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To cite this article: M A Bobrov *et al* 2020 *J. Phys.: Conf. Ser.* **1697** 012175

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Optically pumped non-zero field magnetometric sensor for the magnetoencephalographic systems using intra-cavity contacted VCSELs with rhomboidal oxide current aperture

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Abstract. We demonstrate the possibility of using vertical-cavity surface emitting lasers with intracavity contacts and a rhomboidal oxide current aperture for creating compact optically pumped ¹³³Cs atomic magnetometer operating in non-zero magnetic fields, which is promising to use in magnetoencephalographic systems. The magnetic resonance parameters were studied in a two-beam M_x optically pumped magnetic field sensor scheme based on the effect of the magnetic resonance line narrowing at high laser pumping and high concentrations of alkali-metal atoms. The ultimate sensitivity of OPM was estimated by the ratio of the magnetic resonance steepness to the probe light shot noise level. It is shown that a magnetic sensor based on the vertical-cavity surface emitting lasers and a compact (0.125 cm³ volume) Cs vapor cell can achieve a shot noise-limited sensitivity better than 15 fT in 1 Hz bandwidth. Developed intracavity contacted VCSELs suitable for use in compact atomic magnetometers for magnetoencephalographic systems.

Traditional magnetoencephalographic (MEG) systems use superconducting quantum interference devices (SQUID) for detecting the brain activity signals. The requirement for cooling SQUIDS to a liquid helium temperatures leads to an increase in the total size of the system, and as a consequence to a decrease in spatial resolution. A recently demonstrated alternative version of the MEG system, which allows the patient to move naturally during scanning and does not require cooling. Such systems uses commercially available optically pumped atomic magnetometers (OPM) operating in a spin exchange relaxation free (SERF) mode [1]; the sensitivity of these devices reaches 10 fT/√Hz in the frequency range 1–130 Hz [2]. These compact OPMs (QuSpin Inc., USA) use a single-beam M_z scheme with laser pumping of a miniature (3×3×3 mm³ volume) ⁸⁷Rb vapor cell heated to 150°C [3]. Vertical-cavity surface emitting laser (VCSEL) is used as a pumping light source. The main drawbacks of the OPM operating in the SERF mode when used in MEG systems are 1) a requirement to provide an extremely weak (of order of units of nT) uniform magnetic field and 2) a strong mutual influence of neighboring sensors. In recent work [4] the possibility of obtaining a comparable OPM sensitivity in the non-zero magnetic field sensor using the effect of the magnetic resonance line narrowing at high optical pump power and high concentrations of alkali-metal atoms at [5] in a two-beam M_x scheme [6] was



demonstrated. In this experiment, external cavity laser diodes were used for optical pumping and probing (detecting) of the magnetic resonance in a compact (0.5 cm^3) ^{133}Cs vapor cell.

To implement OPM, laser light sources must provide single-mode generation with a line width of less than 100 MHz, and a fixed polarization plane direction combined with the ability of fine tuning the radiation wavelength to the chosen spectral line of alkaline gas (Rb or Cs). VCSELs are potentially suitable for compact OPM [7]. Based on the previously developed design of VCSEL with intracavity contacts and a rhomboidal-shaped selectively oxidized current aperture (IC-VCSEL) [8], we developed single-mode 894 nm IC-VCSEL with output optical power exceeding 1 mW, >5 GHz modulation bandwidth, more than 15 dB orthogonal polarization suppression ratio, and emission linewidth < 60 MHz at temperature of $65\text{--}75^\circ\text{C}$ range [9], which is optimal for using together with heated compact ^{133}Cs vapor cells.

Here we study the possibility of using IC-VCSEL in non-zero magnetic field OPM, based on the two-beam M_X scheme with miniature ^{133}Cs vapor cell filled with nitrogen buffer gas at 100 Torr pressure. Figure 1 shows a block scheme of laboratory setup; its key elements is a cylindrical multilayer shield with the system of an active stabilization of the longitudinal magnetic field. A compact vapor cell is located in the center of the thermostat with non-magnetic heaters, surrounded by a system of magnetic coils (Helmholtz coil system). Optical pumping and probing of the magnetic resonance was carried out by a semiconductor external cavity laser diodes (ECLDs) or IC-VCSELs. For pumping we used circularly polarized light formed by linearly polarized beam passed through a quarter-wave plate. The pumping beam was aligned to the direction of the static magnetic field; its frequency was tuned to that of the high-frequency hyperfine transition of the cesium D1 line. Probing was carried out using transverse ECDL or IC-VCSEL linearly polarized light, detuned from the absorption line center by ~ 20 GHz. To reduce the effect of the probe laser light amplitude noise in the detection channel, a balanced detection scheme was used. The magnetic resonance was excited by a transverse resonant radio frequency (RF) magnetic field, the frequency of which was set by a AC generator. The AC signal of rotation of the polarization plane of the probe beam in the vapor cell was recorded by a balanced photodetector. The output signal of the photodetector was demodulated with a synchronous detector.

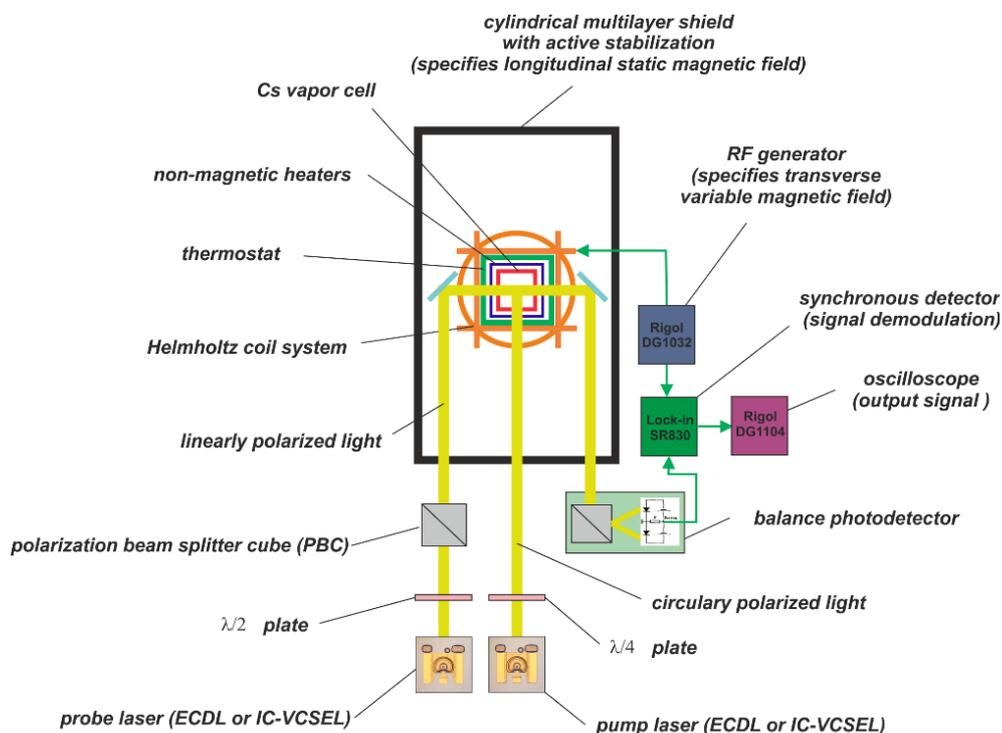


Figure 1. Block scheme of the experimental setup.

The M_X scheme used in the experiment has following advantages over the M_Z scheme used in SERF: 1) the non-sensitivity to the low-frequency noise of the magnetic environment and the laser light due to the resonant frequency transfer from units of kilohertz to the tens of kilohertz range; 2) wider frequency bandwidth; non-sensitivity to the probe laser amplitude noise due to the balanced detection of the polarization rotation.

The possibility of using IC-VCSEL instead of ECDL to excite magnetic resonance in a cubic ($5 \times 5 \times 5 \text{ mm}^3$) ^{133}Cs vapor cell with 100 Torr nitrogen buffer gas pressure was investigated. The magnetic resonance parameters were measured in a $12 \text{ } \mu\text{T}$ static longitudinal magnetic field, which ensured the minimum impact of technical noise at the appropriate Larmor precession frequency of Cs atoms (42 kHz). At each measurement, the amplitude of the RF magnetic field was optimized in order to achieve the maximum steepness of the resonance (i.e. the ratio of the amplitude of the resonant peak to its half-width). The power of the probe (P_d) and pump (P_p) at the entrance of vapor cell was kept constant ($P_d=0.5 \text{ mW}$, $P_p=1 \text{ mW}$) when using both ECDLs and IC-VCSELs. The power level was limited by the output power of the IC-VCSEL. Figure 2 shows a typical signal of optically detectable magnetic resonance measured when scanning the frequency of the RF magnetic field in the vapor cell at the 85°C with ECDL as a pump and probe source. The black curve corresponds to the M_X resonance signal modulus, the red curve – to the X component of the M_X resonance signal, which in the magnetometer scheme is used to detect the magnetic field variations.

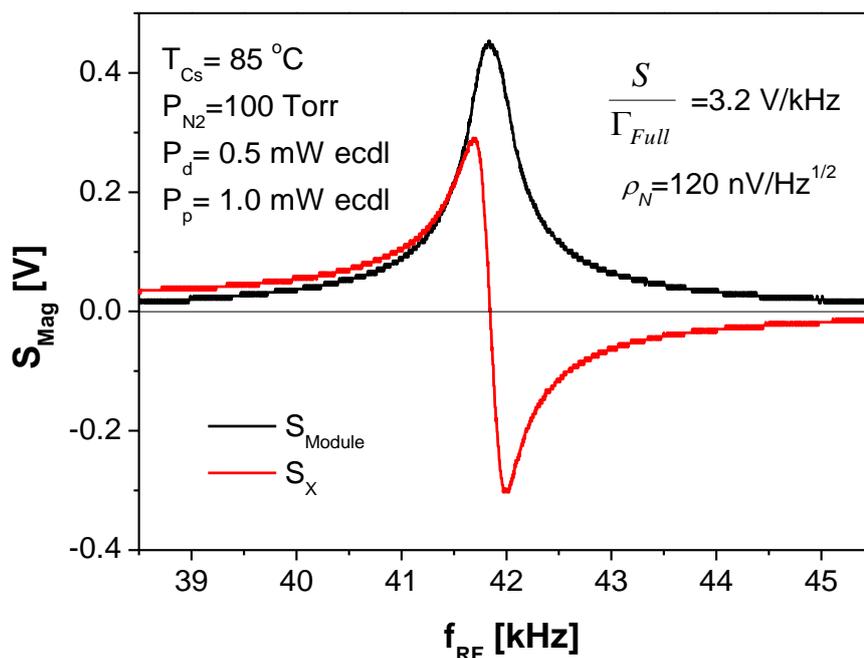


Figure 2. Magnetic resonance signal recorded with ECDLs used as a pump and probe source. Black curve corresponds to the M_X resonance signal modulus, red curve – to the X component of the M_X resonance.

We investigated the noise in the detection channel, and make sure that the noise measured in the absence of probe light (the so-called dark noise) does not exceed the shot noise level. The noise level measured away from resonance line in the presence of probe light with the RF magnetic field switched off matches theoretical short noise level. The noise level measured in the centre of the resonance line exceeds the expected theoretical quantum short noise limit by $\sim 25\%$ (figure 3).

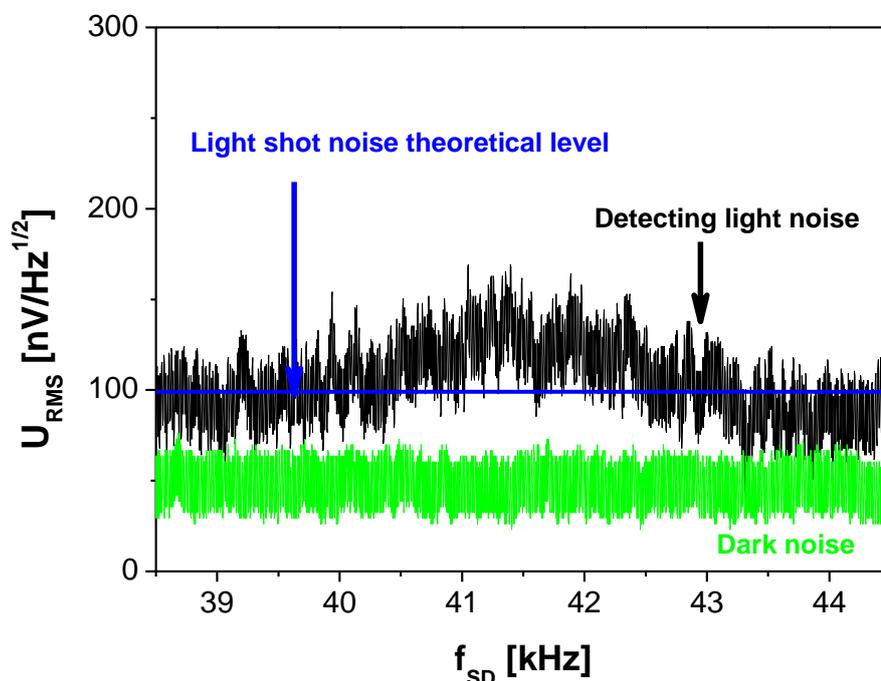


Figure 3. Noise spectral density (r.m.s.) in the detection channel in 1 Hz bandwidth; green curve – measured dark noise, blue – theoretical quantum short noise limit, black – measured noise in the presence of probe light with the RF magnetic field switched off.

The ultimate achieved sensitivity δB_{min} of OPM was estimated by the ratio of the measured light shot noise to the signal steepness, calculated from the experimentally measured amplitude and half-width of the magnetic resonance. The level of light shot noise was calculated from the measured value of the probe light intensity measured on the balanced photodetector.

For most quantum magnetometers, under the condition of predominance of light noise of the photocurrent over other noises, the following formula is valid for estimating sensitivity [10]:

$$\delta B_{min} = \frac{k_F}{\gamma} \cdot \frac{\rho_N \cdot \Gamma_{Full}}{S} \cdot \sqrt{\Delta f}, \quad (1)$$

here ρ_N – r.m.s. noise level, γ – gyromagnetic ratio, k_F (≈ 1) – resonance form factor, Γ_{full} – full resonance linewidth, S – signal amplitude at maximum, Δf – frequency bandwidth, corresponding time measurements τ .

At the first stage, the magnetic resonance parameters with ECDLs in both pump and detection channels were measured as a function of the vapor cell temperature in order to determine the optimal pump and probe power levels. Then, the optimum vapor cell temperature (85°C) was found, at which the best ultimate sensitivity of 10 fT/ $\sqrt{\text{Hz}}$ is achieved at the output power of the pump laser of $P_p=1$ mW and power of the probe laser of $P_d=0.5$ mW (see figure 4).

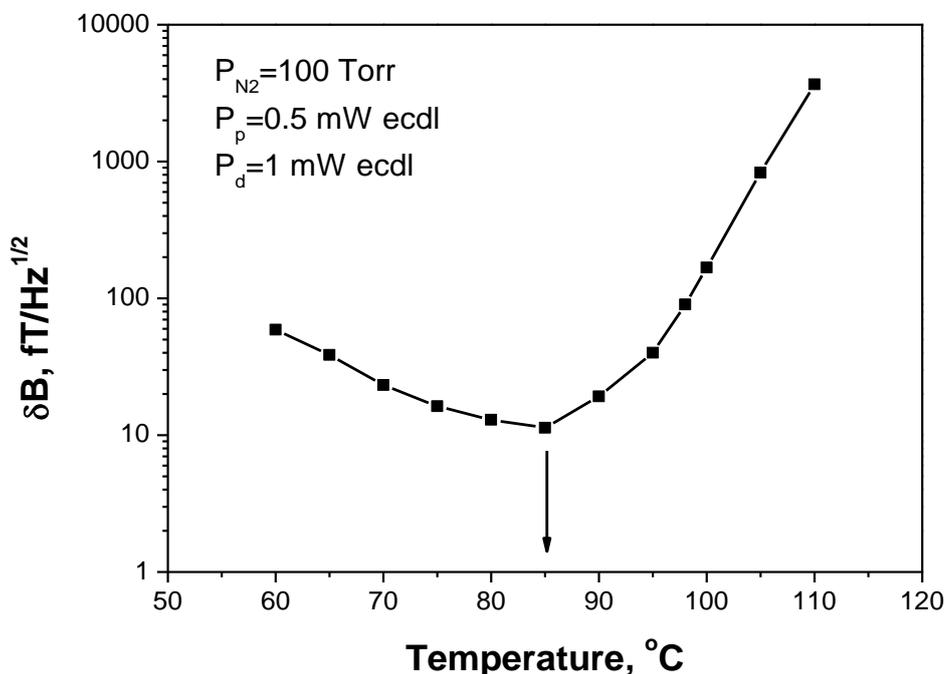


Figure 4. Dependence of estimated ultimate sensitivity measured with ECDLs in both the pump and probe channels, on the cell temperature.

At the second stage of studies, magnetic resonance parameters were measured with IC-VCSELs in the pump and probe channels at 85°C temperature; the optical power of VCSELs corresponded to the ECDL case. To stabilize the wavelength, the IC-VCSEL crystals were mounted into the thermoelectric micromodules with individual thermistors and Peltier elements. Magnetic resonance signals, pumped and detected with IC-VCSEL, showed a steepness of 2.5 V/kHz and r.m.s. noise level 130 nV/√Hz (figure 5). This makes it possible to estimate the ultimate sensitivity of the OPM according to the (1) formula: it is ~15 fT/√Hz, which is comparable to the parameters obtained with ECDL. The achieved sensitivity level is also comparable to the results obtained for compact ⁸⁷Rb vapor cell OPM operating in the SERF mode [3]. Notable, the IC-VCSEL lasers can be placed inside sensor (compact OPM), and there would be no need to distribute the laser light through expensive and acoustic-sensitive polarization-maintaining optical fibers. The usage of ¹³³Cs vapor cell makes it possible to reduce significantly (from 110–120°C to 70–90°C) the cell operating temperature compared to magnetometers using Rb, which also will reduce the distance between the OPM sensitive elements to the object of study and therefore will increase the resolution of the system.

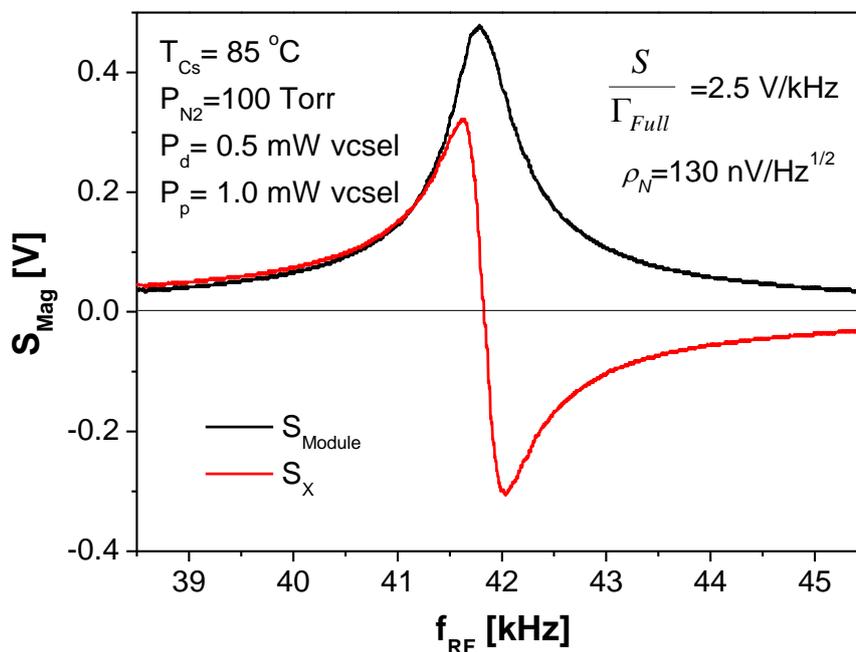


Figure 5. Magnetic resonance signal recorded with IC-VCSELs used as a pump and probe source. Black curve corresponds to the M_X resonance signal modulus, red curve – to the X component of the M_X resonance.

In the presented paper, the parameters of magnetic resonance in a two-beam M_X non-zero field OPM scheme were investigated when using a rhomboidal oxide current aperture IC-VCSELs as optical pumping and detection light sources. The ultimate sensitivity of a magnetic sensor based on the studied vertical-cavity surface emitting lasers with a compact (0.125 cm^3 volume) vapor cell with N_2 buffer gas at 100 Torr pressure was estimated and shown to be at a level better than $15 \text{ fT}/\sqrt{\text{Hz}}$. This value is comparable with the sensitivity estimate obtained using external cavity diode lasers. Thus, the developed IC-VCSEL is potentially suitable for use in compact OPMs in MEG systems.

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