of OPM. The possibility of using VCSEL as a source of laser emission in OPM was shown [1]. Therefore, it seems essential for further improvements of OPM to study in details VCSEL noise characteristics and various peculiarities of their performance in magnetometers.

In this work we experimentally analyzed intensity and polarization noise characteristics of our VCSELS. The comparisons of our results with results of some other works are also provided. We developed vertical cavity surface emitting lasers with 894 nm spectral range, based on a previous VCSEL design with intracavity contacts and a rhomboidal selectively oxidized current aperture (IC-VCSEL) [4, 5]. To study the influence of the laser DBR losses on the noise characteristics of the VCSELs [5], devices with different numbers of top DBR pairs were fabricated. The L-I-V curves of the free-running IC-VCSELS with various top DBR losses $A_m$ measured in CW regime are shown in Figure 1 (a, b). The $A_m$ values were obtained within the transfer-matrix method in the approximation of the absence of internal losses in the mirrors. The VCSEL#1 with high top DBR losses, $A_m \sim 0.71\%$ per one pass, has a threshold current $\sim 0.8$ mA, a slope efficiency $\sim 0.65$ W/A, a maximum output optical power of $\sim 1.4$ mW@3 mA, while the VCSEL#2 with low DBR loss $A_m \sim 0.23\%$ has a threshold current $\sim 0.5$ mA, a slope efficiency $\sim 0.37$ W/A, optical power $1.4$ mW@3 mA. The level of internal losses, obtained from the dependence of the external differential efficiency on the level of DBR losses for the two lasers, gives a value of $\sim 0.35 \pm 0.05\%$. The polarization characteristics of both devices demonstrate the predominance of preferred polarization direction with an orthogonal polarization suppression ratio (OPSR) factor more than 20 dB at injection currents more than $2$ mA.

![Figure 1](image-url)

**Figure 1.** Typical static characteristics and orthogonal polarization suppression ratio (OPSR) of the 2.5 $\mu$m VCSELS with high (a) and low (b) top DBR loss. Emission linewidths as functions of injection current for the VCSEL#1 and VCSEL#2 at 20°C.

The VCSEL emission linewidth for the fundamental mode was measured current using a Thorlabs SA-200 scanning Fabry–Pérot interferometer (free spectral range 1.5 GHz, resolution 7.5 MHz) as a function of the current injection. The emission linewidth for VCSEL#1 was 120-160 MHz, and for VCSEL#2 – 60-70 MHz at an injection current of more than $2$ mA at temperature of 20°C (Fig. 1c). Notable, the dominant polarization vector is directed along the minor diagonal of the rhomboidal oxide current aperture. Higher order modes are suppressed by 30 dB relative to the fundamental mode. We
used low noise Kethley 2400 with self-modeled low pass filter as a power source for the investigated lasers.

The magnitude of the relative intensity noise (RIN) and polarization-resolved RIN of a laser significantly affects the ultimate sensitivity of an atomic magnetometer. In this case, the widespread classical single-beam $M_z, M_x$ scheme of a quantum optical atomic magnetometer is less sensitive to the stability of the laser polarization, in contrast to atomic magnetometers based on two-beam $M_x$ schemes. The RIN of the IC-VCSEL was measured by registering the noise density in 1 Hz bandwidth by synchronous detector (Lock-in SR830) across the resistor ($20 \, \text{kOhm}$) connected in series in the circuit behind the photodetector (PD), which received laser emission. Figure 2 shows the measured relative intensity noise at room temperature and an operating 40 kHz frequency. The black dotted curve corresponds to the VCSEL#1 with high top DBR loss, the red dotted curve - to the VCSEL#2 with low top DBR loss. The theoretical quantum short noise limit of PD calculated and shown as blue curve. For both types of lasers, when the lasing threshold is exceeded with an increase in the output optical power, an almost identical drop in the RIN is observed and their saturation to -148 dB/Hz at an optical power of more than 1 mW. A slight rise in RIN at a power of more than 0.9 mW for VCSEL#2 is due to higher-order mode lasing starts. A balanced detection scheme was used to measure the laser polarization-resolved noise. The laser emission was directed to a beam splitting cube and collected by two PD with a transimpedance operational amplifier. Then the signal was sent to a synchronous detector and in the mode of measuring the noise spectral density (r.m.s.) at the required frequency, the intensity of the laser polarization noise was recorded in the 1 Hz bandwidth. The polarization-resolved RIN for two lasers with different DBR losses was measured at 40 kHz operating frequency at room temperature (figure 3). The polarization-resolved RIN level, measured at the 0.8 mW optical power for VCSEL#1 (black dotted curve), exceeds the expected theoretical quantum short noise limit (blue curve) by $\sim 18 \, \text{dB/Hz}$. While for VCSEL#2 with low DBR loss this difference is $\sim 4 \, \text{dB/Hz}$ and reaches the level of RIN at the same optical power (red dotted curve). In the polarization selection mode, an increase in the RIN level from -148 dB/Hz to -134 dB/Hz (for 0.8 mW optical power) is apparently associated with an increase in the emission linewidth of the laser emission from 60 MHz to 160 MHz with a subsequent increase in plane jitter polarization of the output laser emission. It is also worth noting the influence of the beginning of the second mode generation on the increase in polarization-resolved RIN for VCSEL#2, as well as for the RIN curve.

![Figure 2](image-url). Relative intensity noise (RIN) as a function of optical power in 1 Hz bandwidth at 40 kHz frequency; black dotted curve – measured noise for the VCSEL#1, red dotted curve – measured noise for the VCSEL#2, blue curve – theoretical quantum short noise limit.
Figure 3. Polarization-resolved relative intensity noise (RIN) as a function of optical power in 1 Hz bandwidth at 40 kHz frequency; black dotted curve – measured noise for the VCSEL#1, red dotted curve – measured noise for the VCSEL#2, blue – theoretical quantum short noise limit.

The frequency dependence of the RIN and polarization-resolved RIN measurements were made for both devices (figure 4). For the VCSEL#2 laser with a narrow emission linewidth, the polarization-resolved RIN (green curve) and RIN (black curve) as function of frequency merge into a single curve, which corresponds to the RIN vs. frequency curve for the VCSEL#1 laser. For low frequencies, about ~ 100 Hz, at which zero-field magnetometers operate in the SERF mode, the RIN is the same for both lasers and corresponds to -120 dB/Hz. At the same time, the frequency-dependent polarization-resolved RIN of VCSEL#1 is ~ 13 dB/Hz higher than the polarization-resolved RIN of VCSEL#2. For the VCSEL#2 the achieved relative intensity noise at 10 kHz is also comparable to the results obtained for ULM Photonics VCSEL with 23 MHz linewidth operating at Cs D1 line [6], we also demonstrated the obtained low polarization-resolved RIN at the RIN level.

The ultimate sensitivity of an atomic magnetometer based on the studied VCSELs was estimated by using the criteria of the ratio of the slope of the magnetic resonance signal to the shot noise spectral density and the magnetic resonance 1 kHz FWHM was taken from [7] that characterized parameters of compact cubic (5×5×5 mm³) ¹³³Cs vapor cell with N₂ buffer gas at 100 Torr. Possible atomic magnetometer at an operating 10 kHz frequency using proposed IC-VCSELs, based on single-beam Mz scheme, can potentially have a limiting variation sensitivity to be around ~30 fT/√Hz, and when a dual-beam Mx scheme employed, the ultimate sensitivity can be improved to ~ 20 fT/√Hz. For comparison, the measured sensitivity of a compact magnetometer in the Mx scheme using a cesium cell, a VCSEL with a power 0.15 mW in the detection channel, and a VCSEL with a power of 0.35 mW in the pumping channel was 300 fT/√Hz in the scalar mode and 16 fT/cm/√Hz in the gradiometric scheme [8].

The obtained results confirm that the developed rhomboidal oxide current aperture IC-VCSELs in the 894 nm spectral range are potentially suitable for use in compact atomic magnetometers based on various schemes with ¹³³Cs vapor cells. Notable, the IC-VCSEL lasers with narrow linewidth can be placed inside compact OPM, and there would be no need further to improve polarization by polarization beam splitter cube (PBC), due to comparable RIN and polarization-resolved RIN levels at optical power more than 0.5 mW.
In the presented work, we investigated the RIN and polarization-resolved RIN of vertically emitting lasers with intracavity contacts and a rhomboidal oxideized current aperture with different emission linewidth of laser. We determined the parameters of our IC-VCSELs at which the polarization noise becomes close or even lower than the amplitude noise (relevant parameters: linewidth ~60-70 MHz, optical power ~0.5-1.0 mW, oxide aperture 2.5 µm and at room temperature). This allows these lasers to be used in various OPM schemes. The one-beam scheme with signal absorption detection and the two-beam schemes with polarization rotation signal detection. The ultimate sensitivity of ~20 fT/√Hz is estimated for the potential use of developed IC-VCSEL with an emission linewidth of ~ 60 MHz and optical power of ~ 0.8 mW in a two-beam Mx OPM scheme without PBCs in the detection channel. The developed IC-VCSELs are potentially acceptable for use in compact OPM for MEG.

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