Optically-controlled density of alkali atom vapor for biomagnetic sensing applications

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Abstract. Biomagnetic sensing is a powerful non-invasive tool for sensing the extremely small magnetic signals of living organisms. In recent years, the efforts to achieve higher resolution has brought about a demand for novel methods of increasing this tool’s sensitivity and further its miniaturization. In this paper, we present our studies on the optical control of the atomic vapor density in antirelaxation coated cells for application in optical magnetometry. A special system for homogeneous illumination of the cell walls is used to increase the atomic density, avoid the deposition of alkali atoms on the cell walls and reduce the coating deterioration.

1. Introduction

Biomagnetic sensing is a powerful non-invasive method for registration of the magnetic fields induced by the currents in living organisms, such as magnetocardiogram (MCG), which detects the magnetic field from the heart, magnetomyogram (MMG), from the muscles, and magnetoencephalogram (MEG), from the brain. The main concept behind biomagnetism has to do with ions that move between the living cells and induce extremely small magnetic fields compared to the magnetic interference from the surrounding environment. In order to detect such small biomagnetic signals, very sensitive magnetometers are needed [1,2].

Since the optical (atomic) magnetometers (OM) reached the sensitivity of the superconducting quantum interference devices (SQUID), optical magnetometry has been evolving very rapidly and finding more and more applications. An OM does not require cryogenic cooling and can be positioned closer to the object of interest; also, it does not necessitate shielding during the measurements [3,4]. In an OM, a pumping light polarizes the spin of the atoms. As this polarization is sensitive to magnetic fields, it changes in an external magnetic field $B$. The change of the spin orientation is detected optically by a probing laser light and a polarization detector.

**Figure 1.** AMV – alkali metal vapor, $B$ – magnetic field, PD – polarization detector.
As an example, the OM described in [5] is shown schematically in figure 1. A circularly polarized pump laser beam orients the atomic spins. The orientation of the atomic spin is sensitive to the magnetic field \( B \). This change is sensed by a linearly polarized probe beam.

The uncertainty of the magnetic field measurement performed for a time \( T \) with an ensemble of \( N \) atoms with coherence time \( \tau \) is

\[
\delta B = \frac{1}{g \mu_B} \frac{h}{\sqrt{N\tau T}}
\]

where \( \mu_B \) is the Bohr magneton, \( g \) is the ground-state Landé factor [4].

The sensitivity of the measurements increases with the square root of \( N \), \( T \) and \( \tau \). A way of enhancing the sensitivity of the measurements is to increase the spin-relaxation time \( \tau \), which is basically limited by the depolarization of the atomic spins when the atoms collide with the walls of the vapor cell. In order to increase the depolarization time, a buffer gas is usually employed; or, alternatively, an anti-relaxation (AR) coating, such as paraffin, octadecyltrichlorosilane (OTS), polydimethylsiloxane (PDMS), is applied on the inner surface of the optical cells [6,7]. High-quality coatings allow up to \( 10^6 \) bounces without relaxation. The number of atoms increases with the temperature. However, high temperatures reduce the coatings’ AR properties, because the alkali metal atoms adsorbed on the coating degrade the AR coatings and consequently shorten the lifetime of the optical cell [8]. As a result of the necessity for high density and good AR properties in a very small optical cell, the temperature chosen should not be very high, while the coating itself should remain stable at this temperature.

In general, optical magnetometers make use of alkali atoms. The most appropriate elements from the alkali metals are rubidium (Rb), cesium (Cs), and potassium (K), because their density is sufficiently high even at room temperature.

An alternative way to increase the density of alkali metal atoms confined in an optical coated cell is the light-induced atomic desorption (LIAD). It is a non-thermal process that allows one to control the alkali metal vapor density in AR coated cells by illuminating the optical cell walls with non-coherent and non-resonant light [9]. Upon illumination, the alkali atoms that have been previously adsorbed onto the surface of the coating are desorbed so that the vapor density increases. When the light is turned off, the atoms are adsorbed back on the coating or pumped by the stem, or accumulate on some part of the surface of the coating forming atomic clusters or a monolayer as a result of the inhomogeneous illumination [7,10].

In this communication, we report our investigations on controlling the optical atomic density in optical cells with possible applications in optical magnetometry.

2. Experimental setup

The experimental setup is shown in figure 2. A special system for homogeneous illumination of the cell walls is used to increase the atomic density, to avoid the deposition of alkali atoms on the cell walls, and to reduce the deterioration of the coating or accumulation of atoms [11]. It consists of a sphere coated inside with a high-reflection layer that reflects the desorbing light homogeneously over a coated optical cell; a high-power 460-nm LED; and a controller maintaining the LED current thus controlling the illumination intensity, which is compared to the intensity measured by a feedback photodiode inside the sphere.

A 6-cm long vacuum optical cell is used filled with a natural mixture of Rb isotopes. The inner walls of the cell are coated with a PDMS AR coating, which acts as a Rb dispenser when the desorbing light is switched on. The cell has an open stem filled with solid or liquid Rb depending on the temperature. Without illumination (LIAD), the density in the volume of the cell is defined by the temperature of the coldest point of the cell. In the case of cells with AR coatings, the density usually is slightly lower than that defined by the temperature due to the absorption of atoms by the coating.
3. Results and discussion

The Rb atoms density in the cell is estimated from the absorption of the 780-nm diode laser tuned in resonance with the D2 Rb line. The optical pumping, which is very strong in AR coated cells [12], is made negligible by reducing the laser light power to 4 µW. The absorption coefficient $\alpha(\nu)$ of the medium can be written in terms of $\sigma(\nu)$, the atomic absorption cross-section and $N$, the number density of the atomic vapor

$$\alpha(\nu) = N\sigma(\nu).$$  \hspace{1cm} (2)

![Figure 2. Experimental setup](image1)

Figure 2. Experimental setup

(DL – 780-nm diode laser, HR Sphere – a high-reflectivity sphere, PM – power meter, A – attenuator, LC – laser current and temperature controller, SG – signal generator, PD – photodiode).

![Figure 3. Transmission of the Rb D2 line](image2)

Figure 3. Transmission of the Rb D2 line in a PDMS coated cell with (red curve) and without (black curve) LIAD.
In figure 3, the Rb D2 line transmission spectra in PDMS coated cell are compared for two cases: when the desorbing light is not switched on and when light with intensity of 5.5 mW/cm² illuminates homogeneously the whole cell. As seen, three of the four Doppler-broadened profiles of the Rb D2 line are completely saturated and the vapor is optically thick; however, no reduction of the absorption due to photon-reabsorption [13] is observed. The calculated atomic density in this case is $N = 2 \times 10^{11}$ cm$^{-3}$, which is an increase of almost two orders of magnitude compared with the initial density.

LIAD in the case of homogeneous illumination not only significantly increases the atomic density at room temperature, but also removes atoms from the surface, thus restoring the initial AR properties of the coating. Therefore, the LIAD might contribute to increasing the sensitivity in two ways: increasing the density without decreasing the AR properties of the coating, and by removing the layers or clusters of metals on the surface of the AR coating and in this way increasing the relaxation time.

The results of previous experimental works [8,14], based on different methods of measuring the number of collisions without depolarization of the atomic spin, have shown that the relaxation rate when the density is controlled by LIAD is lower than the relaxation rate when the density is controlled via the temperature.

![Figure 4](image_url)

**Figure 4.** Number of collisions without spin relaxation when the atomic density is controlled by LIAD.

Figure 4 shows the dependence of the number of collisions without spin relaxation on the atomic density when LIAD is applied. After the initial sharp drop in the number of collisions without spin relaxation, a further increase in the atomic density by LIAD shows results in the curve flattening and approaching a constant value. This is not the case with a temperature density control, when the density continues decreasing steeply [14].

4. **Conclusions**

The investigations performed showed the potential of the optical control of the atomic density for the future development of magnetic sensors. The use of LIAD results in better AR properties at lower temperatures, which will increase the sensitivity of the OM sensors as a result of the decreased alkali atoms relaxation rate. The lower operating temperature of these sensors will extend their life as higher temperatures degrade the AR properties of the coatings over time. Lower operation temperatures will also alleviate the need for thermal insulation and consequently will favor the detection of weaker
magnetographic signals. All this will benefit the future development of new magnetic sensors with higher sensitivity and longer lifetime.

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